APPLICATION OF FORMAL SAFETY ASSESSMENT FOR DRY DOCKING EVOLUTION

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Abstract

This research has evaluated the rules, guidelines and regulations related to docking a ship in floating-graving yards. Historical failure data analysis is carried out to identify associated components, equipment and the area of defects related to ship docking evolution problems. The current status of ship docking evolution is reviewed and possible sources which cause accidents are recognised. The major problems identified in this research are associated with risk modelling under circumstances where high levels of uncertainty exist. Following the identification of research needs, this work has developed several analytical models for the application of Formal Safety Assessment (FSA). Such models are subsequently demonstrated by their corresponding case studies with regards to application of FSA for ship docking evolution.

Firstly, in this research a generic floating-graving docking model is constructed for the purpose of hazard identification and risk estimation. The hazards include various scenarios, identified from literature reviewed as the major contributors to ship docking failures. Then risk estimation is carried out utilising fault tree (FT) – FSA where there is sufficient data.

Secondly, with increased lack of data, risk estimation is carried out using FT-Bayesian network (BN) where interdepencies exists amongst identified hazards. This risk estimation method is validated with the appropriate case study identified.

Thirdly, fuzzy rule base and evidential reasoning approaches are used for risk estimation in terms of three risk parameters to select the major causes of component failure that can lead to pontoon deck failure in a floating dock. Possible risk control options (RCOs) are introduced, based on their effectiveness, to select the best RCO for minimising the risks.

Finally, a cost benefit assessment is conducted to select the best risk control option using BN, where selections are based on economic terms. The four subjective novel FSA application methodologies in ship docking evolution are constructed from existing theoretical techniques and applied to real situations where data collection is otherwise not possible. The construction of the novel methodologies and the case study applications are the major contribution to knowledge in this thesis. It is concluded that the methodologies proposed possess significant potential for the application of FSA for ship docking evolution based on the validations of their corresponding case studies, which may also be applied with domain specification knowledge tailored to facilitate FSA application in other shipping industry sectors.

Table of Contents

Chapter 3 Fault Tree – Formal Safety Assessment in Docking Operation…..………………………65

Chapter 5 A Fuzzy Rule-Based Approach For Risk Analysis In Dry Docking Operation……......152

List of Tables

List of Figures

Abbreviations

BN	Bayesian Network
BRB	Belief Rule Base
BRBI	Belief Rule Base Inference
BSL	Bureau of Statistic of Labour
CAF	Cost of Averting a Fatality
CB	Cost Benefit
CPD	Conditional Probability Distribution
CPT	Conditional Probability Table
CS	Consequence Severity
DST	Demspter-Shafer Theory
ER	Evidential Reasoning
FCP	Failure Consequence Probability
FDST	Fuzzy Dempster-Shafer theory
FL	Failure Likelihood
FIS	Fuzzy Inference System
FMEA	Failure Modes and Effects Analysis
FRBS	Fuzzy Rule Base System
FSA	Formal Safety Assessment
FST	Fuzzy Set Theory
HSE	Health Safety Executive
ILO	International Labour organisation
IMO	International Maritime Organisation
IAEA	International Atomic Energy Agency
MSC	Maritime Security Council
NPT	Node Probability Table
OHS	Occupational Health and Safety
OSHD	Occupational Safety and Health Division
RCO	Risk Control Option
RINA	Royal Institute of Naval Architects

Chapter 1 – Introduction

Summary

This chapter first introduces the key information used in this research. The research aim and objectives are then defined, followed by the background analysis. Following on, the challenges of conducting the research, research methodology and scope of the thesis are demonstrated. Finally, the structure of the overall thesis is given.

1.1 Background Analysis

Shipbuilding and repair is an extremely complex business, which means a significant number of tasks must be performed in parallel. The handling and processing of steel through the production process requires the greatest amount of facilities and space in shipyards (Baris, 2012). In such large organisations, processes often depend on complex and distributed interactions between human operators and technical systems, which are intensive and regulated by procedures (Sybert *et al*., 2008). This has contributed to high risk and fatalities. Therefore, there is a need to introduce risk based decision making to optimise resources.

Based on the United State of America Bureau of Statistics, shipyards remain one of the riskiest workplaces in the Some 115 fatalities and 1620 reported accidents were registered in Turkish Shipyards alone, between the period of the year 2000 and 2010, 3.5 times the average of all industry groups (Baris, 2012). The result from this finding shows five major typical accidents at shipyards in order of occurrence as: falling from a height; exposed to electric shock; fire/and or explosion; being struck by or stricking against objects; and caught in between objects.

From a safety assessment point of view, determinants of the complexity of the organisation under study are stated as (Sybert *et al*., 2012): (1) The number and types of entities in the organisation (human roles, technical systems); (2) The number and types of interdependencies between entities in the organisation; (3) The number and types of hazards in the organization i.e. situations/conditions that potentially affect the level of safety; (4) The amount of data available for hazard analysis, and risk control. Perrow (1984) argues that the results of growing complexity of socio-technical systems and human inability to understand and control these accidents should be considered as natural occurrences rather than abnormal phenomena. Hollnagel (2004) builds further on the notion that accidents are normal occurrences and stresses the role of performance variability from the origin of accidents. In dry docking (bringing a ship for repair out of water), there exist some challenges and fatal accidents reports as well. Notably, on March, 27, 2002 at Dubai Dock No 2 (one of the world's largest ship repair facilities) ‘gate failure’ caused uncontrolled flooding of the dock leaving 21 people dead (Paul, 2011).

This incident and others have raised safety concerns in the operation and safety management assessment in shipyards especially dry docking operations. This has been the challenge in respect to shipbuilding and repair system safety standing out as being complex and uncertain. The adoption of the formal safety assessment (FSA) concept will be used to solve existing gaps. Existing gaps within the framework include the lack of experts to carry out a proactive risk based approach to deal with accidents and eliminate its occurrence from its origin as Hollnagel (2004) states.

There has been a high level of uncertainty in historical failure data, which shall be addressed in this study, by using novel subjective approaches (Chiou, 1995). The inherent uncertainty can be caused by imperfect understanding of the domain, incomplete knowledge of the state of the domain at the time where a given task is to be performed, randomness in the mechanisms governing the behaviour of the domain, and/or the combination of these (Eleye-Datubo *et al*., 2006).

FSA, a process of identifying hazards, evaluating risks and deciding on an appropriate course of action to manage this risk in a cost-effective manner, shall be used in this study (Trbojevic and Carr, 1997). This methodology has relevant published applications in the maritime field with successful impact (Wang and Foinikis, 2001; Hu *et al*., 2007; Lee *et al*., 2001). It consists of 5 steps (Hu *et al*., 2007) : hazard identification, risk assessment, risk control options, cost benefit assessments and decision making. In this study, sequential accidents shall be analysed for safety assessment of docking vessels with failure models. A novel decision making technique will be developed for selecting the best risk control options (RCOs) in dry docking operations.

1.2 Research Aims and Objectives

The aim of this work is to develop a new safety assessment methodology for dry docking operations to enable the identification and prioritisation of dry docks hazards, for the quantitative analysis of the associated risks and rational decision of selecting the best control options. The objectives developed to achieve this aim are as follows:

1. To develop qualitative frameworks for representing relationships of components and subsystems of dry docking operation and systems;

2. To develop new risk assessment approaches supporting the novel quantitative method using Fault Tree Analysis (FTA) and FSA.
3. To develop novel models for hazard identification and risk analysis in dry docking under uncertainty using fuzzy set, Bayesian network (BN), and evidential reasoning (ER);
4. To apply fuzzy Truncated Normal ranked nodes Bayesian network in multi attribute group decision making for cost/benefit assessment of RCOs in dry docking operations;
5. To identify software packages based on the applications of the above models in real cases in order to demonstrate their applicability and feasibility.

1.3 Challenges in Conducting this Research

Floating and graving dry dock failure data are scarce or incomplete; as such the uncertainty associated with docking and undocking evolution problems may significantly undermine the risk assessment conducted based on traditional risk assessment techniques. In order to deal with these, novel risk assessment techniques have to be developed and applied as part of this work.

These novel uncertainty treatment methods should be capable of providing satisfactory results. The first challenge under uncertainty comes when risk estimation is conducted for the identified hazards. Hazard identification is normally carried out by employing traditional hazard identification techniques such as preliminary hazard analysis (PHA) and, hazard and operability study (HAZOP).

Hazard identification and risk estimation can also be conducted by utilising techniques such as FTA and event tree analysis (ETA). However, due to high levels of uncertainty related to docking and undocking evolution problems, such techniques may be unsuitable; therefore the solution is achieved by developing a novel approach with the combination of fuzzy set theory, evidential reasoning, and Bayesian networks.

The second challenge is associated with decision making based on risk estimation results under a high level of uncertainty. The problem becomes more complex if interval data has to be taken into account. Interval data increases the complexity of criteria aggregation which further increases the complexity of the problem.

It should be noted that when the complexity of a problem increases, uncertainty will be further increased. These problems can be solved and decision making conducted by combining fault tree (FT), BN, fuzzy rule base and ER. The third challenge under uncertainty arises when risk control options are chosen for identified areas of high risk estimation.

The five steps of the FSA framework (hazard identification, risk estimation, risk control options selection, cost benefit assessment and decision making) can be facilitated to deal with docking and undocking evolution risk analysis problems by developing the above mentioned four subjective fuzzy modelling based approaches with a combination of various uncertainty treatment methods. Expert judgement plays a vital role in this subjective assessment. The uncertainty which comes from the lack of data is recognised as the major challenge of conducting this research.

There is also the challenge of validating the generic models developed in each technical chapter. These are all novel models in an area where no conceptual scientific risk assessment work has been done so far. However, this challenge is partially met by applying these models to real floating and graving dry docks.

1.4 Research Methodology and Scope of Thesis

The main research methodology of this thesis is based on risk assessment conducted under the safety principles of FSA. As described in the previous sections it is achieved by using the four core technical chapters of this thesis. The main methodology is outlined in the following sections. In this research, the FSA method adaptation for risk control in floating-graving docking operations is investigated.

Research on the application of FSA to prevent hazards or failures in these systems is rare. So far, the safety assessment approach for risk analysis in certain identified hazards in floating-graving dock operations has arrived at some conclusions. Nonetheless, the key element for reaching adequate results is gaining suitable data. Often, intelligent building domain data are collected as a linguistic variable. Then they are processed into numerical data with some errors. But even if data are hard to obtain and vary a lot with time, the FSA method based on fuzzy set theory, Bayesian network, and evidential reasoning helps to get an acceptable outcome, has great tolerance and is insensitive to errors made in swapping linguistic into numerical data, which is the biggest problem in such domains of research (Mikulik and Zadjel, 2009).

The FSA management process in dry dock is an enhancement of the traditional safety management process in that the three fundamental components – surveillance, periodic dry dock safety reviews, and maintenance procedures – are central to the procedure. Together they permit informed decision making concerning the manner in which the risks are being controlled. The purpose of this section is to provide an overview of the various aspects of the dry dock formal safety assessment management framework in line with the outcome of this PhD research. A comprehensive framework is illustrated in Figure 1.1.

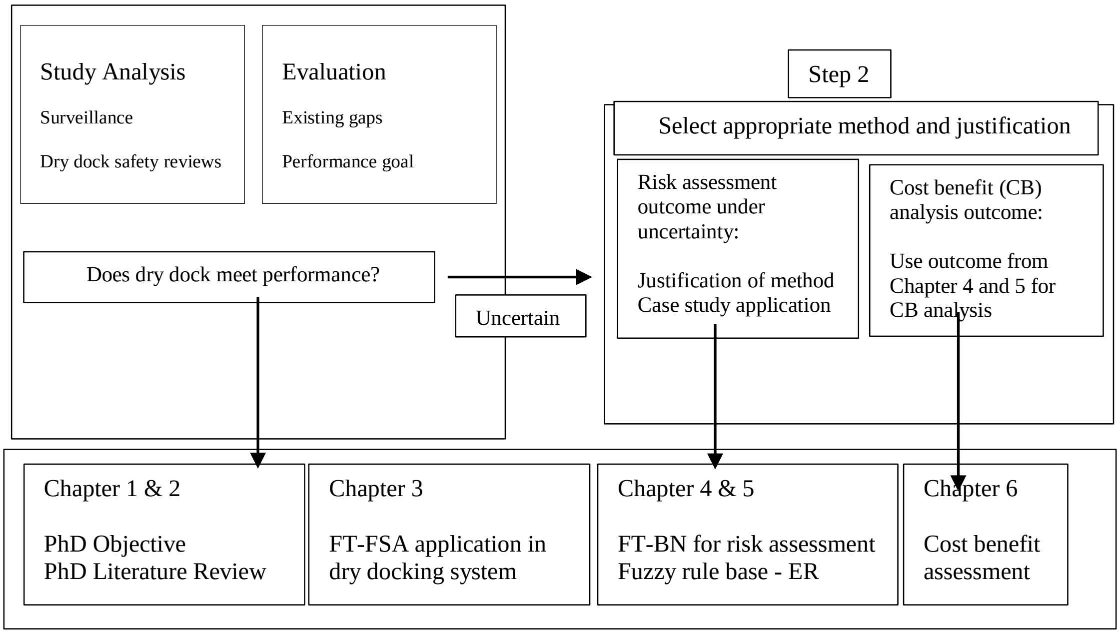


Figure 1.1: Research Methodology

1.4.1 Introduction and literature review

The significance of carrying out an analytic literature review is crucial for the success of this study. It is the first step for conducting this research. Examination is focused on ship repairing systems and risk analysis methods. Relevant conference papers, journals, books, websites will be identified. Priority, however, shall be given to the latest work. Greater attention will be paid to various ‘risk based’ and ‘proactive’ risk assessments, to tackle the objective of this work.

1.4.2 Fault tree –formal safety assessment in dry docking evolution

The relevance of the methodology of FSA has been proven in marine and offshore systems such as fishing vessels, ports, marine transportation, offshore support vessels, containerships, LNG ships, ship hull vibration, crushing ships, liner shipping, high speed crafts, oil tankers, trail studies of passenger roll on/roll off (roro) vessels with dangerous goods and bulk carriers (Nwaoha *et al.*, 2012). By applying the FSA methodology, a new risk analysis framework in the ship repairing industry is outlined below: (1) Hazard identification - The first step is the foundation of FSA. It is to identify hazards in dry docks. Hazard is a physical situation or condition with the potential for human injury, damage to property and/or environment. In a dry dock system, historical data and expert judgement using a brain storming technique are used to identify hazards. Experts are drawn from dry docking design, operations and management.

The FTA approach is used to determine hazards, possible causes and outcomes of each accident category deductively; (2) Risk assessment - The second step is risk assessment. It is to identify the distribution of risk, thereby focusing on high risk areas that need to be controlled. Risk assessment is a comprehensive estimation of the probability and the degree of the possible consequence in a hazardous situation in order to select appropriate safety measures. In this step, risks associated with the identified hazards of dry docks system in step 1, are evaluated to determine their significance. This step provides qualitative and/or quantitative information to decision makers. Many new quantitative risk analysis models will be developed to tackle the inherent uncertainties in this work; (3) RCOs are developed based on results from step 2. The purpose of this third step is to propose effective and practical RCOs comprising of, focusing on risk areas needing control, identifying potential risk control measures (RCMs), evaluating the effectiveness of the RCMs and grouping RCMs into practical regulatory options.

Again, appropriate interviews will be carried out to develop RCOs; (4) Cost benefit assessment - The fourth step is to identify and quantify the cost to be paid and benefit to be expected when each RCO developed is implemented (Lee *et al.*, 2001). Each RCO is evaluated in terms of cost implementation and then by deriving its associated cost per unit reduction in risk (CURR); (5) Decision making- The final step is safety recommendations in dry dock presented in an auditable and traceable manner to relevant decision makers. These recommendations are based upon comparison and the cost benefit analysis of RCOs. A new multi-attribute decision making model will be established in this step.

Many quantitative analyses are required in Steps 1 and 2. Fault Tree Analysis (FTA) is used in these steps to provide the inputs for steps 3, 4, and 5 in dry dock safety assessment. However, challenges of using FSA in dry dock safety assessment are: (1) Gathering enough materials from experts; (2) Quantitative analysis needs the support of various databases; (3) Field measures requires a significant period of time for statistical collection. To overcome these challenges, databases shall be widened to include the following; Marine Accident and Investigation Database (MAID) UK, Shipbuilders Council of America, National Shipbuilding Research Program, American Shipbuilding Association, Occupational Safety and Health Administration UK, Shipyard Workers Union of Turkey, Chamber of Turkish Naval Architects and Marine Engineers, International Dry Dock Accidents and Registration.

FTA on the other hand, is a very popular and diffused technique for modelling and evaluation of large, safety and critical systems. Henley *et al*. (1995) carried out a diffused analysis on dependability modelling using FSA. It is a deductive analysis, starting with potential or actual failures and deducing their causes (Chris *et al*., 2012). Root causes of failures frequently have to be inferred from multiple indirect observations. Fault trees are intended for reliability and fault analysis rather than diagnostic observation (Wojtek and Milford, 2006).

FTA has wide application in system safety engineering such as security design, risk assessment, and the management of safety critical projects (Zhuang *et al*., 2011). FTA shall be undertaken for preliminary safety analysis, especially the qualitative analysis of identifying the root causes for the development of RCOs. FTA is an effective methodology in the safety analysis of system; it also has some deficiencies especially when being used in complex engineering systems such as dry docking. These disadvantages include (Hu *et al*., 1995); (a) Events in FT are assumed to have only two states, namely working or failure, but in actual engineering some events are polymorphic; (b) Events in FT are assumed independent, but actually some of them may have interdependent relations.

1.4.3 An advanced Fault Tree-Bayesian Networking approach for risk analysis

The combination of these two approaches, has been reported in aerospace and manufacturing industries (Zhuang *et al*., 2011). BN is an approach to deal with intrinsic drawbacks in FTA. This method is based on uncertainty treatment theory. It is usually grouped under uncertain categories like fuzzy logic, Markov models, artificial neural networks, Monte Carlo simulation, grey theory, and Dempster-Shafer theory (Yang *et al*., 2005).

BN has great ability in modelling randomness and capturing nonlinear causal relationships. This potential has increased its popularity in recent years. Yang *et al*. (2008) states that it is '*a powerful risk analysis tool*,' because it can be used in a range of real applications concerned with predicting properties of safety critical systems. The most important step is to map FT to BN. Every FT can be mapped to its corresponding BN. Mapping steps used in this study may refer to He and Tao (2011): (1) Create a root node in the BN for each basic event of the FT, and merge the same basic event appearing many times in the FT into one root node in the BN; (2) Assign the root nodes of BN the prior probabilities corresponding to the basic events of FT; (3) Create the corresponding node in BN for each logical gate of FT, and use directed arcs to connect these nodes in order to indicate the relationships between them; (4) Assign the nodes in BN the conditional probabilities for the corresponding logical gates of FT. The advantage of using FT-BN is highlighted in its application to the safety of critical systems such as aircraft (Jiye *et al*. 2011), vessels (Zhuang *et al*. (2011), and software development (Chris and Kernel, 2012).

A novel conversion approach is proposed, consisting of 15 steps, for FT-BN mapping analysis in failure analysis of dry docking. These steps include: gather information, develop FT of dock failure, assigning of occurrence probability of basic events, calculate minimum cut sets, calculate prior probability of top events, mapping fault tree to Bayesian network (4 steps), establishing nodes with dependency, create conditional probability table (CPT) and prior probabilities for each node, normalise probability propagate evidence, and calculate posterior probability.

Consequently, the common uncertainty issue associated with partial dependence among FT events can be appropriately tackled in dry docking safety analysis. A common criticism of the Bayesian approach is that it requires too much information in the form of prior probabilities, and that this information is difficult or impossible to obtain in risk assessment (Yang *et al*., 2008).

Again, the BN approach is based on probability theory; it aggregates data without differentiating aleatory and epistemic uncertainties. Moreover, it requires a priori information which sometimes limits its application to updating existing information (Sadiq *et al*., 2006). Lastly, a BN approach may not properly aggregate multi-expert knowledge where and when it is required. Fuzzy evidence theory addresses these issues effectively and is able to combine conflicts through a belief structure (Lefevre *et al*., 2002; Bae *et al*., 2004; Saliq *et al*., 2006).

1.4.4 Fuzzy rule base with belief degree for risk analysis in dry docking evolution

The success of FSA depends on how practical solutions are provided for decision making under uncertainty in dry docking operations. Fuzzy evidential reasoning (FER) capable of dealing with uncertainty can be used either as a stand-alone method or combined as a part of an FSA methodology (Godaliyadde *et al*., 2009).

The main focus of this thesis is to use fuzzy theory and evidence theory approaches, to deal with linguistic/subjective uncertainties of event probabilities, and the latter is used to handle incomplete/partial ignorance of expert knowledge (Ferdous *et al*., 2009). The FER approach in assessing terrorists attacking ports (Yang *et al*., 2005) and for risk control of a liquefied natural gas carrier (Nwaoha *et al*., 2011) has been tested to yield good results. Yang *et al.* (2005)

highlighted the advantage of using the FER method to deal with those threat-based risks, which are more ubiquitous and uncertain, than hazard-based risks in supply chains. Another advantage is presented by Wang (2000), as a subjective modelling tool, applied to formal ship safety assessment. The richness of the FER algorithm is also reported in several other maritime risk and safety assessment studies (Wang *et al*., 1995 and Wang, 1997).

Fuzzy sets and evidence theory have proven effective and efficient in handing uncertainties in data, especially data unavailability and incompleteness (Cheng, 2000; Sentz and Ferson, 2002; Wilcox and Ayyub, 2003; Bae *et al*., 2004; Ayyub and Klir, 2006). Using this method in dry dock operation, FER is capable of combining uncertain evaluations of failure mode level and implementing hierarchical propagation of evaluations between different levels' of operations. To demonstrate the applicability of these approaches in risk assessment in dry docks, a case study for 'dry dock gate failure' will be revisited.

A fuzzy rule based system with final evidential aggregation is proposed for risk analysis in floating dry dock. Accidents involving transverse bending failures of dry dock pontoons are presented. Fuzzy rule based systems are one of the most popular approaches for representing the knowledge because of some of their unique characteristics. The simplicity of analysis of complex systems and modelling the nonlinear relationships of the input-output in the realm of fuzzy inferences system (FIS) are some of the promising features (Aminravan *et al*., 2011).

A general structure of rule-based belief functions for knowledge representation was presented by Eddy and Pei (1986). Most of the suggested belief rule based systems use evidential reasoning algorithms to aggregate the uncertain knowledge presented on belief structures (Aminravan *et al*., 2011). Amongst all evidential reasoning methods, the Dempster-Shafer theory (DST) (Dempster, 1967 and Shafer, 1976) provided a framework for handling granularity, non-specificity and conflict and was successfully used in different applications.To date, several evidential reasoning algorithms using distributed modelling framework based on DST have been introduced (Yang and Singh, 1994 and Smets, 2007).

The advantage of using this approach in this thesis is that fuzzy rule based systems (FRBS) have the capability to model and interpret vague information in a linguistic environment. FRBs have found a wide variety of applications in various engineering problems.

1.4.5 Risk control options and cost benefit analysis for docking operation

A robust method for evaluating the cost-effectiveness (CE) of risk control options (RCOs) analysis proposed in the outcome of risk analysis is required. However, the deficiencies of current CE methods are highlighted, undermining the lucidity and consistency in application. The proposed approach outlines a subjective mathematical formulation that neatly integrates all aspects of CE measures along with its application based on the ranked nodes with Truncated Normal distribution Bayesian network. This method is used in FSA for docking and undocking evolution demonstrating the ease of the application and clarity of results interpretation.

FSA forms the basis for decision making towards mitigation of risk. The latter is done through determination of RCOs ranking them according to impact on risk and cost, and provision of recommendations as to which RCOs are most sensible. Major FSAs submitted to the International Maritime Organisation (IMO), encompassing different ship types such as LNG carriers, container vessels, and roll-on-roll off passenger vessels, identified a number of RCOs for each ships (Puisa and Vassalos, 2012).

1.5 Structure of the Thesis

This thesis is composed of eight chapters, with Chapters 3, 4, 5, 6 and 7 being highlighted as its core. The titles of the eight chapters are summarised in Table 1.1.

Table 1.1: Summary of Chapters in Thesis

Chapter No.	Title
1	Introduction
2	Literature Review
3	Fault tree-Formal Safety Assessment in Dry Docking Evolution
4	Fault tree-Bayesian Network for Graving Dock Gate Failure Analysis
5	Fuzzy Rule Based with Belief Degree for Structural Failure of Floating Dry Dock Pontoon
6	Risk Control Options and Cost Benefit Analysis of Dry Docking Evolution
7	Integration of the Developed Methods
8	Conclusion

Definitions of typical terms is listed in Appendix 1.
One publication arising from this research is listed in Appendix 2

Chapter 2 – Literature Review

Summary

The literature review conducted in this chapter is broad. It includes a review of standards and regulations of dry docking a vessel, historical failure analysis, a critical review of floating and graving dry dock industry, introduction of Formal Safety Assessment (FSA), a critical review of marine risk assessment, and justification of the research. Generally, this chapter gives an overview of the current status related to dry docking and undocking evolution problems. The fundamental aspects and benefits of FSA approaches to dry dock safety are described. The guiding principles of the application of a FSA framework for risk-based dry dock safety surveillance, periodic dry dock safety reviews, and the operations procedures are outlined. The critical review of traditional and novel risk assessment is conducted to select the most suitable techniques for conducting risk assessment, identify risk control options and conduct a cost benefit assessment based on the safety principles of FSA. Finally, justification of the research is discussed. Though the focus of this work is the safety of existing dry dock systems, the concepts are equally applicable to the design of new ones.

2.1 Introduction

Operating shipping fleets requires professional organisations to execute various processes in terms of administrative, technical, and operational matters (Celik and Er, 2006). Performing docking operations – which are the biggest logistical and planning issue in the context of planned ship maintenance programmes – is one of the critical processes for ship managers under the control of technical and operational divisions (Celik and Er, 2006).

In general, shipyards have specialised workshops and spaces such as mechanical, electrical, steel sandblasting, docking, painting, and others. Routine docking works such as washing, grit blasting, coating, sea chest cleaning, proper dismantling, polishing, controlling of tail shaft and stern tube seals can be listed as the main facilities during a docking period (Celik *et al*., 2009). The shipping firm's roles in the docking process begins with planning the time, period and concept of the work and finishes with the trial voyage and completing the required tests of the systems at the end of the whole process.

The selection of a suitable shipyard with respect to many criteria such as ship position, reputability of shipyard organisation, previous experiences of yards, size of required work, limitations of shipyard, equipment capacity of yard, etc., is needed, and a wide range of market surveys and a detailed analysis are required to make the final decision (DSC, 2013). A shipyard organisation with a well-designed docking system which adapts the required technology into the whole process can manage to perform this process in both a safe and efficient manner. From the viewpoint of shipyard organisational safety, the facilities of design, construction, and docking process should be well organised for the application of FSA to satisfy customer expectations and prevent conflicts after unexpected accidents.

An important change in the dry docking industry is the application of FSA. In the middle of the 1990s, in order to promote and improve maritime safety, the International Maritime Organisation (IMO) adopted FSA, which was initially put forward by the Maritime and Coastguard Agency (MCA) at the 62nd meeting of the Maritime Safety Committee (MSC), which introduced FSA to the marine industry and put it into use, and asked its members to be actively involved in the research on ship safety (Fang *et al*., 2004). FSA is a systematic formal and integral assessment approach.

The purpose of the application of this method in the safe management of dry docking evolution, ship design, and shipping is to use the five-step procedure of FSA to conduct an overall analysis of dry dock design, inspection, operation, and maintenance, etc., thus enhancing maritime safety. FSA can be used as a tool to improve measures and regulations or to make new ones on the basis of the analysis of current dry dock designs and engineering techniques, of ship docking operation and control, standards and regulations of safe management, together with the combination of realistic needs (Wang, 2001). FSA has changed the traditional reactive regulatory framework towards a risk-based and goal-setting regime. Risk assessment and cost-benefit analysis are carried out to complete FSA.

The application of traditional methods of risk assessment may prove difficult when faced with new hazards and uncertainty. Novel approaches and techniques towards risk assessment are required in order to deal with such problems. In this chapter, a critical review of floating-graving dock is conducted to determine the current status of docking problems. A background study is carried out on a floating-graving docking system, highlighting its layout, trends, and factors affecting the selection of a dry dock system. The ship docking specification is also reviewed and the corresponding standards and regulations of floating-graving docks are presented. Following this, an introduction to FSA and a critical review of the marine risk assessment are given. Finally, a justification for this research is presented.

2.2 Review of Failures in Floating-Graving Docking System

Dry or *graving docks* are used to enable the ship's bottom and underwater fittings to be inspected and worked on (Tupper, 2013). They normally consist of a basin dug into the shore of a body of water and provided with a watertight gate on the waterside, used for major repairs and overhaul of vessels. When a ship is to be docked, the dry dock is flooded, and the gate opened. After the vessel is brought in, positioned properly and guyed, the gate is closed and the dock is pumped dry, bringing the craft gradually to rest on supporting keel and bilge blocks anchored to the floor (Cheng *et al*., 2004).

A floating dock on the other hand usually takes the form of a U-shaped box structure with side walls mounted on a base pontoon. A large part of the structure is devoted to ballast tanks which are free flooded to sink the dock. The dock, with the ship, is then raised by carefully controlled pumping-out of the ballast tanks. The sequence of pumping is such as to limit the longitudinal deflection of the dock (and hence the ship in it) to avoid undue longitudinal bending moments (Tupper, 2013). Besides undue longitudinal bending moment is the positioning and stiffness allocation of docking blocks, which are important decisions when docking a ship because mis-positioning or mis-allocation of docking blocks may give rise to unreasonably large block reactions and consequently serious damage to both the docked ship and blocks. Docking block failures may also cause the disruption of docking schedules and an extension of ship downtime. Any failure may lead to the loss of lives (Cheng *et al*., 2004).

Marine dry docks have been subject to study and research from several points of view such as environmental, hydrodynamic design and construction (Najafi-Jilani and Naghavi, 2009). Likewise, docking analysis has attracted the attention of various researchers. Jiang *et al*. (1987) developed a reliable, efficient computer program for predicting block reactions in both graving and floating docking analyses. Cheng and Zeng (1995) proposed a mathematical model for optimising the positioning and allocation of docking blocks which ignored potential uncertainties in their design. Two-level optimisation techniques were employed to solve the optimal solution in their study. Cheng et al. (2004) proposed the convex model (mathematical model) in which the indeterminacy about the uncertainty variables in designing docking blocks is presented. Numerical examples were used to show that uncertainties affecting the optimal solution can lead to an increase in volume of blocks compared to deterministic optimisation. Technical considerations and investigations on docking facilities are discussed within various studies in the literature such as strength analysis of floating docks (Cheng *et al*., 2004), robust design of docking blocks (Cheng *et al*., 2004), predicting dry dock block reactions (Taravella, 2005), and other related research. On the other hand, computer integrated supply chain management (Chrysoolouris *et al.*, 2004), integrating lean model for repair and maintenance (Verma and Ghadmode, 2004) and work flow cost model of repairing activities (McDevitt *et al*., 2005) are seen in the literature as ongoing research regarding the planning and implementation process of docking facilities in shipyards. A fuzzy axiomatic design-based performance evaluation model for docking facilities was proposed by Celik *et al*. (2009), with the goal of overcoming the selection problem with respect to several criteria to find the most suitable shipyard. The effects of dry docks on marine hydrodynamics are mainly related to the significant amounts of pollutants which build up over dry dock surfaces because of intensive industry activity (Akan *et al*., 2000, and Kretzschmar, 2000).

The construction of dry docks is a complex procedure which needs a scientifically integrated management technology (Kumanoto *et al*., 1990). Special design concerns are considered for a dry dock with marginal wharf surface (Thibeaux *et al*., 2004, and Arroyo *et al*., 2002) and also in the control of dry dock operations (Regan *et al*., 2007). A special loading pattern exists on dry docks due to uplift pressures (Kinner and Stimpson, 1983) and the interaction of marine hydrodynamics and structures has also been researched (Fernades and Correia, 1986, Lai and Lee, 1989, Shugar *et al*., 1991, and Cheng *et al*., 2002).

Another concern in the design of dry docks is the total time required to fill them with water (JLARC, 2006). The filling time depends mainly on the specifications of a flooding system which is generally operated by gravity. The main components of the flooding system such as an intake channel and guide walls are generally extremely complex. Also, the interaction of dry docks and marine hydrodynamics and sedimentation is also a major issue in design (Seelam, 2008). Najafi-Jilani and Naghavi (2009) insisted on the necessity to investigate the hydrodynamic behaviours of dry docks, the flow patterns, and the efficiencies of the flooding system using the numerical method as a proposed method to analyse the flow through the flooding system.

The maintenance and safety certification of graving dry docks is essential in supporting fleet operation and readiness. Wu *et al*. (1990) proposed stability analysis and displacement measures of graving dry dock walls using distance measuring instruction. Periodic docking facilities can be recognised as the biggest logistical issue in the content of ship maintenance programmes and are the critical process from the viewpoint of ship-owners. Since the relationship between ship management and shipyard continues during the life cycle of operating ships, it is required to have a well-planned and organised system (Celik *et al*., 2009). In this new era, new safety rules place new demands on ship operators and dry dock operators to increase the quality of floating-graving dry dock operations and improve safety (Inozu and Radovic, 2002).

Docking ships are potentially hazardous operations as the ship passes between the dry and waterborne conditions. A ship may run aground either due to human error in navigation, due to obstacles not recorded on charts, or due to the failure of the ship's control systems (Tupper, 2013). It is therefore important that they are studied in some depth (Tupper, 2013). Although docking is now less frequent because hull coatings to reduce corrosion remain for longer, and although more can be achieved in the way of repairs with a vessel still afloat, the docking industry remains vital in the economy of the shipping industry (Tupper, 2013). Since it is planned to make an evaluation from the viewpoint of shipyard-owners, this research focuses on expectations and execution activities of the technical and operational departments of ship management companies regarding the docking process by implementing FSA. However, uncertainties in material, geometric properties, loads etc., are unavoidable in the design of engineering structures such as floating-graving docks.

2.3 Floating-Graving Docking Systems

Dry docks are structures that allow complete dry access to a vessel for maintenance, overhaul, and repairs, or for new construction and launching. They are the workhorses of ship repair facilities and may be used in lieu of traditional building ways at shipyards devoted to new construction. There are various types of dry docks, including those that physically lift the ship from the water such as floating dry docks, marine railways, and vertical-lift systems, and traditional basin dry docks that dewater an enclosed space around the vessel (Becth and Heger, 2006). Only floating and graving dry docks are considered in this research. This section is intended as an introduction to floating and graving dry docks and their basic principles of design and operation.

2.3.1 Shipbuilding and ship repair yards

Shipyards are industrial plants located in suitable water areas such as a harbour basin, a bay or a river, for building, repair and maintenance of ships. They are generally classified as shipbuilding yards, which produce new ships, and ship repair yards, which are mainly involved in the repair and maintenance of ships. There are also shipyards for both production and repair of ships (Mazurkiewicz, 1980). Their equipment will depend on the prevailing type of production. Thus, in ship repair yards, shipbuilding will be of secondary importance, simply providing work for production units during less intensive work periods. Only the ship repair yard is included in this research. In ship repair, the main criteria are the size and the type of ships repaired, whether large, medium or small (Harren, 2012).

2.3.2 Background on graving dock

The name ‘graving dock’ derives from the dock’s original action, to permit the cleaning of a ship’s bottom, a process known as graving. Graving docks are large, fixed bases built into the ground at the water’s edge (Becth and Heger, 2006). A watertight gate is closed after a vessel is floated into the dry dock and positioned above the blocking that will support it in the dry condition. Once the gate and vessel are in position, the water is pumped from the basin, causing the ship to settle on the blocks, exposing the underbody (Salzer, 1986).

Many construction techniques are used for building graving docks: sheet pile cells filled with sand, caissons of re-enforced concrete, and monolithic cast concrete, to name a few. The factors involved in deciding upon a construction technique include initial cost (often traded off against life expectancy), designer’s or owner’s preference, local influences such as the conditions, and available materials and skills (Salzer, 1986). When the fixed basin is dewatered, hydrostatic uplift tends to lift the entire structure from its foundation, causing it to tilt. In the early days of graving dock design, this tendency was countered by providing an enormous mass of concrete for its construction. Today’s modern approach uses a relieved floor, whereby uplift is avoided by installing a draining area system beneath the floor of the dry dock and pumping water away from contact with the boundaries of the dock (Salzer, 1986).

The dry dock is structurally divided into five parts: the portside wall, the starboard and head walls, the pump room, the entrance, and the dock bottom. All these parts seal off water (Kumamoto *et al.*, 1990). There are three categories that relate to the means used to resist the buoyancy force on the dock resulting from the displacement of water volume of the dock (Harren, 2012): i.e. full hydrostatic graving dock – relies on its own weight or an anchorage system to resist the hydrostatic forces acting on the dock; full relieved graving dock does not have sufficient weight to resist forces acting on the dock, but relies on a drainage system to remove the surrounding water behind the walls and beneath the slab to alleviate the hydrostatic pressure; partially relieved graving dock. Thus it requires relief of the hydrostatic force under the floor slab only.

2.3.3 Background on floating dry dock

Floating dry docks are barge-like floating structures with sufficient displacement, dimension, and stability for physically lifting a vessel from the water. Wing walls are provided on either side of the barge-like pontoon structure. They provide stability during docking operations and add to the sectional strength of the dock. They exist in a wide variety of sizes and designs. Large docks are very complex systems and are designed by professionals who intend to build structure, utilities, mechanical equipment, blocking and crane configuration (Mazurkiewicz, 1980). They are also operated with list and trim to reduce block loading and reduce or eliminate vessel stability problems when docking or undocking (Harren, 2012).

Floating dry docks are composed of a pontoon and wing walls. The pontoon is the main structural component that must be designed to distribute the concentrated blocking loads from the vessel to the dock and ultimately to the uniform buoyant force on the hull. The pontoon provides the transverse strength for the dock as well as contributing to the longitudinal strength (Harren, 2012). Additionally, the pontoon must have sufficient volume to provide displacement to lift the vessel and dock out of the water with buoyancy. The wing walls provide stability when the pontoon is submerged, and the longitudinal strength to distribute the ship's weight to the uniform buoyancy support (Becth and Heger, 2006). These docks are used mainly for ship repair work but they can also be used for launching new ships. In modern layouts, floating dry docks are also equipped with gantry cranes, ensuring greater flexibility during repair or exchange of large parts of the ship under repair (Salzer, 1986).

2.3.4 Layout of ship repair yards

In floating-graving dock ship repair yards the division of organisational units and their location on the shipyard area are different from those of shipbuilding yards because of the different technological processes involved. Generally one can have the following main production workshops in a repair shipyard: hull repair shops, maintenance and paint shops and repair shops for ship machinery. All these workshops are usually located close to the quays and docks (Kumamoto *et al*., 1990). Hence, four kinds of ship repair yard layout exist: (pier arrangement), around a basin, on an island, and on a peninsula. Pier arrangement is very useful because it gives a relatively narrow quay front and very short transport lines. The basin layout results in the least efficient arrangement of workshops because of the extended transport routes and the necessity for dividing equipment repair shops and machine repair shops into two separate centres (Mazurkiewicz, 1980).

Ship repair yards cannot afford the simplicity of single purpose equipment or layout but must be able to cope with any problem and be prepared for any repair job, day and night, from replacing a hull plate to rebuilding a main engine. The rapid growth in ship dimensions in recent years has brought about the reorganisation of ship repair facilities and the constant modification of the layout, mainly as regards size. This has led to the elongation of existing berths but, at the same time, mooring and docking devices that were too small to use. Existing cranes were too weak for the increased loads, such as ship engines, while the individual workshops required a larger area, and larger machine tools and overhead cranes. As a consequence, ship repairs yards on their original sites were not able to keep pace with demand (Mazurkiewicz, 1980).

2.3.5 Trends in the ship repairing industry

The dynamic development of the world economy has naturally resulted in the growth of international and ocean trade; the latter characterised by continuous quality and quantity changes (Kumamoto *et al*., 1990). This means that the rate of the world merchant fleet development is a function of the risk in cargo turnover in ocean trade and of the changes in the fleet structure (at least in the technical sense) as a direct consequence of the changes in the structure of international trade. It is quite possible that a certain decline in repair will occur in the immediate future (Kumamoto *et al.*, 1990).

This does not mean, however, a complete slowdown in the development of international ocean trade. Technical progress in ship repair will lead to new techniques of cargo handling, and new freight systems characterised by the increasing efficiency of ships and by decreasing unit costs for cargo (Mazurkiewicz, 1980). By analysis of trends in international ocean cargo trade and the future economic development of individual geographical regions and their populations, it is possible to estimate the sea cargo turnover. Analysis of the world cargo fleet development finds the following kinds of ships have been distinguished (Mazurkiewicz, 1980): (a) general cargo ships, container ships, ferries, hover-craft, etc.; (b) ships for dry cargo including the oil-bulk-ore (OBO) carriers and ore-tankers; (c) tankers for crude oil and oil products and special tankers for liquefied gas, liquid sulphur carriers, etc.

2.3.6 Factors making ship repairing more efficient

Some characteristics and features are desirable for the efficient operation of a dry dock regardless of type and facility chosen (Becht and Heger, 2003): (1) adequate space is necessary in and around the dry dock for both the people and material to move to and from a vessel in the dock; (2) fast and efficient access is needed to and from the dry dock and the vessel in the dry dock. Access for vehicular traffic is very desirable. The introduction of travelling staging or dock arms for use in basin and floating dry docks has helped to make ship repairing more efficient; (3) adequate light and ventilation are necessary to ensure good working conditions; (4) an efficient method should be provided for moving a vessel in and out of dry dock. Docks are often equipped with tensioning winches, capstans, and other line-handling hardware, which allow the dry dock crew to control the vessel as it enters the dock and position it correctly over the blocks. Electric or electrohydraulic capstans are most often used to handle the lines; (5) a proper blocking system must be provided. Blocks are used to support the weight of the ship while positioning it at a convenient height to provide work access underneath and leave much of the bottom area free for cleaning, repair, and painting. They also provide stability to prevent the ship from tipping over due to high winds or earthquake forces. The blocking can be considered as a mattress that provides support yet yields elastically to account for irregularities in the fit of the ship.

2.3.7 Factors affecting the selection of a dry dock system

The management of nearly every shipyard at one time or another considers an investment in a new or enlarged dry docking capability. Sometimes the choice of system is easy, as only one type of dry dock will meet the shipyard’s need. More often, however, management must evaluate several systems and decide between them (Salzer, 1986). Selection of the appropriate type of dry docking facility will be influenced by many factors including (Becht and Heger, 2003): (1) the dimensions, weight characteristics, and general features of the vessels to be serviced by the dry dock; (2) conditions at the site of the dry dock and the associated land facilities, including available land area, available area in the water, proximity to navigable channels or open water, tides, currents, topography, and soil conditions; (4) the near- and far-term goals of the shipyard and the potential future extension of the dry docking facilities. The most vital factor is the size of vessel and size of dry dock. A summary of factors to be considered in the selection of a floating-graving dock system is presented in Table 2.1 (Salzer, 1986).

Table 2.1: Summary of factors to be considered in the selection of a dry dock system (Salzer,1986)

Factor	Graving Dock	Floating Drydock
Vessel size	Virtually unlimited, the largest docks handle vessels, in excess of 1 million deadweight tons	Recent docks have been built to handle vessel in excess of 350,000 deadweight tons
Sitting restrictions	Local extremes of soil conditions can create extreme variations in initial cost	None
Speed of operation	Dependent on pumping capacity. Typical installations utilize rates of between 6 to 10 hours	Dependent on pumping capacity. Typically 1 to 3 hours
Dredging/ Siltation	Adjacent bottom level must be maintained below sill of gate elevation	Must maintain adequate depth in area of dry dock to permit nominal clearance beneath baseline at submerged elevation
Maintenance	Gate-Periodic drydocking for vessel-like maintenance. Machinery-Preventative maintenance and occasional overhaul. Basin- In-place corrosion control and repair. Protection-Impressed current cathodic protection systems and sacrificial zincs are usually provided for underwater steel elements.	Machinery-Preventative maintenance and occasional overhaul. Dock structures- Floating dry docks are usually designed to be self-docking vessel-like maintenance. Protection-Cathodic protection and sacrificial zincs are usually provided.
Guideline, Annual reserve for maintenance	1-2% of initial cost	1-4% of initial cost
Capital Recovery Potential	None	About 90% of appraised value (less towing and insurance expenses)
Land Area Required	Usually a graving dock is inset into a shipyard site and therefore requires an amount of real estate equal to the footprint of the dock plus access	Requires only frontage on the property line. Can often be moored outside of the harbour’s bulkhead line.
Compatibility with transfer to land berths	Graving docks are very seldom used in conjunction with land berths.	Often utilizes a full or partial grounding mat to stabilize the dock’s level during transfer. Ballasting control is possible and has been used without grounding mass but requires a highly trained dockmaster.
Material flow to vessels in drydock	All material must be removed from area prior to docking and undocking. Cranes are usually installed on dock walls to facilitate handling. New docks are sometimes provided with a vehicle ramp to remedy this traditional shortcoming.	Wing-walls limit access to the end of the dock. Material must be removed prior to docking and undocking. Cranes are often provided on wing-walls to assist.
Earthquake resistance	Special design criteria must be considered for docks to be installed in earthquake prone areas. Ships blocking must also be considered in these areas.	Tsunamis accompanying earthquakes are the major consideration for floating drydocks.
Special features available	Intermediate gates permits subdivision of graving docks for more than one vessel at a time. Double ended docks with intermediate gates are sometimes used to permit a long dock to function as two docks.	Floating dry docks can be designed to be separated into two independent units. Special adaptations and designs have been developed to permit limited access without full drydocking.
Simplicity of drydocking	Winches and centering guides are used to assist in positioning ships. The crew size is a function of the vessel size. Operations are carried out in the relative calm of a protected basin.	Vertical control is maintained by the pumping of water. A certain amount of dock and vessel motion must be contended with to assure safe operation. A skilful docking master is required.

2.3.8 The economics of docking a vessel

The cost of dry docking facilities for any given capacity can vary widely depending on the local conditions. Floating docks can be purchased second-hand and towed to the site. Second-hand costs vary widely but average out at a half to a third of the cost of other docking systems (Mackie, 1999). The tariffs are set to suit their marketing strategy. A dry docking tariff running 10% of the cost to the ship owner of the work done on his vessels is about the limit that will be tolerated by ship owners. In general, the real money is made in ship repair. Provided a dock is reasonably utilised, the annual turnover on repair work will be 2 to 3 times the cost of the facility. This leaves the dry dock as the largest single investment a ship repair company must make – something they may not be willing to do if the market is not stable (Mackie, 1999).

Docking a ship is an expensive business and over the years much effort has been devoted to increasing the intervals between docking and reducing time needed in dock. Measures taken include the following (Tupper, 2013): (1) developing hull coatings which remain effective for longer, including so-called self-polishing paints; (2) using cathodic protection systems to protect the hull and its fitting against corrosion; (3) designing underwater features so that they can be removed and replaced with the ship still afloat.

These economies, however, do not debar the open or public utility dry dock. The tax yield to the state from the economic activity engendered by ship repair at the dock, depending on the levels of taxation and the levels of activity could amortise the capital cost of the dock in 5 to 7 years. Thereafter, the tax yields are free and may be accounted together with the other socio-economic benefits that may flow from a healthy ship repair industry (Mackie, 1999).

2.3.9 Ship dry dock specification

2.3.9.1 Shipyard docking plan

Using the vessel’s docking plan, the shipyard develops an in-house docking plan to be submitted to the ship owner for approval. Based on the vessel-dock configuration, the shipyard needs to determine whether an alternate blocking plan that differs from the ship owner’s docking plan is required (Harren, 2012).

Unless otherwise contractually stated, the docking position usually account for the previously docked positions to ensure that the vessel can be 100% paint coated. The shipyard's docking plan contains information such as (Harren, 2012): the alternate blocking plan, plan view of dry dock with vessel outline, elevation view of dry dock with vessel outline, cross section at propellers, side block table of offsets, table of hull openings below the projected docking, etc. General information on docking position, keel block, and side block is also important.

2.3.9.2 Accuracy factors

Dry docking plays an important role in a ship operation project. The ship's dry docking project is seen as the largest periodic maintenance activity that a ship is exposed to during its life cycle (Inozu and Radovic, 2002). Extensive research has indicated that uncertainty of unplanned/growth of work for ship repair projects can be avoided if historical data and major maintenance job specifications such as ship dry docking are written in a standard and error free format with a good assessment of the ship's condition.

In general, many shipping companies have always accepted the fact that the amount of work required grows during dry dock, due to the complexity of the process. However, they have incorporated this growth into the budget by adding supplementary funding of 20% or more of the initial dry dock budget to cover this item of expenditure rather than investigating how they can eliminate the problem. Figure 2.1 shows some of the most important contributors for proper maintenance in dry dock. Appropriate machinery and hull condition data can be tracked using computer database maintenance and repair tracking system (Inozu and Radovic, 2002).

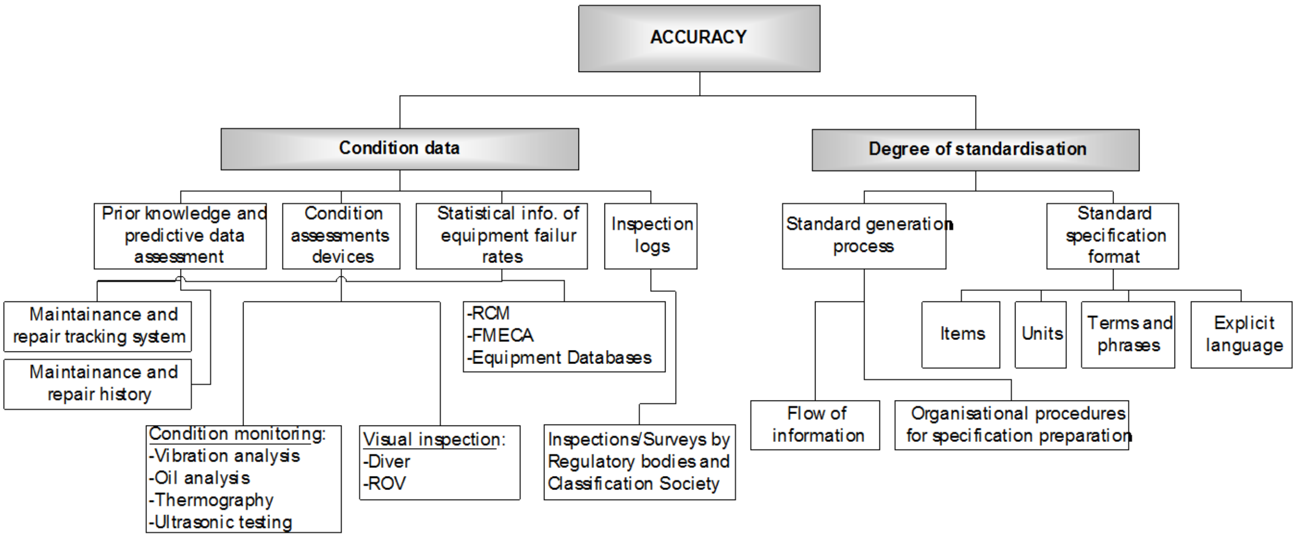


Figure 2.1: Breakdown of specification accuracy factors (Inozu and Radovic, 2002)

It is important to emphasize the need for accurate ship repair and maintenance history when preparing ship dry dock specifications. Historical information on equipment failure rates, poor workmanship in dry dock, planning mistakes, etc. may help predict future maintenance and repair needs. Growth items cost ship operators an average of 50% to 80% more than if they would have been planned and identified in dry-dock specifications before dry-dock starts (Inozu and Radovic, 2002).

Growth items cost ship operators a lot of money. If the growth items could be planned and identified in dry dock specifications before a dry dock project starts, the cost avoidance for these items would be significant. In addition, a poor knowledge of ship hull and equipment condition directly relates to ship safety (Inozu and Radovic, 2002).It is, therefore, in the best interest of the ship operators to examine and monitor a ships condition to minimize potential defects. Proper docking operations are the main emphasis of the FSA approach (Inozu and Radovic, 2002).

2.3.9.3 Top level dry dock specification

The first activity of this research is to identify ship operator's dry docking process top-level map, which is shown in Figure 2.2. It shows the flow of specification documentation and parties involved with its generation (Inozu and Radovic, 2002).

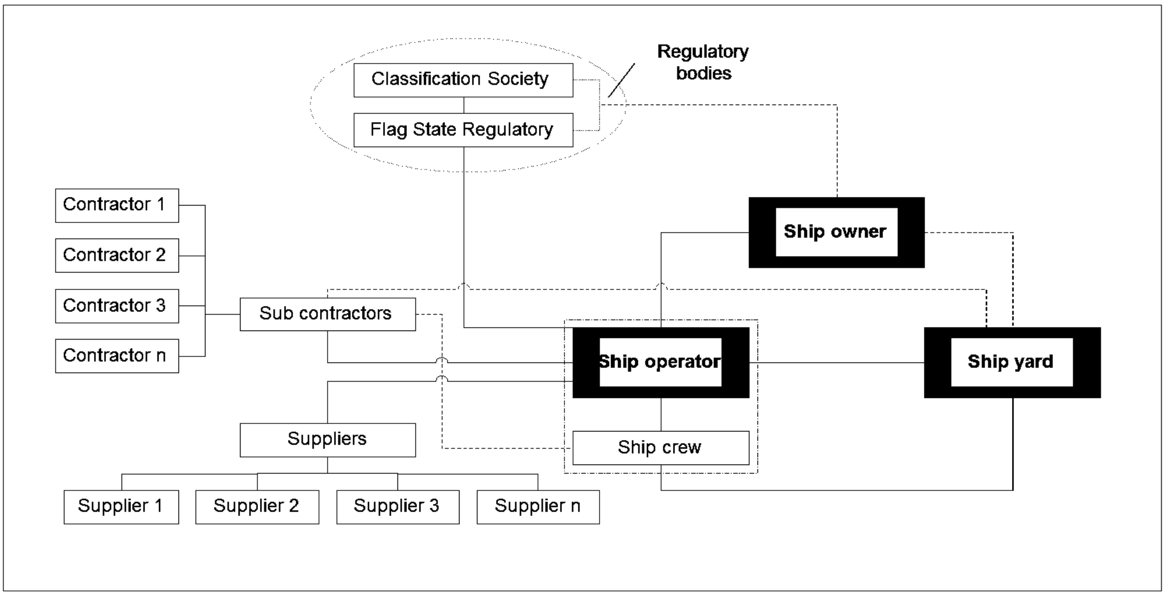


Figure 2.2: Top level dry dock specification (Inozu and Radovic, 2002)

After being approved, the specifications go to shipyards for bidding and the yard chosen in the bidding process works with the ship's crew and port engineer on the execution of tasks identified by the specifications. The effectiveness of each step in the specification generation and dry dock project execution process presents different parts of FSA (Inozu and Radovic, 2002).

2.4 Regulations and Standards on Floating-Graving Dry docks

The international and national legislation, rules and regulations were adopted, implemented and enforced by: IMO and flag states and classification societies.

2.4.1 IMO

IMO stands for the International Maritime Organisation formed as a specialized UN-agency that sets standards in IMO conventions, codes and other instruments, which are developed following proposals made by member flag stages that are both users and providers of international shipping services, and are generally adopted on a consensual basis (Aristo, 2012). These are internationally agreed minimum standards. They are not the highest possible or conceivable standards, but the highest practicable (Aristo, 2012).

The major aims of the IMO are as follows: (1)To provide effective machinery for technical, legal and scientific cooperation among flag states in the field of the protection of the marine environment from pollution from ships and relative activities; (2) To encourage the widest possible acceptance and effective implementation of these standards at the global level (Aristo, 2012).

2.4.2 Flag State implementation

Flag state implementation is new body which developed important instruments and guidelines to facilitate flag states in fulfilling their obligations under the applicable conventions but the core of the problem still remains unresolved. For the time being, there continues to be widespread resistance to granting the IMO any enforcement authority of this kind. A number of ports have adopted the Port State Control (PSC), but their authority is limited and their inspections generally superficial, with insufficient depth and detail (Aristo, 2012), hence many flag states seem to have delegated their responsibility to classification societies.

2.4.3 Classification societies

The main function is to lay down standards for the construction and subsequent maintenance of ships and to ensure that these standards are fully implemented. These standards are published in the form of Rules and Regulations and Procedures. According to the rules for classifications of floating docks (DNV, 2012) rules are based on assumptions that the floating dock will be properly handled at all times, and it is assumed that all loading and ballasting will be in compliance with the approved operating manual. ABS (2009) and KR (2010) also provide similar rules for building and classing steel floating dry docks. Class can only attend periodical surveys as defined in their Regulations and only at the request of the Owner/Operator/Manager. Periodic surveys are carried out on annual, intermediate (2 to 3 years) or special survey (5 years' cycles). Class cannot maintain safety of ships under all circumstances due mainly to the following (Aristo, 2012): Class dependence on the ship-owners or for new building on shipyards: (b) Conflict in interest as class is often carrying out statutory surveys and issuing certificates on behalf of flag state (c) Classification rules and regulations and procedures are the absolute minimum standards: (d) Class has no or at least very limited authority to implement and enforce regulations; (e) Class in fact does not have direct responsibility.

2.4.4 Standards and compliance

As studied, there is a focus on compliance rather than on actually achieving safety. These legislation, rules and regulations can be grouped into technical, safety regulations, economic, operational regulations, and security regulations. An example of docking regulation is Canadian Vickers Regulation (CVR, 2012).

2.4.5 Data collection

The shipyard industry is an important and strategic industry in a number of EU member states and the community as a whole. Shipbuilding is also an attractive industry for developing nations. Japan used shipbuilding in the 1950s and 1960s to rebuild its industrial structure, Korea made shipbuilding a strategic industry for its economic developments in the 1970s and China is now in the process to repeat these models with large state-supported investments in the industry (CESA, 2006). Data collected shows that working in shipyards remains as one of the riskiest occupation in the United States as Bureau statistics of Labour (BSL) records from 1999 to 2007. This record remains true from shipyard accident statistics collected from Health and Safety Executive (HSE) in the UK, where the injury rate in the shipyard industry doubled compared to manufacturing industry. This sends a clear message for the need to examine the existing health and safety management system in shipyards, its characteristics, safety programs, guidelines and shipyard safety standards.

It is often said that "what works in one yard may not necessarily work in another, each yard is best judge of what will work for it."

Nevertheless, every shipyard has its own personality. That personality is the product of many factors including the yard's history, its size, its organisational structure, its employee relations atmosphere, and its management style. Therefore the operations in shipyards are dynamic and not static, hence internal and external influences must be adjusted to enhance safety in shipyards (Frank, 1991).

2.4.6 USA shipyards

Shipbuilding and repair in the United States (US) has historically been considered as a strategic industry, supporting both military and commercial interest. Currently, in the U.S this industry consists of about 250 private companies and five publicly owned and operated repair yards. U.S shipbuilding and repair revenues totalled $ 10.2 billion in 1998 (NSA, 2001). The shipyards on the Eastern and Gulf Coasts account for over 80 percent of these revenues. The six biggest shipbuilders commonly referred to as the Big Six, account for two-thirds of the industry revenue. This big six include (NSA, 2001): Bath Iron Work (Maine), NASSCO (San Diego), Avondale (New Orleans) and Ingalls Shipbuilding (Mississippi) are part of Litton Ship Systems and Newport News Shipbuilding (Virginia).

The shipbuilding and repair industry is a strategic asset analogous to the aerospace, computer, and electronics industry. Frontline warships and support vessels are vital for maintaining America's national security and for protecting interests abroad. In emergency situations, America's cargo-carrying capacity is indispensable for moving troops and supplies to areas of conflict overseas. The following associations affect the shipyard activities in USA: American Shipbuilding Association (ASA), National Shipbuilding Research Program (NSRP), and Shipbuilders Council of America (SCA).

2.4.7 European shipbuilding and repair activities

Over the past 30 years, the European shipbuilding, repair and conversion industry has seen substantial rationalisations, mergers and consolidation. This has been against a background of increasing shipbuilding capacity in China and South Korea and continuing arguments on shipbuilding subsidies (CESA, 2006). The EU has developed a strategy in order to tackle the Korean practices, which include shipbuilding subsidies that have been harmful to EU shipyards. There are more than 150 shipyards in the EU, with capacity of 40 of them active in the global market for large sea-going vessels. EU shipyards employ 55,000 directly and, since the enlargement of the EU, the annual turnover is more than 11.5 billion Euros. The following associations affect shipyards in EU: Community of European Shipbuilders Association (CESA), and Association of European Shipbuilders and Ship Repairs (AWES).

2.4.8 UK shipyards

UK shipbuilding is defined in four broad categories: new-build merchant ships; new-build naval ships; merchant repair and conversion; and naval repair. All companies in this industry are located in the UK and are, degrees of shareholding notwithstanding, British owned and operated (Martins, 2008). There are more than 16,000 shipyard workers employed in the UK (CESA, 2006). There are several shipyards in the UK, some of them include: A & P Type Ltd Newcastle, Pallion Engineering Ltd, Dunston (ship repair) Ltd, A $ P Teesside, Richards Dry Dock and Engineering Ltd, Small and Co Ltd Lowestoft, North-western Ship repairers & Shipbuilders Ltd, BAE Systems and Naval, Fleet Support ltd, VT shipbuilders, VT Halmatic, A & P ship care, and Thames Shipbuilders Burges Marine Ltd. Shipbuilders. Ship Repairs Association (SSA) is one of the organisations in UK that seek to enhance safety in shipyards.

2.4.9 China shipyard

Since the start of the 21st century, China’s shipbuilding industry has enjoyed significant development. Fostered by the state macro policy and great demand both in China and abroad, the industry will still keep fast growth in the coming several years based on the anticipation of Commission of Science Technology and Industry for National Defence (Dilan, 2008). The industry is dominated by two huge state-owned enterprises: China State Shipbuilding Corporation and China Shipbuilding Industry Corporation, the parent of the Dalian company. But in recent years, it has also seen a large number of new entrants, in the form of smaller shipyards run by local governments or private groups, or set up as joint ventures. There are now 3,000 of these smaller shipyards, up from just 350 a decade ago (Dilan, 2008). Shipyards in China include: Dalian Shipyard, Jiangsu Shipyard, Jinlin Shipyard, Wuhu Shipyard, Chenki Shipyard, Mawei Shipyard, Guangzhous Shipyard, Bohai Shipyard to name but a few.

2.4.10 Singapore shipyards

In Singapore, the Work Safe and Health (WSH) Council highlights the need to do more in view of the booming marine industry. The chairman of WSH Council Lee (2008) explains *“as more work and projects are being taken in shipyards, it is critical that they remain vigilant and* *ensure that the necessary safety measures are in place.”* Lee (2008) suggested the need to ensure all shipyards take on Association of Singapore Marine Industries’ (ASMI) suggestion to immediately do a time out and review all systems and processes before resuming work. This is in an effort to rank Singapore shipyards amongst the top around the globe. It is clear that, many organisations are trying their best to rank their shipyards the top in the globe in safety, operation and efficiency. It must come at the expense of cost, whereby the right amount of resources, and tools to realise this goal must be put in place.

2.5 Typical Shipyard Accidents

Several shipyard accidents have occurred over the years. These accidents have paved the way for strikes, tougher legislation and the need to enforce the guidelines on safe working practices in shipyards. Not only have these accidents led to loss of production time, and environmental degradation, but also loss of lives for individuals working to make sure that these vessels remain seaworthy.

2.5.1 Jurong shipyard accident

Greek tanker, Spyros, exploded at Jurong Shipyard in 1978. It remains Singapore’s worst industrial accident killing 76 with nearly 100 injured in an explosion and fire on board the ship at the Jurong Shipyard. The explosion took place after about 150 workers went into the engine room (Jansen and Lee 1978). Sparks from the cutting torch used during repairs, caused a fire which ignited an explosive vapour mixture within the aft starboard bunker tank of the vessel. The fuel tank had been contaminated by crude oil. The explosion ruptured the common bulkhead between the tank and the engine room, releasing the burning oil into the engine room and setting fire. Of those working on board the vessel, 76 people were killed and 69 others injured (Tan, 1990).

2.5.2 Subic bay accident

Three workers died at shipyards at Subic Bay in the Philippines. This caused the International Metalworkers’ Federation (IMF) to raise issues on safety and health in shipbuilding at ILO World Congress on Safety and Health at Work (IMF, 2008). Poor implementation of safety rules and regulations was the main concern about this accident. It was stated clearly that safety permits were not given to subcontractors before work. In the blast incident, the workers on the upper level were doing the grinding while those at the lower level were applying oil near the propeller and the acetylene (tanks). The findings showed the following (Ansbert, 2008): (a) Employees were given only a general orientation of the shipyard, (b) No dry dock orientation was given in case of fire, (c) There was no systematic dry dock fire rail, specific alarm system, exit map and lights.

2.5.3 Tuzla shipyard strikes

More than 5,000 supporters joined the strike action in the Tuzla shipyards in Turkey calling for better health and safety (IMF, 2008). The major cause of this strike was due to fact the that 18 shipyard workers were killed in the previous seven months alone in workplace accidents; in the protest the police arrested 70 workers (IMF, 2008). Another cause of this strike was that the vast majority of workers work for subcontractors, and these firms pay little or no attention to health and safety issues and regulations.

2.5.4 Union Naval de Levante accident

On 3 July, 1997, 18 workers in the shipyard of Union Naval de levante in Valencia died when a ship under construction caught fire. The causes of the accident, Spain's most serious recent accident before the Madrid train bombings, was due to breach of safety regulations. The accident occurred when a ship under construction caught fire while it was loading fuel. Several workers claimed that insufficient safety measures had operated at the shipyard and accused the company of not stopping welding work during fuel loading (Cirem, 1997). The Comisiones Obreras (CC.CO) drew up a report claiming that there had been three fuel leaks during the loading, and that one of these leaks caused the fire by contact with electrical material (Cirem, 1997).

2.6 FSA Applied to Shipping Industry

Shipping is a traditional industry in which safety has been an issue for hundreds of years. Meanwhile, accidents have often led to the recognition of the need for measures to control risks at sea. For example, the Titanic disaster in 1912 in which 1430 lives were lost, led to the first International Conference on Safety of Life at Sea (SOLAS), that set international standards and regulations to prevent such casualties. The capsizing of the linear Andrea Doria prompted the United States delegation to attend the 1960 International Safety Conference and introduced the concept that ship safety should be measured as the extent of damage a ship could survive. The Exxon Valdez disaster in 1990 resulted in the use of double hull tankers mandated by the IMO. These incidents indicate the everlasting necessity for introducing modern risk assessment techniques in the commercial shipping industry (Bai, 2003). In 1993 a particular industry developed type of risk management framework in the ship safety regime was proposed by the

UK to the IMO, referred to as the FSA. Being a tool designed to assist maritime regulators, FSA is not intended for application to individual ships, but for use in a generic way for shipping in general.

To increase safety at sea, IMO has developed a structure and systematic methodology for FSA by using risk analysis and an efficient risk management. FSA is a rational and systematic process for assessing risks and for evaluating the costs and benefits of different options for reducing those risks (Gasporati, 2012). The method provides a means of being proactive, enabling potential hazards to be considered before a serious accident occurs. The main elements introduced by FSA are: a formalized procedure, an auditable process, communicated safety objectives, and priorities based on cost effectiveness. These have made the FSA a more rational risk assessment approach for the regulatory purposes in the shipping industry (Bai, 2003). Risk assessment is a complex process involving the identification of the hazard and its sources, as well as of the consequence and severity of their associated risks. This is used to elaborate strategies for risk diminishing and safety improvement at sea by adopting prevention and control measures and reducing risks (Gasporati, 2012).

2.6.1 Characteristic of FSA in dry docking industry

FSA represents a fundamental change from what was previously a largely piecemeal and reactive regulatory approach to one which is proactive, integrated and, above all, based on risk evaluation and management in a transparent and justifiable manner, thereby encouraging greater compliance with the maritime regulatory framework, in turn leading to improved safety and environmental protection (Gasporati, 2012).

FSA may be used to develop performance-based rules stating safety objectives and functional requirements and rational prescriptive standards based on the performance-based rules. The main characteristics of the FSA are (Gasporati, 2012): (1) a systematic approach considering the shipyard as a socio-technical system. The system may consist of hardware, environment, human organisations, operations, and procedures; (2) risks associated with various hazards are described and analysed. The risk analysis covers a certain time-span, i.e. the operational life, and may involve quantitative or qualitative tools to perform likelihood and consequences calculations; (3) once a risk is quantified, it is then necessary to determine if the risk is acceptable, based on the predefined acceptance criteria. When the risk is acceptable, a cost/benefit analysis may be followed to compare the costs for preventative/protective measures with the benefits; (4) the listed basic elements are integrated into a risk model, where the objective is to recommend the most cost-effective, preventive, and mitigating measures for risk management.

Based on the principles of identifying hazards, evaluating risks and cost-benefit assessment, to effectively manage FSA in the docking industry, there needs to be a loop established, whereby the effects of changes based on the decision-making are monitored to ascertain whether the desired level of safety can be achieved and, if not, further options examined (Hu *et al*., 2007). The FSA has proved to be a method widely applicable, detailed in statistical analysis and effective in assessment, featuring formal operation procedures, serial standards analysis techniques and decision making based on cost-benefit assessment. The core process comprises five steps. These objectives and rational analyses facilitate systematic judgements and effective management of risk (Soares and Teixeira, 2001).

There are three options for safety assessment provided by FSA (Hu *et al*., 2007): (a) Option one: three-step assessment, which means hazard identification (step 1), assessment of risk (step 2) and the recommendation for decision making (step 5); (b) Option two: four-step assessment, comprising hazard identification (step 1), assessment of risks (step 2), risk control options (step 3) and the recommendations for decision making (step 5); (c) Option three: five-step assessment, full steps in the FSA method. The assessment of risks is the core process and plays a significant role in the above categories, among which the establishment of risk models is a critical step (Hu *et al*., 2007).

2.6.2 FSA in other organisations

FSA is today used in many industries worldwide. Its use is not limited to industrial regulators but rather increasingly operators are using this approach to manage pro-actively the risks arising from their industrial activities. It is also used by governmental organisations, both national and international, which do not have a specific regulatory role. Some examples of organisations that have successfully implemented FSA over the years are presented in Figure 2.3 (Vince, 1995 and Xun, 1995): (1) In Holland, the Dutch authorities used FSA to balance risk of the storage and transportation of LPG and motor spirit; (2) The international Labour Organisation (ILO) has an increasing role with the control of chemicals risks to occupational safety and health; (3) The organisation for Economic Co-operation and Development (OECD) use FSA techniques for issues such as the economics of investment policies, food safety and the analysis of nuclear safety technology; (4) International organisations such as the OECD, World Health Organisation (WHO) and ILO have limited resources, as does the IMO. It is necessary for these organisations to focus attention on those issues of highest priority.

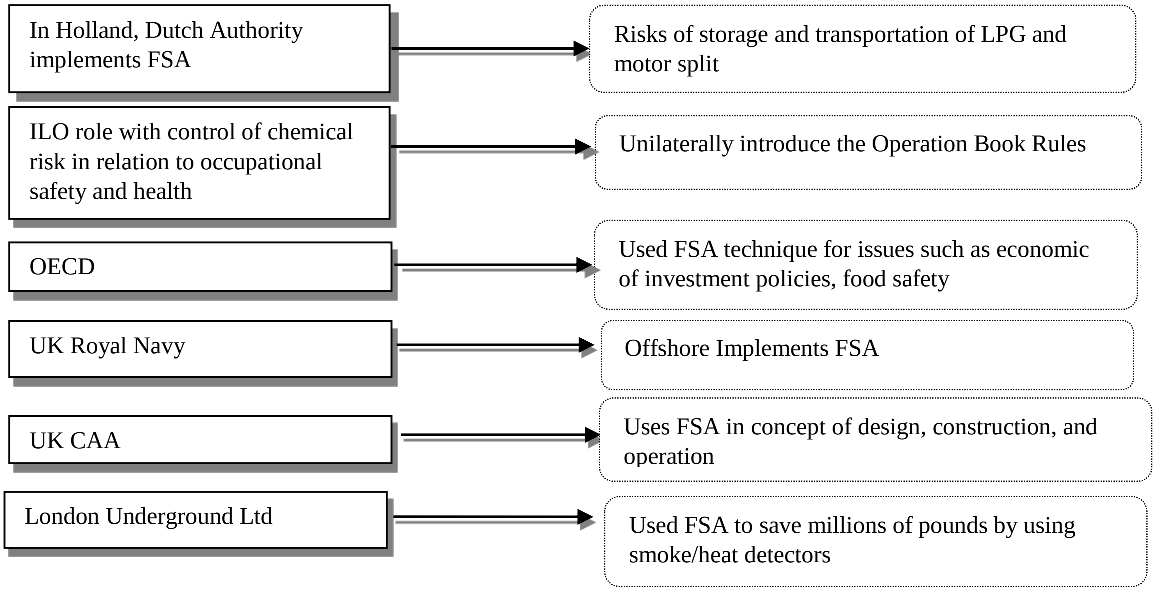


Figure 2.3: Overview on the application of FSA (Vince, 1995 and Xun, 1995)

2.6.3 Implications of the application of FT-FSA

It is important to understand who can apply FSA. The following are the types of administration that can apply FSA (Vince, 1995): (1) an individual administration or an organisation having a consultative status with IMO when proposing amendments to safety and pollution prevention and response-related IMO instruments in order to analyse the implications of such proposals and; (2) an instructed subsidiary body to review the overall framework of safety and environmental regulations aiming at identifying priorities of areas of concern of the current regulations. Figure 2.4 presents the general look at authorities that can apply FSA.

Who applies FSA?				
1. An individual administraion or orgnisation having a consultaitve status with IMO when propsoing amendments to safety and pollution prevention	2.The committee, or instructed subsidiary body, to review the overal framework of safety and enviroment regulations	3. For longer term, the development of FSA should lead to the replacement of prescriptive regulations by perfomance based regulations	4. A small group should be established to consider how the application of FSA would affect IMO's Committee's structure	5. FSA should be applied towards a more rationalised structure and morre efficient mechanism for achieveing a desired goal

Figure 2.4: General look at authorities that can apply FSA (Vince, 1995)

2.6.4 Factors affecting the implementation of FT-FSA

The factors that affect the future implementation of FT-FSA include (Sekimzu, 1995): (1) FSA as a tool for a precautionary approach in the decision-making process. Regulation development in IMO have been described as not being proactive or precautionary; (2) optimum future regulations: through the application of FSA, it would become possible to compare different options of combinations of regulations; (3) justification for the compelling need: the strength of the FSA rests in its systematic application of modern techniques for risk assessment and cost-benefit consideration on all possible control measures; (5) human element: it will be extremely important to take into account the role of the human element in the process of the application of FSA, hence the safety evaluation of shipping as a man-machine system; (6) collection of data: the evaluation of risks depends on the accuracy and volume of data on casualties. Therefore, the collection of data would be a vital element in the successful objective application of the FSA, although it is possible to use subjective evaluation as an interim means with a reasonable degree of accuracy.

2.6.5 Risk evaluation

Risk estimation can identify the areas of high risk – the main contributors to risk-specific hazards. The total risk to human safety, business and the environment may then be estimated. Depending on the scope of the analysis, the output from a risk analysis for a dry dock will provide descriptions of the risk in one, some or all of the following categories (Hartford and Baecher, 2004): individual risk to the public, societal, occupational, environmental, commercial, and socio-economical risk (the extent to which these categories are considered depends on the nature and level of effort of risk analysis).

The outputs of the risk analysis should be structured to be useful inputs to the risk control process. Graphical representations of frequencies of occurrences and consequences are also useful. In quantitative analyses, risk and how it accumulates can be represented in a summarised event tree based on condensed versions of the dry dock failure tree and the failure consequences event tree (Hartford and Baecher, 2004).

Risk is estimated by combining the probabilities of failure-initiating events obtained from the hazard analyses with the probabilities of dry dock failures obtained from the dock response analyses, and the magnitudes of consequences and their associated probability distributions from the consequence analysis phase (SSC, 2002). The principal methods available for conducting risk analysis for dry docks are introduced here and explained in more detail in subsequent sections. The following has been adapted from the Canadian Standard Association (CSA) (1991) '*Risk analysis requirements and guidelines*'. The principal methods are: (1) failure modes and effects analysis (FMEA); and associated methods; (2) fault tree analysis; (3) Petrinets, (4) Monte-Carlo simulation; and (5) Bayesian network (BN).

2.6.5.1 Failure mode identification

Failure mode identification is an essential step in the risk estimation process as it lays the foundation on which the remainder of the study is built (CSA, 1991). The extent to which failure modes are defined may depend on the level of the analysis (Hartford and Baecher, 2004). Failure mode identification requires that the dry dock system are systematically reviewed to identify the manner in which the dry dock, foundation or appurtenant structures may fail under the imposed loading or causative conditions (Hartford and Baecher, 2004).

This systematic review might include: dry dock safety reviews which provide basic dry dock specific input to the process; consideration of appropriate case histories of dry dock failures and historical records of dry dock incidents (experience from previous risk analyses provides useful input to this process); or checklists of causative conditions and failure modes to assist in identifying potential failure modes for dry dock under review – a formal process that provides a structure for raising issues and posing questions to a group of people familiar with all aspects of the project, so that the system is exhaustively analysed with fault tree diagrams (CSA, 1991).

2.6.5.2 Failure modes and effects analysis (FMEA)

FMEA (including such variants as failure modes, effects and criticality analysis and hazard and operability (HAZOP) studies) is a method of analysis whereby the effects or consequences of individual components' failure modes are systematically identified and analysed (Rajiv and Pooja, 2012). While the actual analysis is inductive (i.e. based on the question 'what happens if a component fails?'), it is first necessary to break the dry dock system down into subcomponents (Rajiv and Pooja, 2012).

FMEA is yet another powerful tool used by system safety and reliability engineers to identify critical components/parts/functions whose failures will lead to undesirable outcomes such as production loss, injury or even an accident (Rajiv and Pooja, 2012). FMEA was first applied to naval aircraft flight control systems at Grumman in 1950 (Coutinho, 1964). Since then, it has been extensively used as a powerful technique for system safety and reliability analysis of products and processes in a wide range of industries including marine works. Its main objective is to discover and prioritise the potential failure modes (by computing risk priority number - RPN) that pose a detrimental effect to the system and its performance. The critically debated disadvantage of FMEA based on RPN analysis is that various sets of failure occurrence probability (O_f), severity (S) and detectability (O_d) may produce an identical value; however, the risk implication may be totally different, which may result in high-risk events going unnoticed. The other disadvantage of the RPN ranking method is that it neglects the relative importance of O_f, S and O_d. The three factors are assumed to have the same importance but in real practical applications relative importance among the factors exists. To address these disadvantages related to traditional FMEA, a fuzzy decision making system can be used to prioritise failures (Rajiv, and Pooja, 2012).

2.6.5.3 Fault tree analysis and petri nets

Fault tree analysis (FTA) is a technique, either quantitative or quantitative, by which conditions and factors that can contribute to a specified undesired event (called the top event) are deductively identified, organised in a logical manner and represented pictorially (Peterson, 1999). The faults identified in the tree can be events that are associated with component hardware failures, human error or any pertinent event that leads to the undesired outcome (e.g. dry dock flooding) (Rajiv, and Pooja, 2012). Contrary to fault trees, Petri nets can more efficiently derive the minimum cut and path sets. Also, the absorption property of Petrinets helps to simplify the Petri net model and determine minimum cut sets and path sets by re-organising the transitions which is possible as long as firing time is not taken into consideration i.e. transfer of tokens does not take place (static condition) (Singer, 1990, Liu and Chiou, 1997, Adamyan and David, 2002). Similar to fault tree, petri nets makes use of digraph to describe cause and effect relationship between conditions and events. Petri nets have two types of nodes named place '*P*' and transition '*T*' (Peterson, 1999).

From literature studies it is observed that Petri nets and fault trees methods are used for software reliability analysis (Kumar and Aggarwal, 1993); analysis of coherent fault trees (Hauptmanns, 2004) and fault diagnosis (Mustapha *et al.*, 2004). The limitations of these current failure analysis techniques are: (1) not being capable of evaluating sophisticated industrial systems and; (2) based on unrealistic assumptions which are not intuitively comprehensive so that they are not able to manage risky behaviours of the system and predict potential sequential failures of systems which lead to catastrophic incidents. These traditional approaches can be handled by an integrated approach which incorporates fuzzy logic in the concept of petri nets to develop a new sequential analysis technique. To this effect, both probabilistic and non-probabilistic methods available in literature are used to treat the element of uncertainty (Rajiv, and Pooja, 2012).

2.6.5.4 Bayesian network

Based on mature scientific theory, this probabilistic method deals with uncertainty that is essentially random in nature but of an ordered kind (Yang *et al*., 2008). It is an exercise aimed at estimating the probability and consequences of accidents for the dry dock facility under study. The ability of the Bayesian network (BN) in modelling randomness and capturing non-linear causal relationships is widely known. (Sadiq *et al*., 2006). Therefore, BNs can provide a powerful risk analysis tool, and are used in a range of real applications concerned with predicting properties of safety-critical systems (Sadiq *et al*., 2006).

The Bayesian approach is based on probability theory, which ‘aggregates’ data without differentiating ‘aleatory’ and ‘epistemic’ uncertainties. Moreover, it requires too much *a priori* information, which sometimes limits its application to updating existing information (Sadiq *et al*., 2006). Consequently, earlier work has indicated that it is beneficial to combine fuzzy logic and Bayesian reasoning for the purpose of compensating their individual disadvantages. Again, Bayesian and evidential reasoning theory are widely known in risk analysis and play an important role in the management of uncertainties, especially where multi-expert knowledge is desired in a decision-making process (Yang *et al*., 2008).

2.6.5.5 Floating-graving dock response

Depending on the scope, the dry dock response analysis can take various forms including qualitative failure modes and effect modes analysis, various levels of event tree and/or fault tree analyses, and/or detailed quantitative analyses with formal treatment of uncertainty. Dry dock response analysis involves modelling the response of the dry dock to the full ranges of loads due to hazards and/or operating conditions (CSA, 1991).

The first stage of this process involves selection or development of a suitable model and identification of data requirements. The second stage involves providing input data and running the model for the various conditions under consideration. Disaggregation or decomposition of the failure mechanism into its constituent parts are a key element of the analysis process. The extent to which this disaggregation or decomposition is required will depend on the complexity of the failure mechanism and the level of the analysis (CSA, 1991).

2.6.5.6 Consequence analysis of docking accidents

Consequence analysis involves estimating the direct and indirect impacts of the failure or incident (CSA, 1991). The consequence analysis should provide a clear picture of what emergency response personnel would be faced with should the failure occur, as well as a picture of the long-term effects of the failure (CSA, 1991).

Consequence analysis consists of identification of potential losses and loss magnitude estimation. In some cases it may be necessary to describe the estimate of consequences probabilistically and account for temporal variation in the characteristics of the inundated area. There are essentially five aspects to failure consequence analysis (CSA, 1991): Dry dock gate flooding definition, fire impact analysis, dry dock collapse impact analysis, transverse bending failure of the pontoon definition and failure of ship to land on blocks analysis.

Computer programs for dry dock flood definition, developed for traditional dry dock safety applications, are commercially available. These programs provide estimates of flooding arrival times, and average flood depth and velocity with time at defined cross sections in the inundated area (CSA, 1991). Dry dock collapse impact analysis requires the characteristics of the inundated area including details of population at risk, property and environmental impacts as well as the responses to the inundation conditions.

2.6.5.7 Assigning probabilities

Risk analysis for dry dock safety is fundamentally a characterisation of the uncertainties in the performance capability of a dock under the loading conditions of interest (Vicky, 2002). Risk analysis is useful because it provides a systematic structuring of uncertainty, and this structuring allows us to better understand how uncertainty arises and how information may lessen it. The most commonly used measure of uncertainty in the dry dock safety study is *'probability'* (Vicky, 2002). Probability is a mathematical construct used to express degrees of uncertainty about occurrence of events, state of the world and truth of propositions. Two principal interpretations of probability are common: probability as *'frequency'*, and probability as '*degree of belief*' (Vicky, 2002). Because there is more than one interpretation of the meaning of probability, there is also more than one way to assign probabilities.

A review of the contemporary literature creates the impression that there is no unique way to assign probabilities in dry dock safety risk analysis, and such an impression is correct. That two distinctly different interpretations of probability exist makes it necessary for the analyst to differentiate which is used for specific probabilities in the risk analysis. As a general rule, probabilities describing rates of occurrence are interpreted as frequency, while probabilities describing states of nature (e.g. parameter values) or the truth of hypotheses are interpreted as degrees of belief (Hartford and Baecher, 2004).

2.6.6 Uncertainty in applications of FSA

The analysis of an engineering system often involves the development of a model of the system. The model can be viewed as an abstraction of some aspects of the system. In performing this abstraction, an analyst or engineer must decide which aspects of the system to include and which to leave out (SSC, 2000). Whether probabilities are assigned by statistical analysis, engineering modelling, expert opinions, or some combination of these approaches, they are almost never specified precisely (Hartford and Baecher, 2004).

For fully engineered floating-graving docking systems, such as graving dock gates, given a robust model and quality data the quantification process might be expected to provide results within an order of magnitude or so of the long-run frequency or the actual future observation. Also, depending on the state of knowledge about the system and the background of the analyst or engineer, other aspects of the system might not be known, thus increasing the overall uncertainty of the system (SSC, 2000). Clearly, as uncertainty in the models and data increases, the uncertainty in the quantified risk also increases. However, while the result may not even be to within an order of magnitude, the process of quantification remains useful in that it permits an interpretation of the situation under consideration that cannot be achieved any other way (Hartford and Baecher, 2004).

2.6.7 Expert judgement protocol in FSA

Expert judgement has always played a large role in science and engineering. Increasingly, expert judgement is recognised as just another type of scientific data, and methods have been developed for treating it as such. Expert opinion is mostly usually considered to be a statement of the reasoned degree of belief of the expert concerning a parameter, physical state or occurrence of an event (Hartford and Baecher, 2004). FSA studies typically rely strongly on expert judgement. Several studies have been published on the elicitation and use of expert judgement (Keeney and von Winterfeldt, 1991; Chhibber *et al*., 1992; Cooke, 1991; Cooke and Goossens, 2000).

The following are expert judgement protocols for FSAs (Rosqvist and Tuominen, 2004): (A) The basic framework for using expert judgement in FSA step 2: Risk assessment follows the phases of the revised NUREG-1150 expert judgement protocol (Keeney and von Winterfeldt, 1991), i.e. Phase 1: Identification and selection of the issues (i.e. issues brought from the FSA step 1: Hazard identification); Phase 2: Identification and selection of the experts; Phase 3: Discussion and refinement of issues; Phase 4: Training for elicitation; Phase 5: Elicitation; Phase 6: Analysis aggregation, and resolution of disagreements; Phase 7: Documentation; (B) Quantities subject to expert elicitation should be decomposed using a common risk model (i.e. Fault Tree model). This amounts to agreeing on a single ‘model-of-the-world’ (Chhibber *et al*., 1992). This is related to Phase 3 of the proposed protocol.

The earlier outline of an expert judgement protocol used in this research reflects Rosqvist and Tuominen’s (2004) experiences from conducting FSA that: (a) specification of a common risk model avoids the problems related to the aggregation of experts’ judgements based on different modelling; (b) it is difficult to find track records of expert performance with respect to bias; (c) it is time-consuming to assess possible dependencies between the experts; (d) sophisticated expert models, including parameters for bias and dependence (Chhibeer *et al*., 1992), motivated for sensitivity analysis as a specification of the parameters are usually not feasible due to lack of track records; (d) rational consensus (Cooke, 1991; Cooke and Goossesns, 2000) is an empirical control method for providing credible estimates of risk model parameters based on experts’ judgements. The practical feasibility of calibrating experts for the elicitation session is, however, problematic in the case of FSA risk models, with many parameters requiring different expertise and experts.

Experts’ judgements can be elicited quantitatively or qualitatively. When expressed quantitatively, they can have several forms: probabilities, ratings, odds, and weighting factors. Qualitative expression will include a textual description of the experts’ assumptions in reaching an estimate and natural language statements of probabilities of events such as ‘likely’ or statements as to the expected performance such as ‘generally poor’ (Hartford and Baecher, 2004). The challenge for an expert is to demonstrate that his/her judgements (revised judgement) are consistent with all of the information available now as well as consistent with any previous judgement.

2.6.8 Risk control and cost benefit analysis in FSA

There are two methods to control risk, namely preventive approach (to reduce the frequency of an initiating event), or mitigating option i.e. to reduce the severity of the failure (Bai, 2003). The actions for controlling risk include applications of engineering and implementation of procedures. Practical risk control approaches are investigated and their ability to reduce the risk documented (Bai, 2003). The effect of risk control actions can be determined by repeating risk analysis and comparing results to the original case. The benefits are the avoidance of accidents and these can be measured by evaluating the avoidance of harm to people, damage to property, environment and other costs. To achieve a balance, the benefits of a risk control measure must be considered and compared to the cost of implementation. This is done through a cost-benefit analysis (Bai, 2003).

2.6.9 Recommendation for decision making in FSA

Since dry docks generally impose risk on third parties and the environment, it is appropriate for risk evaluation for dry dock safety to be consistent with approaches to risk evaluation that are evolving for other societal activities. The risk analysis, risk control and cost benefit evaluation processes must be comprehensive, fair, transparent, consultative, and defensive (Hartford and Baecher, 2004). These are the basic principles of FSA, and the application of these principles depends on the nature of the risk and the objective of the FSA. Those responsible for making decisions concerning risk should identify the extent to which the above principles may apply in the risk analysis, risk control, and cost-benefit evaluation process, as it will vary from owner to owner and is within an owner's portfolio of risks to be managed (Harftord and Baecher, 2004). This final step in the FSA is decision making, which gives recommendations for safety improvements. The selection of risk control options for the decision making is based on the cost-effectiveness and the principles of ALARP (As Low As Reasonably Practicable). Intolerable risk shall be controlled regardless of cost. Reasonable – means that the costs are in gross disproportion to the benefits (Bai, 2003).

2.7 Introduction to Risk Assessment Methods Applied in this PhD

2.7.1 Fault tree – Formal safety assessment

Fault tree analysis (FTA) - Formal safety assessment (FSA) is a technique, either qualitative or quantitative, by which conditions and factors that can contribute to a specified undesired event (called the top event) are deductively identified, organised in a logical manner and represented pictorially (Hartford, and Baecher, 2004). The faults identified in the tree can be events that are associated with component hardware failures, human error or any pertinent event that leads to the undesired outcome (e.g. dry dock flooding) (Rajiv, and Pooja, 2012).

Starting with the top event, the possible causes or failure modes on the next lower functional system level are identified. Following the step-by-step identification of undesirable system operation to successively lower system levels will lead to the desired system level which is usually the component or element failure mode (Rajiva and Pooja, 2012). FTA starts by identifying a problem and all possible ways that the problem occurs. Since 1960 the tool has been widely used for obtaining reliability information about complex systems. In this method, obtaining minimum cut sets of complex systems is a tedious process.

It is important to note at the outset that FTA-FSA is one of many tools available to the risk analysis team. In a risk analysis for floating-graving docking systems, various methods will generally be used to build a logic structure to analyse the expected future performance. As such, FTA-FSA will simply be one of the methods used. In the course of the risk assessment it is important to coordinate how the FTA-FSA for a system fits into the overall risk analysis model (Hartford, and Baecher, 2004). This theme is critical to the risk analysis in general and to the FTA-FSA in particular and will be repeated throughout this research. Since it presents an integral part of this research it is important to outline the advantage and disadvantages of FTA-FSA (Hartford, and Baecher, 2004). In many respects, fault tree construction and model evaluation is a craft that depends as much on the knowledge and depth of experience of the analyst as it does on the required sound engineering and scientific analysis techniques (Hartford, and Baecher, 2004). Building models that are too detailed or too coarse for a particular application are obvious downsides to any sophisticated tool (Hartford, and Baecher, 2004).

As a result, a premium is placed on experience, particularly when the system to be analysed is large and complex. Some of the recognised advantages of FTA-FSA include (Hartford, and Baecher, 2004): (a) it provides a logical and graphical means to model and analyse system failure modes, even for large systems; (b) it is oriented to identifying system faults that have a bearing on the undesired event (e.g. system failure); (c) as a modelling technique for assessing the reliability of systems it is well developed and accepted; (d) it is an efficient tool when it comes to modelling the potentially large number of events and event combinations that can lead to failure; (e) sophisticated software tools make the job of fault tree construction, documentation and quantification an efficient and manageable task.

2.7.2 Fault tree – Bayesian network

The application of mapping a Bayesian network from a fault tree is seen in safety analysis of aerospace, ship vessels, microchip processing software testing and QNX software systems. Various applications in this section will be extensively analysed, in order to identify existing gaps and investigate the theories behind FT-BN application. A detailed analysis is conducted on the particular idioms adopted in each study.

2.7.2.1 Rotor Failure System Analysis

In 2011, Shao *et al*. (2011) carried out an analysis on the rotor of an aircraft. They saw a rotor as the most critical component of the aircraft's mechanical system. Hence, research was carried out on rotor reliability, with the use of the FT-Bayesian network mapping approach. Four kinds of common rotor faults were considered: rotor imbalance, thermal bending, bearing fault, and axis flaw, based on working conditions. A fault tree was constructed, based on engineering experiences, with 10 bottom events, six gates, and four intermediate events. A total of 16 events and their corresponding symbols and values were assigned on experience basis. In quantifying the prior probabilities of the mapped Bayesian network model, an ASSUME '0.02' value of rotor operating normally was used (meaning there is no obvious fault by the level of working condition).

A table was constructed to demonstrate the occurrence probabilities of the failures of rotor imbalance, thermal bending, bearing fault, and axis flow as 0.6%, 0.5%, 5.4%, and 0.3% respectively. All probability of faults was lower than 5.5%. Based on these values, the occurrence probability of system fault level P (R) = 6.7%. The value of 6.7% meant the rotor is working normally and no fault occurred, which was assessed as being the same as engineering experience (Shao *et al*., 2011). The conditional probability of working conditions P(R) = 1, (which means the system fails), led to the posterior probability of basic events or nodes in Bayesian model (denoted E1-E10) was calculated and E8 (lack of lubricant) gave the highest posterior probability value of 74.7, hence highlighting the weakest part of the rotor system.

In conclusion, they used causal reasoning to predict system failure probabilities, showing that different components have different reliabilities in the rotor system and their corresponding effects on the whole reliability of the rotor system, providing further evidence to support the use of a Bayesian network to identify weak links. Therefore, this approach supports the strong reasoning ability of dealing with incomplete and uncertain information in quantitative computation. This helps locate the weakest link without need for minimum cut sets in FT. Lastly, various conditional probabilities could be easily calculated for component or system failure, which is required in reliability analysis.

2.7.2.2 Vessel Oil System Safety Analysis

This analysis was done by Harbin Engineering University, China with the aim of reducing marine disasters by researching into static electricity of a vessel's oil system. In this same year, the aviation industry in China used FT-BN mapping to improve software safety tests. China's interest in FTA-Bayesian networks alone encouraged researchers into this approach. Zhuang *et al*. (2011) saw a vessel's oil system as constituting oil compartments, oil pumps, piping, and related instruments. A fault tree was developed, based on past engineering experiences where explosion of the vessel's oil system was assumed as the top event, consisting of eight intermediate and 17 basic events. Interestingly, unlike Shoa *et al.* (2011),

Zhuang *et al*. (2011) used Boolean algebra to determine the minimum cut sets in the fault tree to develop what they called '*The Success Tree of vessel's oil system*.' This approach is usually relevant when dealing with large systems that cannot be calculated mathematically. The fault tree had seven minimum path cuts, and, based on these cuts, the structure of importance of basic events was obtainable, which concluded, based on fault tree analysis, that 'poor ventilation' and 'reaching its explosion limits,' were seen as the most important factors leading to the explosion of the vessel's oil system. In mapping fault tree to Bayesian network (BN), a BN model was represented, due to the dimorphic element, which the fault tree could not handle as a discrete approach. Hence the conditional probability table (CPT) of intermediate events was calculated based on the dimorphic state. Quantitative analysis was not carried out in this study, because there were no statistics to obtain probability values of basic events.

2.7.2.3 Modelling using FTA

FTA is a deductive, structured methodology to determine the potential causes of an undesired event, referred to as the top event. The top event usually represents a major accident causing safety hazards or economic loss (Lewis, 1994). Building the fault tree is by a basic procedure, assuming that the top events have occurred and then work backwards to determine the set of possible causes. The necessary preconditions are described at the next level of the tree with either an ‘AND’ or an ‘OR’ relationship.

From here, the immediate events should be considered as sub-top events and the same process should be applied to them until all leaves describe events of calculable probability or are unable to be analysed for some reason. After that, the fault trees are built by the events in the analysis process of this step (He and Tao, 2011). A typical example is seen in Figure 2.5.

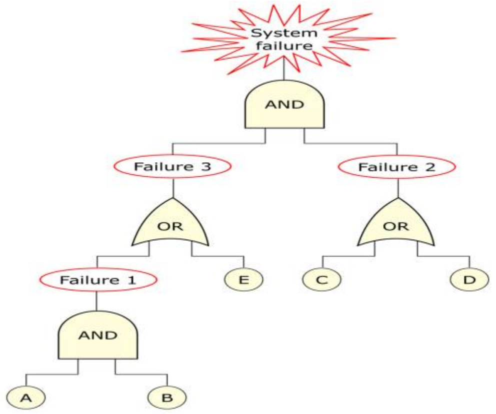


Figure 2.5: Fault tree of system failure

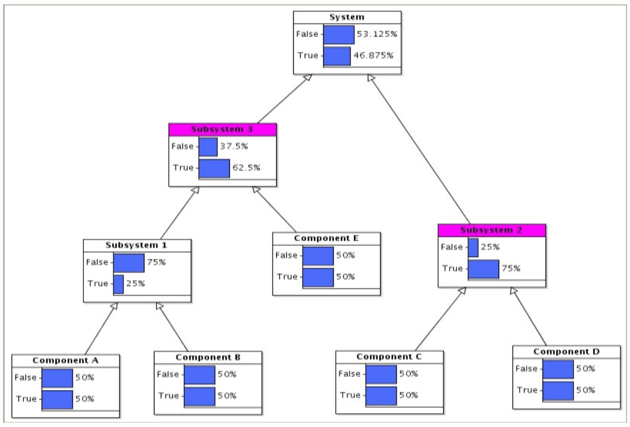


Figure 2.6: BN translated for further analysis

The system will fail if both failure 3 *and* failure 2 occur. Failure 2 will occur if either a failure at leaf C *or* a failure at leaf D (or both) occurs. Failure 3 will occur if either failure 1 *or a* failure at leaf E (or both) occurs. Failure 1 will occur if both failure at leaf A *and* a failure at leaf B occur (Hopps and Developer, 2012). If a failure follows an exponential distribution, then the likelihood of occurrence of the system failure at time t is expressed in equation 2.1 as follows: $P (t) = 1\text{-}e\text{-}^{\alpha t}$*, where* α *is failure rate* (Hopps and Developer, 2012)

$$\text{Failure rate, ‘}\alpha\text{’} = 1/\text{mean time between failure} \qquad (2.1)$$

Calculating the system failure of the fault tree developed above, the Boolean gates are expressed thus: $P\ [S_F] = P\ (F3.F2)$, $P\ [F2] = P\ [C+D]$, $P\ [F1] = P\ [A.B] = P\ [A] + P\ [B] - P\ [A.B]$*, if events are independent of each other,where* $P[X]$ *represents the probability of failure. F1, F2, F3 are failures 1, 2 and 3 respectively, and* S_F *is the system failure in Figure 1.* The minimum cut sets is calculated*:* $SF=F3.F2$, $F2=C+D$, $F3=F1+E$, $F1=A.B$, $F3=A.B+E$, $S_F=F3.F2$, $S_F= (A.B+E). (C+D)S_F= \underline{ABC}+\underline{ABD}+\underline{EC}+\underline{ED}$. Four minimum cut sets expressed can cause the occurrence of the top event, and, by preventing set events from happening, system failure can be avoided. If, for example, the mean time between the failure of events A, B, C, D, and E is 10,000 hours and the system failure is at, t = 5000 hours, failure rate of each events A, B, C, D and E is calculated using equation 2.1:

$$\text{Failure rate, } \alpha, = 1/10{,}000 = \underline{0.0001,}\ P\ (A, B, C, D, E) = 1\text{-}e^{-\alpha t} = 1\text{-}e^{-0.0001x5000} = \underline{0.39}$$

The value 0.39 follows an exponential distribution. The occurrence probability of top event system failure (S_F) can be calculated using absorption laws in fault tree quantitative analysis

$$P\ [S_F] = P\ [\underset{U}{\underline{ABC + ABD}} + \underset{V}{\underline{EC + ED}}]$$

$$P\ [S_F] = P\ [U + V] = P\ [U] + P\ [V] - P\ [U.V]$$

$$P\ [S_F] = P\ [\underset{W}{\underline{ABC}} + \underset{X}{\underline{ABD}}] + P\ [\underset{Y}{\underline{EC}} + \underset{Z}{\underline{ED}}] - P\ [(ABC+ABD)\ (EC+ED)]$$

$P\ [W+X] = P\ [W] + P\ [X] - P\ [W.X]$, $P\ [ABC+ABD] = P\ [ABC] + P\ [ABD] - P\ [\{ABC\}\ \{ABD\}] = P\ [ABC] + P\ [ABD] - P\ [ABCD] = 0.39x0.39x0.39 + 0.39x0.39x0.39 - [0.39x0.39x0.39x0.39] = \underline{0.095}$

$$P\ [Y+Z] = P\ [Y] + P\ [Z] - P\ [Y.Z]$$

$$P\ [EC+ED] = P\ [EC] + P\ [ED] - P\ [\{EC\}\ \{ED\}]$$

$$= P\ [E]\ P\ [C] + P\ [E]\ P\ [D] - P\ [C].P\ [D].\ [E] = \underline{0.245,}$$

Therefore, $P\ [W+Y] = 0.095+0.245 – P\ [ABCEC+ABCED+ABDEC+ABDED] = 0.095+0.245 – [ABCE+2ABCDE+ABDE] = 0.095+0.245-0.064 = \underline{0.276}$. Conversely, if data available shows that the system failed once over a 12-month period, using equation 2.2;

$$P = \alpha x \Omega^{-1} \qquad (2.2)$$

$$1 \text{ failure/365 days } (1\text{failure/day})^{-1} = \underline{0.27\%}$$

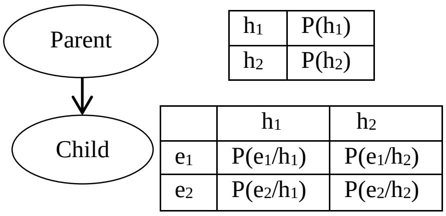
The value 0.276 means the system fails once in a 12-month period. Where the system fails twice every year, the probability of failure (P) of the top event is 0.54% using equation 2.2. Using the FT + software available, '*0.27'* failure rate of the top event is obtained using the same values of basic events' failure rates. This trivial system is represented in Figure 2.6; the minimum cut sets can be calculated as {E, C}, {E, D}, {A, B, C}, {A, B, D} but for realistic trees, computer programs are needed to identify minimum cut sets.

2.7.2.4 Bayesian network

The Rev. Thomas Bayes published his famous theorem in the 18th century. If *belief* can be identified with *probability,* then the theorem allows reasoning from effect to cause as follows: if *E* was true then *H* would result. *H* is actually true. This increases my belief in *E* by a certain amount. Clearly, depending on *a priori* unlikeliness of *E*, the amount by which *E* increases the belief may be very small or quite large. For example, if two events '*e'* and '*h'* are considered where event '*e'* is the influenced node and event '*h'* is the influencing node, the Bayes' theorem P (e) is the prior or marginal probability of *e*, P (*e/h*) is the conditional probability of *e* given *h*, P (*h/e*) is the conditional probability of *h* given *e* and P (*h*) is the prior or marginal probability of *h*. More formally, given a hypothesis '*h'* and some evidence '*e'*, Bayes' theorem states that (Hobbs and Developer, 2012):

$$P\,(h/e) = \frac{P\,(e/h)\;P\,(h)}{P\,(e/h)\;P\,(h) + P\,(e/\neg h)\;P\,(\neg h)} \tag{2.3}$$

Where *P (X|Y)* is the probability that *X* occurs given that *Y* has occurred and ¬*X* means "*not X*". As a trivial example, assume that: '*h'* is the hypothesis that "It is raining at the moment". '*e'* is the evidence that "I have just seen Chris with his umbrella". A node is generally drawn as an oval or circle, representing the variable or event. The arc is generally a straight line with an arrow head illustrating the direction of the link from the source node, often called the '*parent node'*, to the target node, often called the '*child node'*, as in Figure 2.7, which represents a simple BN consisting of events *e*, and *h*.



h_1	$P(h_1)$
h_2	$P(h_2)$

	h_1	h_2
e_1	$P(e_1/h_1)$	$P(e_1/h_2)$
e_2	$P(e_2/h_1)$	$P(e_2/h_2)$

Figure 2.7: CPT for a simple BN structure

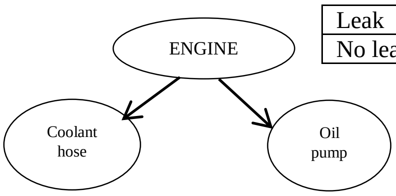
The CPT of parent '*h'* has two states, namely h_1 and h_2, together with probabilities P (h_1), P (h_2). The CPT of event '*e*' has two states, e_1 and e_2, but the states are influenced by event '*h'*. Bayesian networks allow for this difference in failure information by accepting evidence for the failure rate of any node, then using Bayes' theorem to calculate the '*posteriori'* probabilities of the failure rates of the sub-elements, reasoning from effect to cause. Chris carries his umbrella 60% of the time when it is raining [P *(e/h) = 0.6*]. Chris carries his umbrella 30% of the time when it is not raining [P *(e/ ¬ h) = 0.3*]. In the area where Chris lives it rains 20% of the time [P *(h) = 0.20*].

This is known in the literature as the '*prior'* probability because it is a measure of the probability of the hypothesis before any evidence is considered. Given these values, a person observing Chris in the street with his umbrella can calculate the probability that it is raining

(Hobbs and Developer, 2012) using equation 2.3 expressed as: (0.6 x 0.2)/ {(0.6 x 0.2) + (0.3 x 0.8)} = 0.33. This theorem forms the basis of BN modelling. It is therefore a directed acyclic graph (DAG) that encodes a conditional probability distribution (CPD) at the nodes of the basis of the arcs received to form an equivalent conditional probability table (CPT). From an engineering analysis point of view, given a 'ship engine' that requires '*oil*' for lubrication and '*water*' for cooling, three nodes can be constructed with engine as child node and coolant pipes and oil pumps as parent nodes.

Coolant pipes have two states, either '*leak*' or '*no leak'*; oil pumps states are '*fail*' or '*working*'; and engine states are '*fail*' or '*running*'. A visual representation of nodes and events that can represent this analysis is presented in Figure 2.8.

Leak	30.0	fail	50.0
No leak	70.0	working	50.0



Oil	fail		working	
Coolant	leak	No leak	leak	No leak
Fail	100	100	30	5
Running	0.0	0.0	70	95

Figure 2.8: CPT for Engine, coolant hose and oil pump

Parent nodes are given prior probability and child is given posterior probability. This shows 30% that the coolant pipe will leak and 70% that there is no leak. Similarly, the probability of the oil pump failing or working is 50% from historical failure data, age of the component, and relevant variables. Adopting a chain rule, the nodes, 'coolant pipe' and 'oil pump' are termed '*Q*' and '*T*' respectively, and the 'engine' is termed '*S'*. S_f signifies state '*engine fails'*. The probability of '*engine failure'* using equation 2.2 can be calculated as:

$$P\ (S_f) = \sum_{i=1}^{2} . \sum_{j=1}^{2} \mathrm{p(C1QT)p(Qi)p(Tj)} \qquad (2.4)$$

Event modelling can also be carried out by using the Hugin software which gives the same results (0.56) as calculated mathematically using equation 2.4.

P(engine fail)= P(oil fail) x P(coolant leak) x P(prior engine fail)+P(oil fail)x(coolant no leak)x P(prior engine fail)+P(oil work)x(coolant leak)x P(prior engine fail)+P(oil work)x(coolant no leak) x P(prior engine fail)

= 0.5 x 0.3x 1+0.5x 0.7x 1+0.5 x 0.3 x 0.3 + 0.5 x 0.7 x 0.05= <u>0.56%</u>

2.7.3 Fuzzy set theory and evidential reasoning

The fuzzy philosophy states that everything is a matter of degree: a world of multivalence, the opposite of which is bivalence. Positivism demands evidence, factual or mathematical. Based on binary logic it comes down to law: *A* or not -*A* – it cannot be both *A* and not -*A* (Fellow and Liu, 2008). Fuzzy logic is reasoning with fuzzy sets. A fuzzy cognitive map is a fuzzy causal picture of the world and a fuzzy system is a set of fuzzy rules that converts inputs into output. Fuzzy is a mathematical formalisation which enables representation of degrees of membership of members in sets (Fellows and Liu, 2008).

There are various techniques of fuzzy logic such as '*discrete'* (Godaliyadde *et al.*, 2010; Wang *et al.*, 1995 and Yang *et al.*, 2005) '*continuous fuzzy sets'* (Mukaidono,, 2001; Koa *et al.*, 2007 and Ung *et al.*, 2006), and '*fuzzy rule base'* (Yang *et al.*, 2006; Kowalewski *et al.*, 2007 and Yang *et al.*, 2009) that have been used in risk assessment in the maritime industry. According to Nwaoha *et al*. (2012) the '*discrete fuzzy set' is preferred* due to its simplification. Discrete fuzzy set also helps to define fuzzy rule base more easily. This section presents the background of discrete fuzzy set associated with *failure likelihood*, *consequence severity* and *failure consequence probability*. The fuzzy set representation are Nwaoha *et al*. (2012):

$$S_i = C^s \text{ o } F^{CP} \text{ x } F^L \tag{2.6}$$

This is represented in terms of membership functions µ, as follows

$$S_{i\mu} = C^s_\mu \text{ o } F^{CP}_\mu \text{ x } F^L_\mu \tag{2.7}$$

where, Si is the Risk/safety score of the ith event FCP is the Failure consequence probability. FL is the Failure likelihood probability. O is the Fuzzy composition operation. X is the Fuzzy Cartesian product operation. Cs is the Consequence severity (Nwaoho *et al*., 2012). Expressing linguistic parameters in terms of membership functions, C^s_μ is the description function of C^s in terms of the membership degree of µ (1, 2, 3, 4, 5, 6, 7) associated categories in Table 2.2. F^{CP}_μ is the description function of F^{CP} in terms of the membership degree of µ (1, 2, 3, 4, 5, 6, 7) associated categories in Table 2.3. F^L_μ is the description function of F^L in terms of the membership degree of µ (1, 2, 3, 4, 5, 6, 7) associated categories in Table 2.4. $S_{i\mu}$ means the description function of S_i in terms of the membership degree µ (1, 2, 3, 4, 5, 6, 7) associated categories are obtained using a max-min method based on equation 2.7 (Nwaoho *et al*., 2012)

Failure likelihood describes the failures' frequencies in a certain time, which directly represents the numbers of failures anticipated during the design lifespan of a particular system or an item. Linguistic variables for Table 2.2 are defined thus: very low (VL), low (L), reasonably low (RL), reasonably frequent (RF), frequent (F) and highly frequent (HF), per shipyard year (PYS) and definite variable (*E*).

Table 2.2: Failure Likelihood (Nwaoho *et al.*, 2012)

F	**Definition**	**PSY**	Linguistic Variable Membership sets Category F^{L}_{μ}						
			1	***2***	***3***	***4***	***5***	***6***	***7***
VL	Likely to occur once per year in the floating dry dock	$0.1<E$	1	0.75	0	0	0	0	0
L	Likely to occur once in the life in all the floating dry docks	0 $0.01<E<0.1$	0.25	1	0.75	0	0	0	0
RL	Likely to occur 10 times per year in floating dry dock	$0.1^{-2}<E<0.1^{-1}$	0	0	0.25	1	0.75	0	0
A	Likely to occur once per year for all floating dry docks	$0.1^{-3}< E<0.1^{-2}$	0	0	0.5	1	0.5	0	0
RF	Likely to occur one time in 10 years for all floating dry docks	$0.1^{-4} <E <0.1^{-3}$	0	0	0	0.75	1	0.25	0
F	Repeated failure	$E= 0.25^{-1}$	0	0	0	0	0.75	1	0.25
HF	Failure is almost inevitable	$E> 0.25^{-1}$	0	0	0	0	0	0.75	1

Consequence severity describes the magnitude of possible consequences, which is ranked according to severity of the failure effects. Its variables are described in Table 2.3 as negligible (N), marginal (MA), moderate (MO), critical (CR) and catastrophic (CT).

Table 2.3: Consequence Severity (Nwaho *et al.*, 2012)

F	**Definition**	Linguistic Variable Membership sets Category C^{s}_{μ}						
		1	***2***	***3***	***4***	***5***	***6***	***7***
N	Minor injury or unscheduled docking required	1	0.75	0	0	0	0	0
MA	Multiple injury, operations interrupted marginally	0	0.25	1	0.75	0	0	0
MO	Multiple injury, operation and production interrupted	0	0	0.75	0.25	0.25	0	0
CR	Single dead, high degree of operational interruption	0	0	0	0.75	1	0.25	0
CT	Multiple deaths, total system loss	0	0	0	0	0	0.75	1

Failure consequence probability is the probability that ensued consequences given the occurrence of the event where the linguistic terms described in Table 2.4 are highly unlikely (HU), unlikely (U), reasonably unlikely (RU), likely (L), reasonably likely (RL), and definite (D).

Table 2.4: Failure Consequence Probability (Nwaoho *et al*., 2012)

F	**Definition**	Linguistic Variable Membership sets Category F^{CP}_{μ}						
		1	***2***	***3***	***4***	***5***	***6***	***7***
HU	HU given occurrence of failure event (extremely unlikely to exist)	0	0	0	0	0	0.75	1
U	U but possible given occurrence that the failure event happens	0.25	1	0.75	0	0	0	0
RU	RU given the occurrence of failure event	0	0.25	1	0.75	0	0	0
L	L given that failure event occurs and no detection	0	0	0.5	1	0.5	0	0
RL	RL given occurrence of failure event from time to time due to operational weaknesses or design weakness	0	0	0	0.75	1	0.25	0
HL	HL given occurrence of failure event due to highly likely potential hazardous situation	0	0	0	0	0.75	1	0.25
D	Possible consequence given the occurrence of a failure event repeated during operations	0	0	0	0	0	0.75	1

Table 2.5 describes the membership expression as poor (P), average (AV), good (G) and excellent (E).

Table 2.5: Safety Membership (Nwaoho *et al*., 2012)

$S_{i\mu}$	Categories						
	1	2	3	4	5	6	7
P	0	0	0	0	0	0.75	1
A	0	0	0	0.5	1	0.25	0
G	0	0.25	1	0.5	0	0	0
E	1	0.75	0	0	0	0	0

In better understanding the membership expression for poor in Table 2.5, P [0, 0, 0, 0, 0, 0, 0.75, 1] with a more expressive failure likelihood VL [1, 0.75, 0, 0, 0, 0, 0, 0, 0] in Table 2.5, the safety expression poor can be incorporated into the appropriate safety score. A membership expression of [‘1’/1, ‘2’/0.75, ‘3’/0, ‘4’/0, ‘5’/0, ‘6’/0, ‘7’/0] (S_{ip}) can be expressed:

$$S_{ip} = C^{s}_{CT} \circ F^{CP}_{D} \times F^{L}_{HF} \tag{2.8}$$

The safety expression for average, good and excellent is likewise expressed. Using the best fit method, the safety risk description S_i of the i^{th} basic event can be mapped back to one (or all) of the defined four safety expressions in this study (Wang *et al.*, 1998, Nwaoho *et al*., 2012). The method uses the distance between S_i and each of the safety expressions to represent the degree to which S_i is confirmed to each of them. An illustration is given when using safety expression poor,

$$D_{i1}\,(S_i, \text{poor}) = \left[\sum_{j=1}^{7}\left(\mu_{S\,i}^{j} - \mu_{poor}^{j}\right)^2\right]^{1/2} \tag{2.9}$$

When the unscaled distance D_{i1} (j=1, 2, 3, 4) is equal to zero, S_i is just the same as the jth safety expression in terms of membership functions. In such a case, S_i should not be evaluated to other expressions (Nwaoho *et al.*, 2012).

Because of this D_{iJ} (1<J<4) is introduced and defined based on D_{ij} for any given distances for S_i is used to calculate $\alpha_{i.}$ In order to more clearly express the safety level of S_i the reciprocals of the relative distances between S_i and each safety expression, D_{ij}, expressed as α_{ij} are normalised into new indexes β_{ij} (j=1,2,3,4). α_{ij} can be defined in relation to the distance as:

$$\alpha_{ij} = 1/\, D_{ij}/\,(D_{iJ}) \qquad j = 1, 2, 3, 4 \tag{2.10}$$

If D_{ij} is equal to zero, it follows that β_{ij} is equal to 1 and the others are equal to 0. In other situations, β_{ij} can be expressed as:

$$\beta_{ij} = \alpha_{ij}/\textstyle\sum_{m=1}^{4} \alpha_{ij} \qquad j= 1,2,3,4 \tag{2.11}$$

Each β_{ij} (j=1,2,3,4) represents the extent to which S_i belongs to j^{th} defined safety expression. Mapping back to safety expression output (SO) implies:

$$SO\,(S_i) = [(\beta_{i1}, \text{‘P’}), (\beta_{i2}, \text{‘AV’}), (\beta_{i3}, \text{‘G’}), (\beta_{i4}, \text{‘E’}) \tag{2.12}$$

The fuzzy approach offers alternatives to positivism (Eleye-Datubo, 2006; Kosko, 1965 and Zadeh, 1965). The real applications are not as simple; sometimes an understanding of mathematics is required. The applications of fuzzy theory to economics, the social science, management, psychology and other areas have been published so far. In these applications there are some common approaches in uncertain environments, fuzzy modelling, and uncertain structure identification and decision making which is a topic in operations and research (Zimmerman, 2001). It is worth noting that the limitations of discrete fuzzy set manipulation led to development of fuzzy rule base and evidential reasoning to be highlighted later in this Chapter.

2.7.4 Evidential reasoning

The application of the ER approach was illustrated by Nwaoho *et al*. (2012). They carried out an illustrative application of fuzzy set theory to failure modes modelling uncertainty treatment of a LNG spherical moss tank design. The first part of their study included a hazard identification process using a brainstorming technique on various causes of events in LNG moss design tankers using a fault tree analysis diagram. The second part of their illustration was risk assessment, where risks associated with failure modes are assessed. This is the most detailed part which includes gathering subjective language from experts on the three risk parameters in the study and applying Fuzzy evidential reasoning (FER) mathematics to obtain a crisp value of risk of each base event (Eleye-Datubo, 2006).

Twelve (12) base events were identified and the overall safety expression of the top event was estimated to be ‘poor’. This implies that the three risk control options – regular inspection, training of crew, and effective maintenance – needed to be re-enforced to improve safety. In conclusion, FER was proven once more as an outstanding method for an effective risk estimation and control of hazards in marine engineering structures using a fuzzy set logic/or fuzzy rule base and evidential reasoning in applications where there is lack of data. The next section presents the mathematics of FER (Eleye-Datubo, 2006).

Once the safety output is obtained from the basic event using equation 2.12 and expressed in its corresponding safety expression output (SO), then it is important to access a situation where two multi-national experts are involved. This section seeks first to establish the mathematics of using ER with two experts where there is no software. In this study care is given to how equation 2.21 is derived. Where more than three experts are involved the software is required to be used; nonetheless, the safety expression aggregated can be transformed to its crisp value. The mechanism of ER can be explained using the aggregation of two safety assessments. Suppose the two safety assessments are denoted $\beta^{j}{}_{S_{ij}}$ and expressed (Nwaoho *et al.*, 2012):

$\beta^{j}{}_{S_{i1}}$ and $\beta^{j}{}_{S_{i2}}$ represent,

the extent to which the safety assessments of two basic events, S_{i1} and S_{i2}, are confirmed to j^{th} safety expression. Suppose the relative weights for SO (S_{i1}) and SO (S_{i2}) are w_1 and w_2. The relative weights of SO (S_{i1}) and SO (S_{i2}) are normalised using the expression as follows:

$$\sum_{k=1}^{2} w_k = 1 : 0 \leq w_K \geq 1 \qquad (2.13)$$

For SO (S_{i1}) and SO (S_{i2}), their probability masses S_{i1m} and S_{i2m} are expressed as follows:

$$S_{i1m} = w_1\, \beta^j{}_{Si1} \text{ and } S_{i2m} = w_2\, \beta^j{}_{Si2},\ m = 1, 2, 3, 4 \tag{2.14}$$

Meanwhile, the following can be obtained $S^{\wedge}{}_{i1H} = 1 - w_1 = w_2$ and $S^{\wedge}{}_{i2H} = 1 - w_2 = w_1$:

$$S^{♀}{}_{i1H} = w_1\left(1 - \sum_{k=1}^{2} \beta^j{}_{Si1}\right) = w_1\,[1-(\beta^1{}_{Si1} + \beta^2{}_{Si1} + \beta^3{}_{Si1} + \beta^4{}_{Si1})]$$

$$S^{♀}{}_{i2H} = w_2\left(1 - \sum_{k=1}^{2} \beta^j{}_{Si1}\right) = w_2\,[1-(\beta^1{}_{Si2} + \beta^2{}_{Si2} + \beta^3{}_{Si2} + \beta^4{}_{Si2})] \tag{2.15}$$

$S^{♀}{}_{i1H}$ and $S^{♀}{}_{i2H}$ represent the degree to which other basic events can play a role in the assessment. $S^{\wedge}{}_{i1H}$ and $S^{\wedge}{}_{i2H}$ are the individual remaining belief values unassigned for SO (S_{i1}) and SO (S_{i2}) respectively. $S_{i1H} = S^{\wedge}{}_{i1H} + S^{♀}{}_{i1H}$ and $S_{i2H} = S^{\wedge}{}_{i2H} + S^{♀}{}_{i2H}$ where S_{i1H} and S_{i2H} represent possible incompleteness in the subsets SO (S_{i1}) and SO (S_{i2}). The combined probability masses, S_{i1m} and S_{i2m}, and S_{i1H} and S_{i2H} are as follows:

$$S_{im} = K\,(S_{i1m}S_{i2m} + S_{i1m}S_{i2H} + S_{i2m}S_{i1H}) \tag{2.16}$$

$$S_{iH} = K\,(S_{i1H}\, S_{i2H}), \qquad m = 1, 2, 3, 4 \tag{2.17}$$

$$K = \left(1 - \sum_{T=1}^{4} \sum_{R=1}^{4}\right) S_{iA} S_{i2B}{}^{-1} \tag{2.18}$$

The combined degree of belief (T^m) can be calculated as follows:

$$T^m = S_{im}/(1 - S_{iH}), \qquad m = 1, 2, 3, 4, \tag{2.19}$$

To rank the 'very high' risk hazards, the crisp values of their safety descriptions can be calculated as follows:

$$Q_i = \sum_{m=1}^{4} T^m \times P^m \tag{2.20}$$

$$P_1 = P^1{}_4/\, P^1{}_1,\ P_2 = P^1{}_3/\, P^1{}_1,\ P_3 = P^1{}_2/\, P^1{}_1,\ P_4 = 1$$

$P^1{}_1$, $P^1{}_2$, $P^1{}_3$, $P^1{}_4$ represent the unscaled numerical values associated with the linguistic terms (i.e. poor, average, good and excellent) of the safety expression. $P^1{}_1$, $P^1{}_2$, $P^1{}_3$, $P^1{}_4$ can be calculated as follows (Nwaoho *et al.*, 2012):

$P^1{}_1 = [0.75/(0.75+1)]6 + [1/(0.75+1)]7 = 6.571$, $P^1{}_2 = [0.5/\,(0.5+1+0.25)]4 + [1/0.5+1+0.25]5 + [0.25/(0.5+1+0.25)]6 = 4.854$, $P^1{}_3 = [0.25/0.25+1+0.5]2 + [1/0.25+1+0.5]3 + [0.5/(0.25+1+0.5)]3 + [0.5/(0.25 + 1 + 0.5)]4 = 3.141$, $P^1{}_4 = [1/1(1+0.75)]1 + [0.75/(1+0.75)]2 = 1.428$.

Substituting the values of $P^1{}_1$, $P^1{}_2$, $P^1{}_3$, and $P^1{}_4$ in equation 14 yields:

$$Q_i = 0.271 \text{ x } T^1{}_i + 0.478 \text{ x } T^2{}_i + 0.739 \text{ x } T^3{}_i + 1.0 \text{ x } T^4{}_i \qquad (2.21)$$

2.7.5 Fuzzy rule base

With the purpose of modelling more general, complex decision-making problems under uncertainty, the belief rule idea was proposed by considering a belief distribution in a conclusion (belief degree), the relative weight of the rule (rule weight) and the relative weight of an antecedent attribute (attribute weight). Mathematically, a belief rule base (BRB) which captures the dynamic of a system consists of a collection of belief rules and the fuzzy inference system (FIS) is defined as follows (Yang *et al.*, 2006):

$$R_k : \text{IF } x_1 \text{ is } A_1^k \wedge x_2 \text{ is } A_2^k \ldots\ldots\ldots x_{Tk} \text{ is } A_{Tk}^k \text{ THEN } \{(D_1, \beta_{1k}),\ (D_2, \beta_{2k}), \ldots.\ (D_N, \beta_{Nk})\} \qquad (2.22)$$

With a rule weight θ_k and attribute weight $\delta_{k1}, \delta_{k2}, \ldots\ldots\ \delta_{KTk}$, where $x_1, x_2, \ldots\ldots\ x_{Tk}$ represents the antecedent attributes in the *kth* rule R_k, A_i^k (i = 1,2…, T_k, k = 1,2…L) is the referential value of the k*th* rule R_k, $A_i^k \in A_i$, $A_i = \{ A_{ij}, j = 1,2,\ldots. J_i\}$ is a set of referential value, θ_k ($\in R^+$, k = 1,2,…L) is the relative weight of the *k*th rule $R_{k,}$, $\delta_{k1}, \delta_{k2}, \ldots.\ \delta_{KTk}$ are the relative weights of the T_k antecedent attributes used in the *k*th rule R_k, and β_{ik} (i=1,2…,N, k = 1,2….,L) is the belief degree assessed to Dj which denotes the *j*th consequent. If $\sum_{i=1}^{T_k}.\ \beta_{ik} = 1$, the *k*th rule R_K is said to be complete; otherwise, it is incomplete. Note that "∧" is a logical connective to represent the "AND" relationship. In addition, suppose that T is the total number of antecedent attributes used in the rule base.

2.7.5.1 Belief rule-based inference

Given an input to the system, $U(t) = \{U_i(t),\ i = 1,2\ldots,\ T_K\}$, how can the rule-base be used to infer and generate the output? As mentioned earlier, T_k is the total number of antecedents, which can be one of the following types (Yang *et al.*, 2006): continuous, discrete, symbolic and ordered symbolic. Before the start of an inference process the matching degree of input to each referential value in the antecedents of a rule needs to be determined so that an activation weight for each rule can be generated.

This is equivalent to transforming an input into a distribution on referential values using belief degrees and can be accomplished using different techniques such as the rule or utility-based equivalence transforming techniques (Yang, 2001, and Yang *et al.*, 2007). Using the notations provided above, the activation weight of the *k*th rule R_k, w_k, is calculated as (Yang *et al.*, 2006):

$$W_k = \frac{\theta_k a_k}{\sum_{i=1}^{L} \theta_i a_i} \tag{2.23}$$

where a_k is called the normalised combine matching degree. This reflects the individual matching degree to which the input matches its referential value A_i^k of the packet antecedent A^k in the kth rule R_k and $a^k_i \geq 0$ and $\sum_{i=1}^{T_k}. a^k_i \leq 1$. In BRB it can be generated using various ways depending on the different types of input information. In Yang's (2001) paper, an important technique, i.e. rule based information transformation technique, was proposed to deal with the input information that includes qualitative assessment and quantitative data. This paper gives a detailed overview for quantitative data.

2.7.5.2 Rule based FIS using belief structure

In this section, the FIS structure is described in the proposed framework. In many applications, the knowledge that is used to make the rules in an FIS is uncertain. The uncertain rules can be generated by experts or from training datasets. In the design of rule-based systems, ignorance may occur owing to weak implications of experts in assigning a certain relation between antecedents and the consequents (Yang *et al.*, 2006). In this case, different antecedent attributes indicating the inputs of the FIS are defined using linguistic variables. The uncertainty in the relationship of different attributes and consequent terms can be represented while the vagueness in the consequent grades is modelled through fuzzy focal elements (Aminravan *et al.*, 2011) as presented in Figure 2.9.

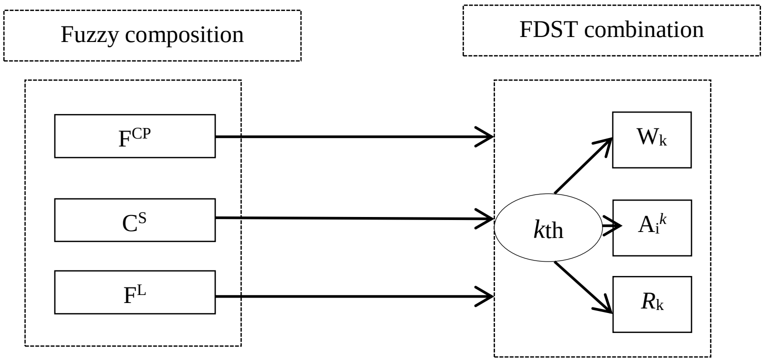


Figure 2.9: The schematic of belief structure FIS

Generally, inference by human beings (i.e. subjective assessment) is based on an implication of a small numbers of features. Most rules that an expert provides are nonlinear mappings of the attributes, characterised by linguistics terms, to the consequent basic probabilities. The nonlinear mapping in a rule-based FIS is modelled using fuzzy implications. As in the proposed belief structure, this models more facets of uncertainty compared to classic FIS; the subjective knowledge can be expressed with a higher number of rules (i.e. more uncertainty mappings from the antecedent to the consequent space). Hence, a challenge in a belief structure FIS is dealing with the higher computational overhead compared to classic FIS engines (Aminravan *et al.*, 2011). The proposed FIS engine uses a mathematical manipulation inference procedure to determine the firing strength of each rule. Different weights for each antecedent attribute and each rule are considered. To account for the importance of each attribute, the rule combination and defuzzification are followed by the classic pattern of an FIS. The rule combination on activated rules can be represented as a distributed assessment or can be the input to another FIS engine (Aminravan *et al.*, 2011).

To properly represent real-world knowledge, fuzzy production rules have been used for knowledge representation to process uncertain, precise and ambiguous knowledge (Chen, 1988, Liu *et al.*, 2012). Another kind of uncertainty exists when a strong correlation between premise and conclusion cannot be established. That condition means the evidence available is not adequate, or experts do not support a hypothesis totally but only to a degree of belief (Liu, *et al.*, 2013).

2.7.5.3 Rule weight

The effect of rule weights in the rule-based classification system have been considered by previous researchers (Ishibuchi and Yamamoto, 2001, 2005). Some rule-based classification systems do not assign different weights to the rules. In most cases with this condition, the membership of different levels of attributes is extracted from datasets (Ishibuchi and Yamamoto, 2001). Thus, the membership is modified using the training data to compensate for assigning the same weights to all rules. Adjusting the membership can result in lower comprehensibility of the rule-based system. As a solution, some approaches use constraints to compromise between accuracy and comprehensibility of the FIS. However, where real training data is not available, memberships and rules are defined using expert knowledge. A rule weight approach in this case can improve the accuracy of FIS (Ishibuchi and Yamamoto, 2001).

2.7.5.4 Attribute weight

The attribute weights are assigned based on expert opinion presented on a comparison non-linear matrix and will remain fixed in the proposed FIS. In general, a feature in antecedent space can be a fuzzy piece of evidence. It can be a crisp (singleton) input but most of the time, due to the unreliable nature of input data, they may better be represented by a fuzzy membership which conveys the dispersion of information or an equivalent concept of the distribution of the feature (Ishibuchi and Yamamoto, 2001).

2.7.5.5 Fuzzy logic systems and their properties

A fuzzy logic system consists of four components as shown in Figure 2.10: fuzzy rule base, fuzzy interference engine, fuzzifier, and defuzzifier. *Fuzzy rule base* A fuzzy knowledge/rule base consists of a set of fuzzy IF-THEN rules. It is the core of a fuzzy logic system in the sense that all other components are used to implement these rules in a reasonable and efficient manner. Human knowledge has to be represented in the form of the fuzzy IF-THEN rules. The three major properties of fuzzy rules are outlined as follows: (1) A set of fuzzy IF-THEN rules is consistent if there are no rules with the same IF parts but different THEN parts; (2) A set of fuzzy IF-THEN rules is continuous if there do not exist such neighbouring rules whose THEN part fuzzy sets have empty intersections (Eleye-Dutaba, 2005).

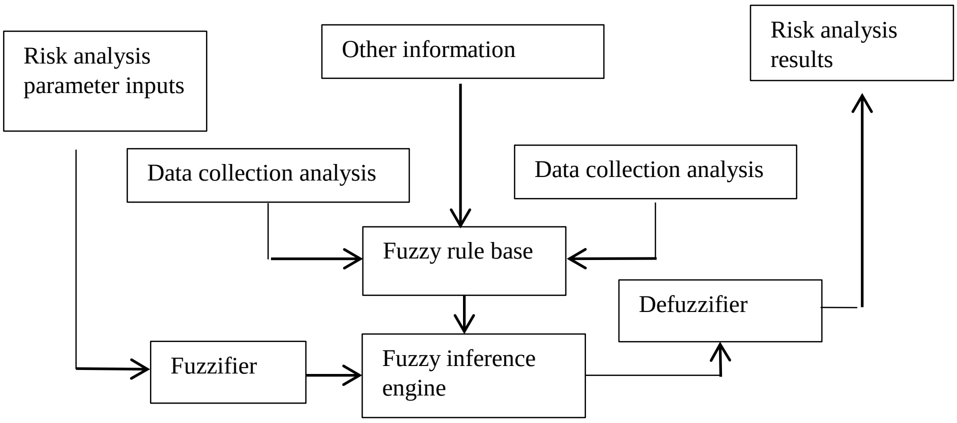


Figure 2.10: An overview of the safety model using a fuzzy rule base approach (Eleye- Dutaba, 2005)

Fuzzy inference engine:In a fuzzy inference engine, fuzzy logic principles are used to combine the fuzzy IF-THEN rules in the fuzzy rule base into a mapping from a fuzzy set.

Fuzzifier: The fuzzy interference engine combines the rules in the fuzzy rule base, and then it carries out a mapping from one fuzzy set to another. Owing to the fact that in most applications the input and output of the fuzzy system are real-values numbers, we must construct interferences between the fuzzy inference engine and the environment. *A fuzzifier* is defined as a mapping from a real-valued point to a fuzzy set. The fuzzifier should consider the fact that the input is at the crisp point. The fuzzifier should help to simplify the computations involved in the fuzzy inference engine.

Defuzzifier: The defuzzifier is defined as a mapping from fuzzy set (which is the output of the fuzzy inference engine) to a crisp point. Conceptually, the task of the defuzzifier is to satisfy a point that best represents the fuzzy set. This is similar to the mean value of a random variable. There exist a number of choices in determining this representing point such as the *'centre average defuzzifier', which* is the most commonly used defuzzifier in fuzzy systems.

2.7.5.6 Establish experts real-valued hazard data

Anticipated and identified causes or factors related to technical failure of a floating dry dock system operation are collected for multiple attributes and experts' knowledge. As related to the experts' interpretation, their crisp values are then entered from database knowledge for the obtained parameters. The inputs are directed into a process that determines the degree to which they belong to each of the appropriate fuzzy sets via membership functions (MFs). The algorithm uses either *symmetric*, *singleton*, *rectangular*, *triangular* or *trapezoidal MFs*, uniformly distributed by each universe of discourse (Ishibuchi and Yamamoto, 2001).

2.7.5.7 Fuzzy input set to extract rules

The next step is to take inputs and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions. Based on the $\{A_i^k\}_{i=1}^N$ (fuzzy sets in $U_i \alpha R$), which denotes the value of input linguistic variables $\{x_i\}_{i=1}^N$ (conditions), rules can be extracted for the antecedent such as 'x_1 is A_i^k and ……….. x_N is A_N^k. Thus, the membership value associated with the input x_1 is A_i^k (Eleye-Dutaba, 2005).

2.7.5.8 Extraction of rules from input fuzzy sets and fuzzy rule base

Based on the input fuzzy variables, rules can be extracted from the antecedent/premise, which is denoted as '*x is A'*. Moreover, each given rule has more than one part in a BRB system; fuzzy logical operators of 'AND' or/and 'OR' are applied to evaluate the composite function firing strength of the rule. Once the inputs have been fuzzified, the degree to which each part of the antecedent has been satisfied for each rule is recognised (Eleye-Dutaba, 2005).

If a given rule has more than one part, the fuzzy logical operators are applied to evaluate the composite firing strength of the rule. Fuzzy relations play an important role in fuzzy inference systems. Fuzzy relations use notions from crisp logic. Concepts in crisp logic can be extended to fuzzy relations by replacing 0 or 1 values with a fuzzy membership value. A singleton fuzzy rule that assumes the form 'if x is A, then y is B, where x € U and y € B is called the "consequent conclusion" (Eleye-Dutaba, 2005). Interpretation of a fuzzy rule base rule involves two distinct steps. The first step is to evaluate the antecedent, which involves fuzzifying the input and applying necessary fuzzy operators. The second step is implication, or applying the result of the antecedent to the consequent, which essentially evaluates the membership function (Eleye-Dutaba, 2005).

2.7.5.9 Evaluation of rules for output fuzzy set

To produce safety evaluation for each cause of a technical failure at the bottom level of a hierarchical system, the consequence/conclusion as denoted by '*y is B'* is formed for the output fuzzy variable in the system. Its output set can be defined using fuzzy safety estimate sets in the same way as the fuzzy inputs (Eleye-Dutaba, 2005). The implication method of the *minimum* or the *product* then shapes the output membership functions on the basis of the firing strength of the rule. This input for the implication process is a single number given by the antecedent, and its output is a fuzzy set (Eleye-Dutaba, 2005).

2.7.5.10 Aggregation and de-fuzzification

Aggregation is a process whereby the outputs of each rule are unified. Aggregation occurs only once for each output variable. The input to the aggregation process is the truncated output fuzzy sets returned by the implication process for each rule. The output of the aggregation process is the combined output fuzzy sets. The input of the aggregation process is the list of truncated output functions returned by the implication process of each rule (Aminravan *et al*., 2011).

The output of the aggregation process is one fuzzy set for each output variable. As this method is always commutative, the order in which the rules are executed is not important. The max (maximum) method is applied to the *aggregation* of consequent, '*y is B', across the rules.* The *normalisation* is required to make the sum of weights equal to 1 (Eleye-Dutaba, 2005).

This is achieved by dividing each membership value in the fuzzy conclusion set by the sum total of all membership values in the set. Defuzzification is used to obtained a single number output; the input for the process is a fuzzy set (the aggregated output fuzzy set), and the output of the defuzzification process is a crisp value obtained by using a defuzzification method such as the centroid, height, or maximum (Aminravan *et al*., 2011).

2.8 Problems in Application of FSA in Dry Docking Industry

In the application of FSA in the floating-graving docking system some problems are encountered similar to applying FSA in the ship navigational system (Hu *et al*., 2007). Firstly, for many years, the statistical data associated with dry docking accidents is customarily based on laws and regulations on the statistics of water-traffic accidents. The classification of the ships and the power of their main engine, the number of deaths and the direct economic losses are considered as the main standards in ranking the shipping-dry docking accidents. Another problem is that there are certain disadvantages in achieving management in a time span, so that it is difficult to obtain the accurate statistics of the consequences of accidents. How to determine new models of risk consequences with the help of the accident ranking records?

Secondly, case statistics and analysis are the basic tasks in FSA. It can make preliminary analysis and assessment of ‘what would go wrong’ before the occurrence, but the key point of analysis is how to make full use of recorded dry docking evolution cases. However, in this kind of analysis, it is inevitable to encounter the problem of the quantity of case-statistics samples, and the accuracy of the result of the generic model based on a few samples is doubtable. To obtain more accurate assessment results, which can be frequently quoted, it is necessary to build another type of risk-assessment model.

Thirdly, the statistical span of the generic model is great, and the risk levels of research subjects in the analysis are quite intensive because of various restrictions, so it is not easy to collect detailed quantity data of docking activities so as to effectively identify the main risk problems. In order to show the frequency and severity of the main hazardous events in a Poisson process, it is necessary to build a relative risk-assessment model to better understand the construction and influential factors of risks. Lastly, although the generic model takes ‘frequency’ and ‘severity’ into consideration, it is necessary to consider ‘obligated severity’ in the detailed analysis of the research subjects, such as the proportion of each research subject on the obligation of faults in occurrences of accident.

2.9 Justification of Research

A floating-graving structure is a complex and expensive engineering structure composed of many systems and is usually unique with its own operational characteristics (Wang and Ruxton, 1997). These structures need to adopt new approaches, new technology, and to new hazardous situations, and each element brings with it a new hazard in one form or another. Therefore, safety assessment should cover all possible areas including those where it is difficult to apply traditional safety assessment techniques. Such traditional safety assessment techniques are considered to be mature in many applications. Depending on the uncertainty level/the availability of failure data, appropriate methods can be applied individually or in combination to deal with the situation. All such techniques can be integrated in the sense that they formulate a general structure to facilitate risk assessment and FSA (Pillay and Wang, 2002). When dealing with floating-graving system risk analysis, it is clear (see Section 2.6.5) that FTA, HAZOP, FMEA, PNs and MCS techniques cannot be easily implemented since such techniques need the frequencies of hazardous situations to be usually estimated based on historical failure data. Almost invariably, failures are assumed to be random in time; that is, the obtained number of failures is divided by an exposure period to give a failure rate and this is assumed to be age-dependent (Wang and Trbojevic, 2007).

Using common sense it can be seen that, many modes of failure are more common in the earlier or later years of the life of a component or a system. Even with high-quality data, sample sizes are often small and statistical uncertainties are relatively large. Lack of reliable safety data and lack of confidence in safety assessment have been two major problems in the safety analysis of various engineering activities. To solve such problems, further development may be required to develop novel and flexible safety assessment techniques for dealing with uncertainty properly and also to use decision-making techniques on a rational basis (Pillay and Wang, 2002).

Again, the challenging task of assigning probability values, for instance for use in a FTA, has attracted a lot of attention and discussion. These flexible safety assessment techniques advocate that branch probabilities can be estimated in one of four ways or in a combination of the following (Hartford and Baecher, 2004): (a) engineering model based on physical processes; (b) fault tree analyses based on logical constructions; (c) judgements by experts; and (d) statistical estimates based on empirical data. Statistical estimates are characterisations or summaries of past observations.

Engineering models are constructed based on reasoning from first principles of physics. Uncertainties in the model parameter values and in the model itself are propagated through the calculations to establish probabilities that the floating-graving docks can fail to carry out their operations properly. Fault trees differ from engineering models in that they model the logic of a system rather than the physics of the system. Judgement is based on experts’ intuition and reasoning which reflects a base of knowledge and evaluated experience. Collective judgements of experts, structured within a process of debate, may yield as good an assessment of probabilities as can be obtained by mathematical analyses. Some might claim a better assessment (Vick, 2002). Therefore, a fuzzy logic modelling approach (see Section 2.6.3) may be more applicable to conduct hazard identification, risk estimation and risk control option selection based on risk management information. This is also true for cost-benefit assessment where techniques such as cost per unit risk reduction (CURR) cannot be effectively used due to a high level of uncertainty in the data. As such, an appropriate solution may be a fuzzy logic modelling approach with the combination of expert judgements. Also, software safety analysis is another area where further study is required. In recent years, advances in computer technology have been increasingly used to fulfil control tasks to reduce human error and to provide operators with a better working environment in floating-graving systems (Pillay and Wang, 2002).

Based on the critical review of floating-graving docking/undocking evolution and discussion of the experts in the area, it was found that ship repair companies often have a poor organisational structure. This would entail documentations of accident records, systems and components that would be difficult to come by and the availability of data for quantitative analysis is either unavailable or far from being in the ideal format. This was the major challenge of this research and subsequently resulted in risk assessment of docking operations under uncertainty treatment methods such as evidential reasoning (ER), fuzzy set theory (FST) and Bayesian network (BN).

Three types of software (Fault tree ++, Intelligent decision software (IDS) and AgenaRisk Desktop) were adopted to overcome the challenge in application of these novel methods. In summary, this PhD research develops a novel subjective risk assessment methodology for floating-graving docking/undocking evolution problems based on the safety principles of FSA. This research provides insight as to the relative merits between the use of judgement (degrees of belief) and statistical analyses. It does conclude that the approaches provide equally important information, but usually different information, which can be applied in different parts of risk analysis.

2.10 Discussions and Conclusion

The floating-graving docking systems are connected with ship repairing and ship conversion. This includes the consideration of all accidental or intentional dangerous effects coming from the environment or humans. The operations of bringing ships out of the water for maintenance brings a lot of hazards at the point of contact between humans and technology or humans and the environment (Mikulik and Zadjel, 2009). Each of them, excluding natural disasters, can be caused by accidents or intentional human actions. Such hazards can lead to physical destruction of the floating-graving system or even collapse. In the face of such hazards appearing, particularly during docking and undocking evolution, suitable strategies of reaction ought to be taken into consideration. A functional system of the floating-graving docking system, made of various hardware, is able to take advantage of the FSA method and, as a consequence, reduce such danger (Mikulik and Zadjel, 2009).

In this research, the FSA method adaptation for risk control in floating-graving docking operations is investigated. Research on the application of FSA to prevent hazards or failures in these systems is rare. So far, the safety assessment approach for risk analysis in certain identified hazards in floating-graving dock operations has arrived at some conclusions. Nonetheless, the key element for reaching adequate results is gaining suitable data. Often, intelligent building domain data are collected as a linguistic variable. Then they are processed into numerical data with some errors. But even if data are hard to obtain and vary a lot with time, the FSA method based on fuzzy set theory, Bayesian network, and evidential reasoning helps to get an acceptable outcome, has great tolerance and is insensitive to errors made in swapping linguistic into numerical data, which is the biggest problem in such domains of research (Mikulik and Zadjel, 2009).

The FSA philosophy has also been approved by the IMO for reviewing the current safety and environmental protection regulations and studying any new element proposal by the IMO; and justifying and demonstrating a new element proposal to the IMO by an individual organisation (Pillay and Wang, 2002). Concerns regarding the use of FSA in floating-graving docking evolution are enormous. FSA may be a tool to support development of rational regulations, and enable focusing on important issues and justify modifications (Bai, 2002). Although many elements of the approach described in previous sections are well established in other contexts, their applications to the ship repairing industry in a generic or specific way are relatively new and unproven. Trial applications are being encouraged to be undertaken, with the intention of accumulating relevant results and experience.

The development of suitable mechanisms and procedures in which the FSA process can be applied by the IMO committees in future decisions can be considered in the dry docking industry. Useful risk estimation data include: incident statistics, equipment reliability, structural reliability, human reliability and docking (exposure) data. The cost data relate to the estimation of investment costs, operating costs, inspection and maintenance costs, and the cost for clean-up, pollution, etc. In many cases, data are insufficient to conduct an appropriate estimation of risk (Bai, 2003). As with all risk assessments, the results obtained are dependent on data and also on judgement in interpreting the data and anticipating industry trends, the impact of changes in technology, the potential for future accidents, etc. The results of an FSA study are therefore dependent upon both the availability of relevant data and qualified analysts who can undertake rational judgements. The quality of a FSA is as good as the data provided, expertise used and mathematical models applied. There are many challenges in collecting and interpreting risk data in floating-graving docking operations. In many cases, it is found that the data have not been recorded or not in the way that enables FSA.

Mathematical modelling and computer simulations may be the alternatives to the data. An expert's opinion may be a necessary substitute for or complement to statistical data. For those in the ship repairing industry, this research can be considered a starting point of a new method for enhancing or controlling the quality of the shipboard-floating-graving environment by minimising or avoiding reviewed problems using scientific assessment approaches. The platform provided in this research consists of four chapters. They are namely, a fault tree-formal safety assessment in the ship repairing industry, fault-tree-Bayesian network for dry dock gate failure, fuzzy rule base with belief degree for risk estimation in docking operation, and truncated normal distribution Bayesian network for cost-benefit analysis for ranking risk control options in docking operations. By utilising these four core chapters, the five steps of FSA methodology are completed. Each chapter has its own research methodology which is subsequently demonstrated by its corresponding case study. Although there have been recent concerns on the subjectivity of FSA based on incomplete information, it is important to improve efforts to find specialists with long experience and good background in relevant case studies and to train these experts in expressing judgements in probabilistic terms.

Chapter 3 – Fault Tree – Formal Safety Assessment in Docking Operation

Summary

Fault tree-Formal Safety Assessment (FT-FSA) is the premier scientific method that is currently being used for the analysis of maritime safety and for formulation of related regulatory policy. To apply FSA in this Chapter, all five steps are considered and critical information highlighted in each step as reviewed in the literature. A novel 15 steps approach of FT-FSA is introduced in the systematic accident scenario considered in this study as emergent phenomena from variability and interactions in shipyard (considered as a complex system). The results of this Chapter will be useful for guidelines and regulatory reforms in the ship repair industry as demonstrated by identifying 'fall from height in ship repair occupational hazards' for recommendation in decision making.

3.1 Introduction

In the maritime industry, questions must be asked. Why should the industry have to wait for an accident to occur in order to modify existing rules or propose new ones? The safety culture of anticipating hazards rather than waiting for accidents to reveal them has been used in industries such as nuclear and the aerospace industry (Kontovas and Psaraftis, 2009).

The international shipping industry has begun to move from a reactive to a proactive approach to safety through what is known as Formal Safety Assessment (FSA) (Kontovas and Psaraftis, 2009). FSA is a formal, structured and systematic methodology, aimed at enhancing maritime safety, including the protection of life, property, and marine environment, by using risk and cost-benefit assessments (Maistralis, 2007).

The use of FSA is consistent with, and should provide support to any decision making body (Maistralis, 2007). Based on Wang and Trbojevic (2007) it is a new approach to marine safety which involves using the techniques of risk and cost-benefit assessments to assist in the decision making process. First introduced by the IMO as a rational and systematic process for assessing the risk related to maritime safety and the protection of the marine environment and for evaluating the costs and benefits of IMO's options for reducing risks as reference in Maritime Security Committee (MSC cir. 1023, MEPC circ. 392, 1993) it has been seconded to none so far. Before its adoption by IMO, FSA has been an object of research leading to several academic papers written by Wang (2001), Soares and Teixeira (2001), & Rosqvist and

Tuominen (2004). The relevance of the methodology of FSA over the span of ten (10) years, has been proven in marine and offshore products such as fishing vessels, ports, marine transportation, offshore support vessels, containerships, LNG ships, ship hull vibration, crushing ships, liner shipping, high speed crafts, oil tankers, trial studies of passenger roll on/roll off (roro) vessels with dangerous goods and bulk carriers (Nwaoho *et al*., 2011).

The Royal Institution of Naval Architects (RINA) has also published a collection of some 15 papers on the subject, covering various contexts of the problem (RINA, 2012). Fault tree (FT) on the other hand, is an analysing tool, used in FSA. This chapter is developed from statistics and preparatory work (Baris, 2012), on shipyard fatalities from, USA, UK, Turkey, and Singapore. Reports on a critical review of FSA by Kontovas and Psaraftis (2009), guided in highlighting the shortcomings of steps in FSA.

The aim of this Chapter is to show that FT-FSA methodology of safety-relevant scenarios in occupational accidents in shipyard can be analysed. Our exemplary application is a ‘Fall from Height’ scenario, which deals with concurrently interacting human operations and technical systems. In particular, the assessment considers the risk of falling from height due to scaffold failure. The systematic risk assessment approach portrayed in this Chapter intends to be an effective means of providing feedbacks to both contractors and designers in shipyards. The findings and conclusions are of interest to ship repair owners, maritime researchers, and other safety policy and regulator makers in dry docks.

Specifically, the audience for this Chapter is obviously ship repair managers, where FSA as a subject of non-trivial complexity tool, serves to provide a vehicle to explain how resources can be efficiently managed in the system, through identifying, analysing, and proposing improvements on specific critical systems. This Chapter is organised as follows: Section 3.2 presents the statement of problem. Section 3.3 functional components of FSA in dry docking. Section 3.4 is the accident data analysis. Section 3.5 presents an illustrative example, followed by discussions.

3.2 Statement of Problem

In dry docks, occupational accidents are frequent. An occupational accident is defined as an unexpected and unintended incidence while occupied in an economic activity, which results in one or more workers getting injured or loss of life (Baris, 2012). Every fifteen seconds, a worker dies as a result of occupational accidents or work related diseases. 160 workers have an occupational accident statistically every fifteen seconds. Over 2.3 million deaths per year and more than 336 million accidents occur at work annually (ILO, 2011). In shipyards, these occupational accidents are classified by several statistical agencies under the construction, or repairing categories. Shipbuilding and repair is a complex business, with huge tasks performed in parallel. Steel handling and processing production process requires great space, which must be inspected, sorted and stored. On these steels, further activities are required, which include blasting, priming, shaping, forming to designed shape, welding to make assemblies, panel, fabrication, block assembly, pre-outfitting, air conditioning, electrical cable fitting, surface preparation and coating (ILO, 2011). This has been the challenge in respect to shipbuilding and repair system safety, standing out as being complex and uncertain.

The adoption of FT-FSA concept will be used to solve existing gaps. An existing gap within the framework, is the unavailability of experts to carry out proactive risk based approach to deal with accidents and eliminating its occurrence from its origin. FSA consist of five steps. FT is a formal method used in step 1 and 2, in this study. Hollnagel (2004) categorizes these accident models in the following three types: (a) a sequential accident model describes an accident as a result of a sequence of events that occurred in a specific order; (b) epidemiological accident model which describes an accident in an analogy with the spreading of diseases; (c) systemic accident model describes the performance of a system as a whole, rather than on the level of cause-effect mechanisms or epidemiological factors.

From a safety assessment point of view, researchers have rather failed to identify which accident model is used. Depending on the model of accidents, different methods and result will be obtained. FT-FSA over the past decades, has received no attention in the dry docking industry, as the literature review indicates. The purpose of this Chapter is to introduce FT-FSA methodology in the ship repair industry and propose ways of implementation. All steps of FSA are considered and possible pitfalls or other deficiencies are identified, and proposals are made to alleviate such deficiencies, with a view to achieve a more transparent and objective approach in the ship repair industry.

FSA is time consuming, and where experts are required, opinion varies and conflicts arise. Researchers are getting fed up with new existing subjective approaches instead of increasing awareness of companies coming together for data collection (Kontovas, and Psaraftis, 2009). The criticism of using MSC guidelines has been strongly submitted by Greece, yet there has been no response on reforms (Kontovas and Psaraftis, 2009). The different types of analysis provided by researchers have led to increased confusion as to which method is better to use and in what areas. These and many other disadvantages, have led many researchers to avoid the term ‘FSA’. Many love eye catching titles like ‘risk analysis under uncertainty’, etc., yet using the same FSA methodology. In this regard, this Chapter, revisits the origin of MSC guidelines in the application of FSA, in its simplest form, and brings to light short comings that have plagued its application in recent years from adopting a direct approach in its implementation.

This chapter provides a rather, individualistic research, based on time scheduling and critical thinking, hence by-passing so many obstacles presented by time-wasting generic opinions from experts. Lastly, many researchers limit its application to ships and offshore structures, impairing creative thinking in other maritime sectors. To overcome these disadvantages, the next section, looks closely into FT-FSA framework and its application in shipyards, and weaknesses of each step highlighted.

3.3 Functional components of FSA in dry docking

3.3.1 System definition

FSA is built around a suite of technical analyses of a wide range of topics. Some of those topics are listed below and then discussed in greater detail (Hu *et al*., 2007). Although not part of the formal FSA structure, it is good practice to write technical and management philosophies at the start of the FSA project. Philosophies can be written for each operational activity. A philosophy will generally consider the following issues (Hu *et al*., 2007):

- The physical scope of work and boundary conditions for the project and the FSA.
- The standards, regulations and classification society to be followed. They can be internal to the company or from an outside organization.
- The modelling techniques to be used.
- The consequence of accident on the designed model.

A detailed system description is essential to the risk assessment. Such description usually consists of a structure, including all hardware, people, procedures and environment, being described in a structural manner (Kontovas, and Psaraftis, 2009). The hardware that comprises a generic shipyard is the most basic layer in the system definition. This hardware can also include the design of the shipyard system.

The interface between hardware and human operators, i.e. the so-called man-machine interface, forms the second layer. The external environment could be considered the third layer. The overall safety is influenced by the hardware, individuals & organization, and external environment, which may vary during the docking life cycle. Figure 3.1 shows the ship-docking interface.

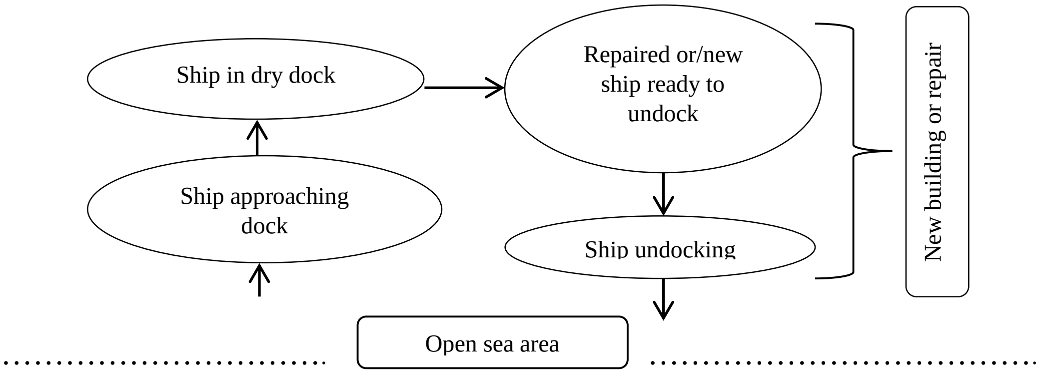


Figure 3.1: Overview of dock

The variables require theoretical and operational constructs to be established in order to build the model. Only the operational constructs is considered in this research. Operational definitions specify precisely how a variable is measured in a particular study. Once the structure of model has been established, and its performance scrutinise to be suitable for the objectives, appropriate values can be input for the necessary variables and the resultant outputs calculated as guided in Figure 3.2 (Taha 1971 and Checkland, 1989).

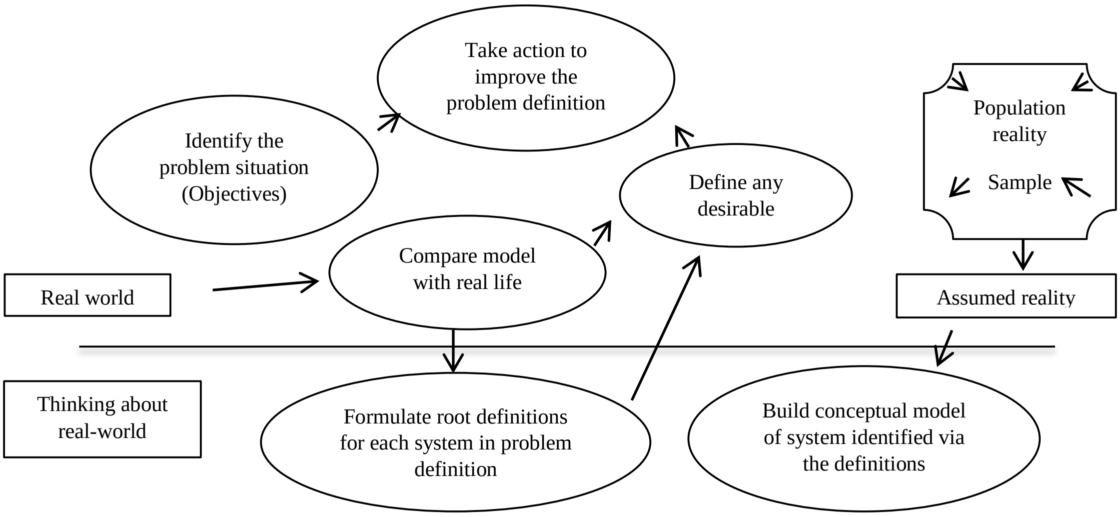


Figure 3.2: Modelling process (Taha 1971 and Checkland 1989)

Much floating dry dock risk models research involves the measurement of hypothetical constructs (or theoretically constructed), e.g. management, maintenances, etc. It can be said that these entities are hypothesised to exist on the basis of indirect evidence (Fellow and Liu, 2008). A generic floating-graving docking system may involve the following stakeholders: crew, ship-owner, classification society, insurer, and coastal state. Various stakeholders may have different views of the safety, as well as the cost/benefits derived from the changes of the shipping safety. The interaction among these parties is complex, and will significantly influence the safety of floating-graving docks. Figure 3.3 presents floating-graving dock mother model, with basic hardware involved and Figure 3.4 is docking evolution.

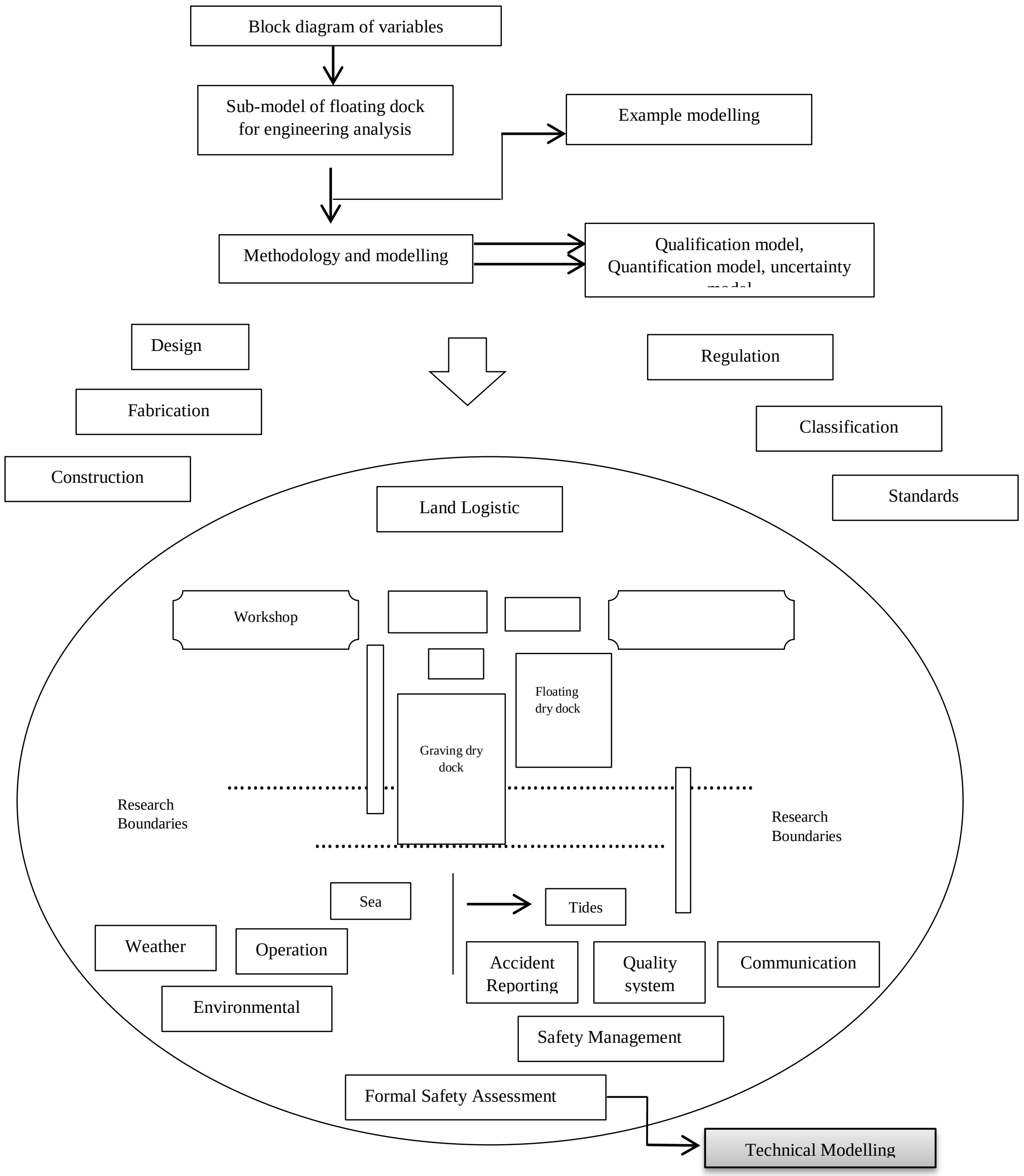


Figure 3.3: Mother model

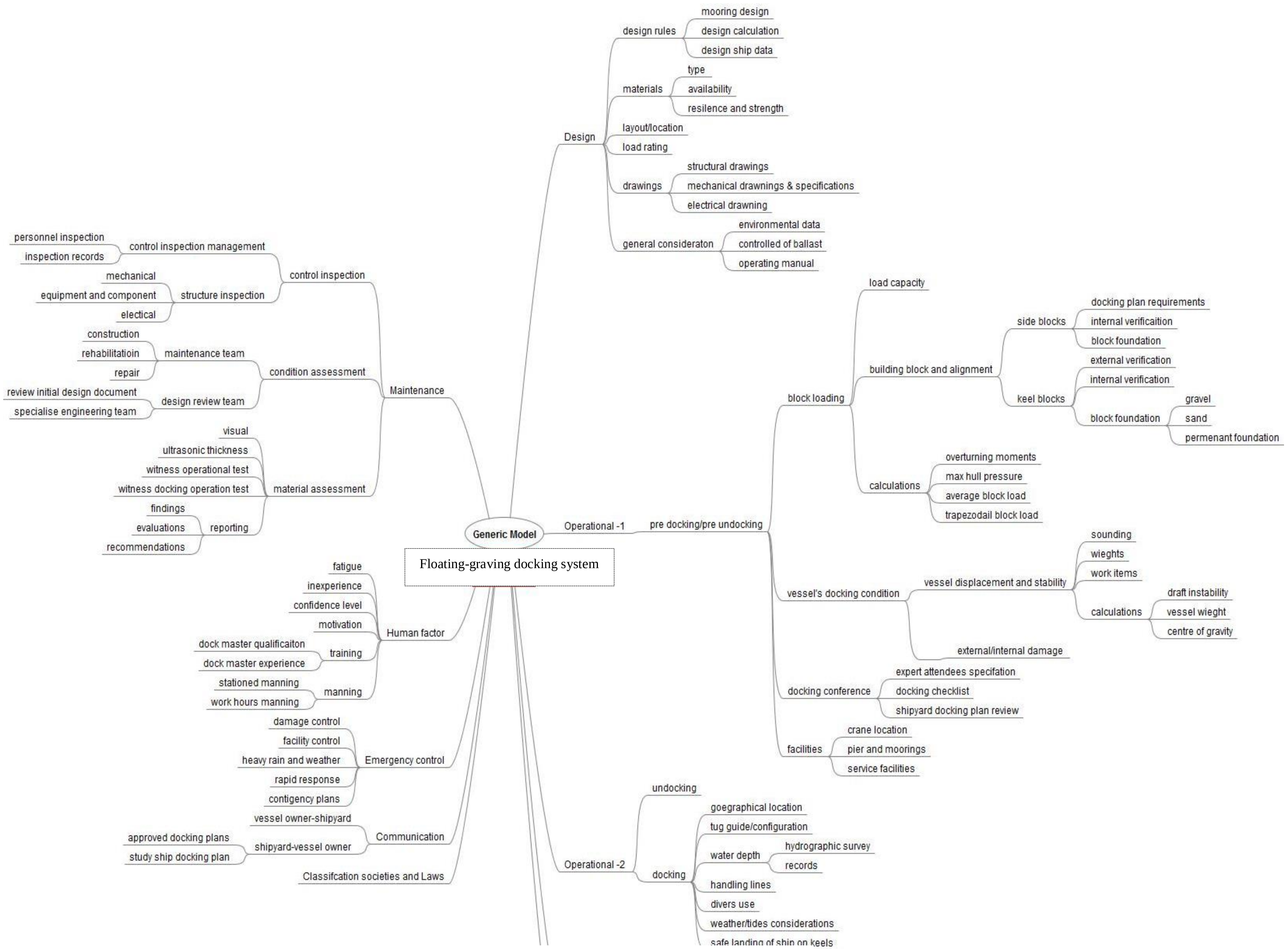


Figure 3.4: Docking and undocking evolution

3.3.1.1 Docking and undocking activities

Four activities are vital to maintaining and operating a dry dock safely. These are (Harren, 2012): (a) condition assessment – this assessment evaluates the physical condition of the dry dock, review the design documentation, and performs calculations to determine the capacity of the dry dock in its current condition; (b) maintenance – this include preventive maintenance tasks as well as maintenance to correct deficiencies that are identified through a condition assessment; (c) control inspection – is a comprehensive but qualitative review of dry dock facility to evaluate the effectiveness of maintenance program; (d) docking operations - which encompasses all tasks associated with the act of docking a vessel in a floating-graving dock. This include but not limited to calculations to ensure the stability of the vessel and dock throughout the evolution, proper blocking to ensure proper loading of both the vessel and dock, and procedure requirements (Harren, 2012).

An abstract from ASCE Manuals and reports on engineering practice prepared by the dry dock asset management task committee of the ports and harbors committee of the coasts, oceans, ports and rivers institute of the American Society of Civil Engineers is herein presented to describe the four activities vital for safe operation of floating-graving dock. These are the essential elements identified to relate with the floating –graving operation model developed in Figure 3.4. The five aspects mentioned here are: docking evolution, communication, facilities, docking a vessel, undocking evolution, maintenance, human factors and environment.

3.3.1.2 Docking evolution

This operation is divided into five section, communication, and undocking, docking, normal operation of facilities and emergency operations. This section is discussed as upon the model developed in Figure 3.4 and its various branches as indicated. The reasons for the selection of these parents’ nodes are discussed.

3.3.1.3 Communication

The communication which takes place before a ship is docked is very vital. The vessel and shipyard have a role to play for safe communication. This communication is before docking and during docking. Before docking the following communication is important (Harren, 2012). Documentation and information must be well organised and communication must exist between shipyard and owner. This report contains many documents such as the position of vessel, shipyard plan, conditions of docking and undocking drafts and undocking displacements, the work required, structural fabrication, modifications required, equipment changing, and work on the propulsion system. Vessel responsibility: These are details but not limited to some information required to be communicated between both ship owner and dry dock master. The vessel information sent to the dry dock master is important to plan docking activities. These are vessel’s docking plan, vessel’s displacement and other curves of form (Hydrostatic table), vessel’s trim and stability booklet, vessels service requirement, and dry dock report from prior dry docking (Harren, 2012). Dry dock master’s responsibility: Shipyard shall calculate the bearing loads on keel and side blocks, to confirm that these loads are within the acceptable limits of the dry docks as initially assessed. What the dry dock must have in place is a LOG BOOK. This book contains all pertinent work regarding the docking facility during all operations. The details of this Log book might vary depending on work intensity. Communication is two way: owner first, detailing vessel’s information and work to be done and then shipyard second, doing preliminary calculations to check if the dry dock has the facility and capacity for the vessel. After this the shipyard shall submit to the ship owner a shipyard docking plan for approval (Harren, 2012).

The shipyard docking plan: is developed with vessel outline as provided during owner-shipyard communication (Harren, 2012) : (a) Vessel outline shall include hull openings, appendages, and protuberances that may affect the docking; (b) Longitudinal and transverse position of the vessel’s docking reference point or stern reference point (SRP) from a fixed reference point on the dry dock; (c) Blocking arrangement showing the longitudinal and transverse position, as well as spacing of the keel blocks and side blocks, from a fixed reference point on the dry dock; (d) Pumping plans. Lastly, during operation, another form of communication is required, which include two way radios, push to talk phones, cell phones, and/or hand signals. Vessel owner and shipyard owner must ensure safe communication (Harren, 2012).

3.3.1.4 Facilities

This is the capability of the shipyard facility to adequately support and accommodate class and type of ships, and have the required maintenance system in place to handle such operation. The term, ‘dock rating’ indicates the capacity of the dry dock for any given operation in accordance with its facilities (Harren, 2012). This is the capability of the dry dock to support the docking of a class or type of vessel. Physical inspection of the facility is also required. Facility safety equipment may include fire alarms location, emergency power, and emergency ballast/dewatering pumps (Harren, 2012).

3.3.1.5 Docking vessel

After the above communication between owner and shipyard is affirmed, the vessel is ready to be docked (Harren, 2012). There must be an approached plan that includes the geographical location, channel features and markers, location of facilities, mooring and pier locations, and dry dock location (which must be suitable for safe entrance) (Harren, 2012). The hydro-graphic survey of the underwater depths and the approach lines of vessel to pier-side facilities and dry dock, guide tugs with any other guide requirements must also be considered as experience demands. Specific docking procedures are usually followed after preparation. Care is however required at the critical stages in the docking process of settling dock on keels and closing gates. The docking shall include (floating dry dock) (Harren, 2012): (1) Divers standing by to assist; (2) Positioning the ship, which includes centring devices such as centring bobs and battens or lines, and longitudinal markers such as line of sight markers to align ship's docking at reference point; (3) Landing ship is considered the most crucial step, positioning ship longitudinally and transversely in dock. Drafts at landing at bow, mid, and aft shall be noted; (4) Pumping operation to deballast dock is done, when ship has successfully landed and all line handlers are stationed; and (5) Side blocks condition, is checked so that both transverse and longitudinal position are acceptable (Harren, 2012). Once the ship is successfully brought into dry dock, it is important for the ship to safely land on blocks. This is called 'Safe Landing' (Harren, 2012).

Safe landing of ship before and after landing must be observed. Divers are usually used to make sure landing is properly conducted. The gangways and service lines can be installed. Lastly, grounding cables to protect vessel from the effects of welding and electrical storms shall be attached to the vessel (Harren, 2012). General inspection after water de-ballasting, is made to check condition of both vessels and block. Situations of excessive crushing must be corrected by refloating, and this process can continue for a long time, and is sometimes frustrating, if events persist (Harren, 2012).

3.3.1.6 Undocking evolution

After work is done, vessel must be undocked. Calculations are done, and assessment conditions shall include liquid loads, cargo, and work items required to be loaded or unloaded prior to undocking. General vessel specification must be followed. These are, float off draft and vessel ballasted & trim minimised. After observing the float off draft and trim, the following is required before floating ship: (a) Be ballasted to match vessel's trim. This condition shall be shall be used to determine the block load and generate the dock's pumping plan for undocking; (b) Phases of undocking must be followed certain standards by (NAVSEA, 1996); (c) The dry dock master is required to undertake sounding, itemized list of weights aboard the vessel (i.e. crew, stores, cargo, and ammunition), work items (i.e. contractual work carried out), undocking calculations (vessel draft instability and block loads), and a pumping plan; (d) Undocking conferences are usually done to clarify the undocking particulars. These conferences sets out some important checklists. Undocking in floating dock, is called submerging the dock from semi to full submergence (Harren, 2012).

3.3.1.7 Human factor

Humans play an important role in shipyard. The manning of the humans and working hours is very important. Stationing on various positions to dock and undock vessel is vital. Also, they carry out all the necessary work on the vessel once the vessel is docked. Working in awkward position, confined spaces and under hull propeller work area is done by humans. Manning the ship in and out of dock is done by captain/pilot and chief engineer’s crews. The qualification, experience, training and management of workers are important. Management shall include roles such as recording all training in log books, as improvement on personnel experience is carried out every year. Considering the operation, communication, maintenance and other roles human play in the system, there is an increased tendency towards fatigue, inexperience, and/or overconfidence on specific tasks if not properly supervised or organised (NAVSEA, 1996).

3.3.1.8 Maintenance and inspection

Control inspections and maintenance are put together for purpose of better understanding. In certain cases, these are different. Inspection proceeds maintenance. The former is usually done on newly designed and fabricated shipyards (Harren, 2012). Control inspection is done to evaluate effectiveness of maintenance management. Control is periodic and is done frequently. Structures, mechanical and electrical systems, equipment and components shall be inspected. The inspection model is developed to inspect personnel, records and the inspection management. This is an important department in regards to safe operation (NAVSEA, 1996). A maintenance organisation adopts different structures depending on decisions by owners. This organisation can be run by internal management or made use of engineering organisation with expertise on designing and maintaining waterfront or marine type facilities. Other functions that may be incorporated, include, organisation planning and computerised maintenance management system. Auditing operations are usually conducted for efficacy of maintenance program. Conditioning assessment is another aspect that is adopted by maintenance organisation.

3.3.1.9 Environment

The geographical location and mud deposition are important considerations for design, selection and operation of dock. An area with increased mud deposition would require increased dredging, hence affecting the cost of the operation. Other aspects here include, wave, wind, hurricane, earthquake, rising tides and weather predictability (NAVSEA, 1996). The environment is initially carefully considered before any work is done. Counter natural disasters can then developed depending on environment. Certain regions were selected for shipyard design without environmental considerations (Harren, 2012).

3.3.2 Hazard identification

In the FSA regime, a hazard is broadly defined as a situation in floating-graving docking evolution with the potential to cause harm to human life, the environment and property. Hazards become a problem when they develop into accidents; generally this occurs through a sequence of events. Once characteristic of these hazards is that, at different phases of the operation, the floating-graving system could experience different kinds of hazards. Hazard identification is performed by selected professionals and/or literature review and the purpose of hazard identification is to identify all conceivable and relevant hazards.

Typically a team of 6-to-10 experts, including naval architects, structural engineers, machinery engineers, dry dock master, marine engineering surveyors and meeting moderator, provide the necessary expertise. The hazards are identified using historical incident databases and expertise of the team. The identified scenarios are ranked by their risk levels, and prioritizing hazards are given a focus and may be subjected to more detailed analysis. For a generic floating-graving system and its associated sub-systems just described, the following important hazard categories are identified: (a) collision and grounding, (b) landing errors, (c) extreme environmental conditions, (d) loading errors, (e) loss of structural integrity, (f) contact event, (g) fire, (h) fall from height, etc.

3.3.2.1 Gate collapse

Typical accidents may include collapse of dock walls due to static lateral soil pressure and dynamic earthquake loads. A recent accident involving caisson gate failure on 27 March 2002, at Dubai Dock No 2, one of the world’s largest ship repair facilities, caused uncontrolled flooding of the dock (Harren, 2012) leaving 21 people dead. Again, if the dry dock is not founded on deep foundations, such as piles, then a net uplift would result, causing the dry dock to float and tilt.

3.3.2.2 Failure of pontoon deck-structural failure

Structural failures of floating dry dock pontoons due to excessive transverse bending stresses were thought to be relatively rare occurrences. Accidents reported were due to steel plate panels that have their axis parallel to the longitudinal axis of the dock and perpendicular to the line of transverse compressive stress in the plate when docking a ship (Heger, 2003). These accidents usually occur while the dock is being ballasted in a manner that unknowingly magnifies the compressive stress in the pontoon deck plates to point which exceeded their buckling strength (Heger, 2003).

3.3.2.3 Stability failure

In considering the capability of a facility to dry dock a ship, many factors affect the safety of the dry docking operation. To determine the lifting capacity of a floating dry dock, the following limits are considered: physical characteristics, structural limits, and buoyancy and stability limits (Wasalaski, 1982). MIL-STD-1625D was prepared as a guide for certifying floating dry docks to establish the maximum size each dry dock can safely dock. In reviewing MIL-STD-1625D, there are two major parts to '*the design limits* and a review of the operation of floating dry docks as related to '*lifting capacity'.* The dangers of avoiding a low value of GM during docking generated list at a critical instant in the Vigor accident where stability failure lead to collapse of floating dock. Such a circumstance whereby the dry dock sinks and a tug capsizes is considered as highly undesirable and raises some concerns in the industry. Another stability concern in the Vigor accident was an incorrect stability calculation for the ship (GCaptain, 2013).

3.3.2.4 Docking block failure

The positioning and stiffness allocation are important to docking blocks. These are important decision when docking a ship because mis-positioning or mis-allocation of docking bocks may give risk to unreasonably large block reactions and consequently serious damage to both the docked ship and blocks (Cheng *et al*., 2004). Docking failure may also cause the disruption of docking schedules and extension of the ship downtime. Any failure may even lead to the loss of lives (Cheng *et al*., 2004).

3.3.2.5 Grounding

A ship may run aground either due to human errors in navigation, due to obstacles not recorded on charts, or due to the failure of the ship's control systems (Tupper, 2013). Accordingly, the designer must legislate for all these eventualities. Docking vessels operations are carried out under predictable conditions and are carefully planned. The naval architect produces the ship data together with details of the actual loading condition of the ship at the time. Grounding is unpredictable. It involves a more variable set of circumstances including the point of grounding (along the length and transversely), the nature of the sea bed, the prevailing weather and tide conditions and the actions of the crew. All influence what happens to the ship in terms of structural damage and flooding (Tupper, 2013). In a studies period 1990 – 2007, one grounding event occurred when a ship was under repair due to bad weather conditions, the mooring broke and the ship drifted and was stranded. No injuries or fatalities were registered, and no oil spilled during docking an oil tanker (SSC, 2002).

3.3.2.6 Dry dock wall failure

Failure of dry dock walls may be caused by the combination of the static lateral soil pressure and the dynamic earthquake loads. In general, there are two types of wall failure modes. During the earthquake, due to repetitious dynamic loading, the pore pressure of the soil behind the wall may increase to nearly the total pressure, thus effective stress and shear strength of the soil will approach zero and soil liquefaction may occur (Wu *et al.*, 1990). If the dry dock is not founded on deep foundations, such as piles, then a net uplift would result, causing the dry dock to float and tilt. This type of failure is however, not likely to occur for a graving dry dock (Wu *et al.*, 1984).

3.3.2.7 Contact events

In a studies period 1990 – 2007 (SSC, 2002), three cases of contact events happened when trying to dock an oil tanker. In one case, a ship was in dry dock when the dry-dock gate was struck by a tsunami (bad weather conditions). In the other two cases, the ship was under manoeuvring to enter the dry dock with pilot on-board. No injuries or fatalities were registered.

3.3.2.8 Fire events

In a studies period 1990 – 2007 (SSC, 2002), Eighteen (18) fire events happened when trying to dock an oil tanker for repairs. In 8 cases out of 18 fires events, there was a significant number of injuries and fatalities. In 4 cases out of 8, there was a clear statement that the fire started due to ‘hot-works’.

3.3.3 Steps of FSA in dry docking operation

The modern risk assessment techniques have been applied to the nuclear and offshore industry successfully, but the first proposal to apply the modern risk assessment techniques to the shipping industry was put forward by the UK delegation in 1993 to the Maritime Safety Committee of the IMO (Lee, 1997). In doing so, a lot of concerns were focused on the proactive philosophy of FSA which is expected to provide a means of enabling potential hazards to be considered before a serious accident occurs. The Formal safety assessment that has been proposed by the UK MCA consists of five steps which are: hazard identification, risk estimation, risk control options, cost benefits assessment, and recommendation.

3.3.3.1 Problem definition and generic model

The purpose of problem definition is to carefully define the problem under analysis in relation to the regulations under review or to be developed. The definition of the problem should be consistent with operational experience and current requirements by taking into account all relevant aspects (MSC 2002). In general, the problem under consideration should be characterized by a number of functions. Where the problem related for instance to a ship type, these functions include carriage of payload, communication, emergency response, manoeuvrability etc. Alternatively, when the problem relates to a hazard, for instance fire, the functions include prevention, detection, alarm, containment etc. (Tzifas, 1997). The generic model is not viewed as an individual model but as a collection of systems, including organisational, management, operational, human, and electronic and hardware aspects which fulfil the defined functions (Wang, 2007). The functions and the systems should be broken down to an appropriate level of detail. The results from this study should include (MSC 2002: Maistralis, 2007): (1) Problem definition and setting of boundaries and; (2) Development of generic model.

3.3.3.2 Step 1: Hazard identification

The purpose of this first step is to identify as many hazards, specific to the generic model or problem definition in question, and to generate a prioritized list of accidents introduced by those hazards. This step identifies and generates a selected list of hazards specific to the problem under review (Wang, 2007). Hazards may or may not have already been realised as accidents. With the passage of time, changing technology, and the influence of human factors, new hazards will arise and existing hazards may materialise into accidental events not previously experienced (Peachey, 1995). The objective of this step is to describe what the activity is, and identify what can go wrong. The overall objective of this step is outlined in Figure 3.5. Hazard identification methodology is concerned with using the ‘brainstorming’ techniques involving trained and experienced personnel to determine the hazards (Wang, 2007).

Lee (1997) explains much of the work is constructed by the activities of HAZID meeting. MSC committee (2002) looks at the method to implement hazard identification by getting a compromise of a combination of both creative and analytical techniques. The creative element is to ensure that the process is proactive and not confined only to hazards that have materialized in the past. Various scientific safety assessment approaches exist in hazard identification. They include (MSC, 2002; Mistrials, 2007): Preliminary Hazard Analysis, Failure Mode, Effects and Criticality Analysis, and Hazard and Operability (HAZOP) study. The results from this step involve a list of hazards and associated risk levels.

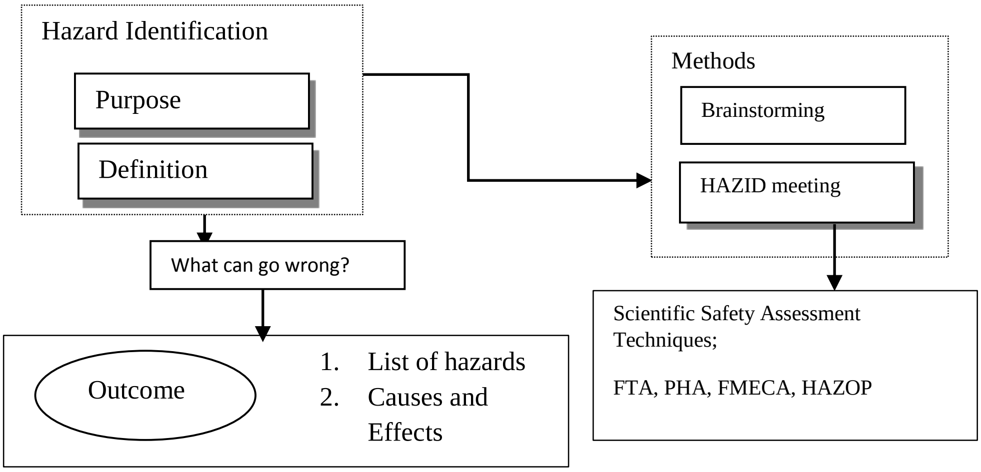


Figure 3.5: Flow chart for hazard identification

The objective of this step is to identify all potential hazardous scenarios in shipyards that could lead to significant consequences and to prioritise them by risk level. The first objective requires a creative part (mainly brain storming) to ensure that the process is proactive and not only confined to hazards that have materialised in the past. In simple FSA studies, historical data can be used, although its disadvantages are highlighted by Davanney (2008) where he states, '*caution is required in identifying casualty database and to correctly identify accident causes*.' His view is shared by Kontovas and Psaraftis (2009), who carried out a research on critically analysing the pitfalls and deficiencies in application of FSA in maritime research. They strongly recommended, probabilistic modelling of failures and development of scenarios as an alternative in IMO FSA guidelines, by using formal methods, such as fault trees, event trees, influence diagrams, human reliability analysis, human element analysing process, and possibly others.

The second objective is to rank hazards and to discard scenarios judged to be of minor significance. Ranking is done using available data and modelling supported by expert judgement. A group of experts in dry docks rank risks associated with accident scenarios and a ranked risk is developed starting from the most severe. This is done, using the MSC guidelines risk matrix. Estimation of risk related to a hazard identified in Step 1 begins with estimation of frequency (F) from following fractions: F = No of Casualties/shipyard years, consequence potential, called Potential Loss of Life (PLL) according to FSA guidelines is: PLL = No of Fatalities/shipyard years. Risk = Probability x consequence. Log (Risk) = (Probability) + Log (Consequence). Combining both indices, a third index, the Risk Index or risk ranking number is achieved:

$$\text{Risk Index} = \text{Frequency Index} + \text{Severity Index} \tag{3.1}$$

Equivalent total is to integrate risk index. It makes use of the fact that both the frequency and severity banks of the risk matrix are approximated logarithmically. Table 3.1 presents the frequency rate and severity value in shipyard and Table 3.2 is shipyard severity value.

Table 3.1: Shipyard frequency and severity rate

Frequency rate Likely to happen in shipyard	General Interpretation
F4: 1-12 months	Frequent
F2: 2-3 years	Likely to occur
F2: 5-10 years	Remote
F1: Over 10 years	Unlike to occur

Table 3.2: Shipyard severity value

Severity Value	General interpretation in shipyard
S1	Minor injury
S2	Major
S3	Fatality

This risk matrix is *3x3* as opposed to *3x7* matrix proposed by MSC, due to nature of ship repair industry. A criticism of this method (risk matrix) as a standalone, gives no distinction among hazards that have more than 10 fatalities. Again, in this risk matrix, constructed for all combinations of the frequency and severity indices equations, the probability is equated to frequency, in comparing scenarios in terms of risk, some scenarios stand a chance to be ranked lower or higher than required.

Though, risk matrices are not used for decision making however, they constitute a simple yet most important tool that is provided to a group of experts in the hazard identification step to rank hazards. These matrices are simple to use, but the above disadvantage, are not ignored in this chapter. In cases where a group of experts are asked to rank objects according to one attribute using natural numbers, multi grouping is required. A multinational group of experts is not rare in FSA studies. A number of 10 experts is reasonable for such groups demonstrated in concordance coefficient W in equation 3.2:

$$W = \frac{12\sum_{i=1}^{I=i}\left[\sum_{j=1}^{j=J} xij - \frac{1}{2}J(I+1)\right]^{\wedge}2}{J2\ (I3-I)} \tag{3.2}$$

The coefficient W varies from 0 to 1. W= 0 indicates that there is no agreement between the experts. On the other hand, W= 1 means that all experts rank scenarios equally by the given attribute. This equation, can be found in MSC guidelines for detailed study, but has hardly been used in any of its application in maritime research.

Table 3.3: Shipyard risk matrix

S/F	F1	F2	F3	F4
S1	1	2	3	4
S2	2	3	4	5
S3	3	4	5	6

3.3.3.3 Step 2: Risk analysis

Once hazards have been identified, the risk associated with the realisation of those hazards can be evaluated, so as to ascertain whether those risks are significant (Peachey, 1995). The assessment of risk involves studying how hazardous events or states develop and interact to cause an accident (Wang, 2007). Figure 3.6 presents a risk assessment flow chart.

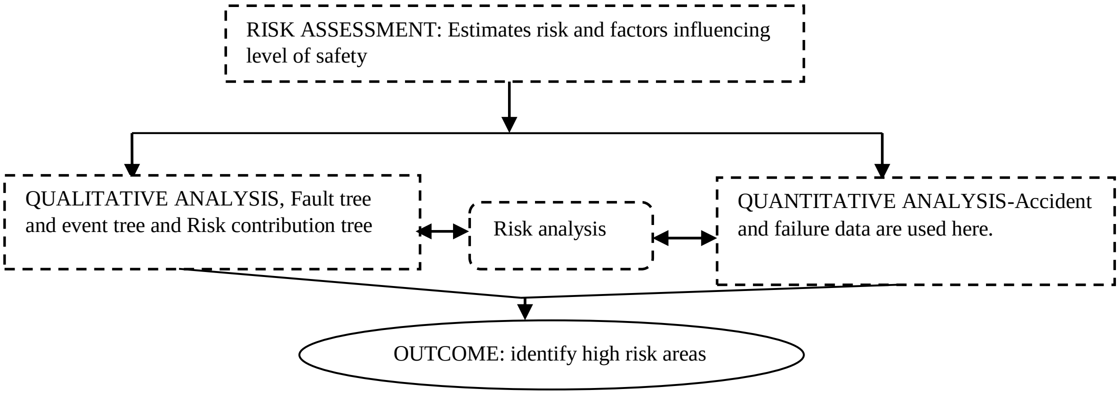


Figure 3.6: Risk assessment flow chart

3.3.3.4 Step 3: Risk control option

The purpose of this step is proposing effective and practical RCOs comprising the following four principal stages (MSC, 2002: Maistralis, 2007): (1) focusing on risk areas needing control; (2) identifying potential risk control measures (RCMs); (3) evaluating the effectiveness of the RCMs in reducing risk by evaluating step 2 and; (4) grouping the RCMs into practical regulatory options.

Structural review techniques are typically used to identify new risk control measures for risks that are not sufficiently controlled by existing measures. Many risks will be the result of complex chains of events and a diversity of causes. Risk control measures should be aimed at

(Sekumizu, 1995): (1) reduction of the frequency of failures; (2) mitigation of the effect of failure; (3) alleviation of circumstances where failures may occur; (4) mitigation of the consequences of accidents. The prime purpose of assigning attributes is to facilitate a structured thought process to understand how an RCM works, how it is applied and how it would operate.

Attributes can also be considered to provide guidance on the different types of risk control that could be applied. The results required to be obtained in this step include (MSC, 2002: Maistralis, 2007): (1) a range of RCOs which are assessed for their effectiveness in reducing risk and; (2) a list of interested entities affected by the identified RCOs. Figure 3.7 is the application of RCO and outcome in dry docking operation.

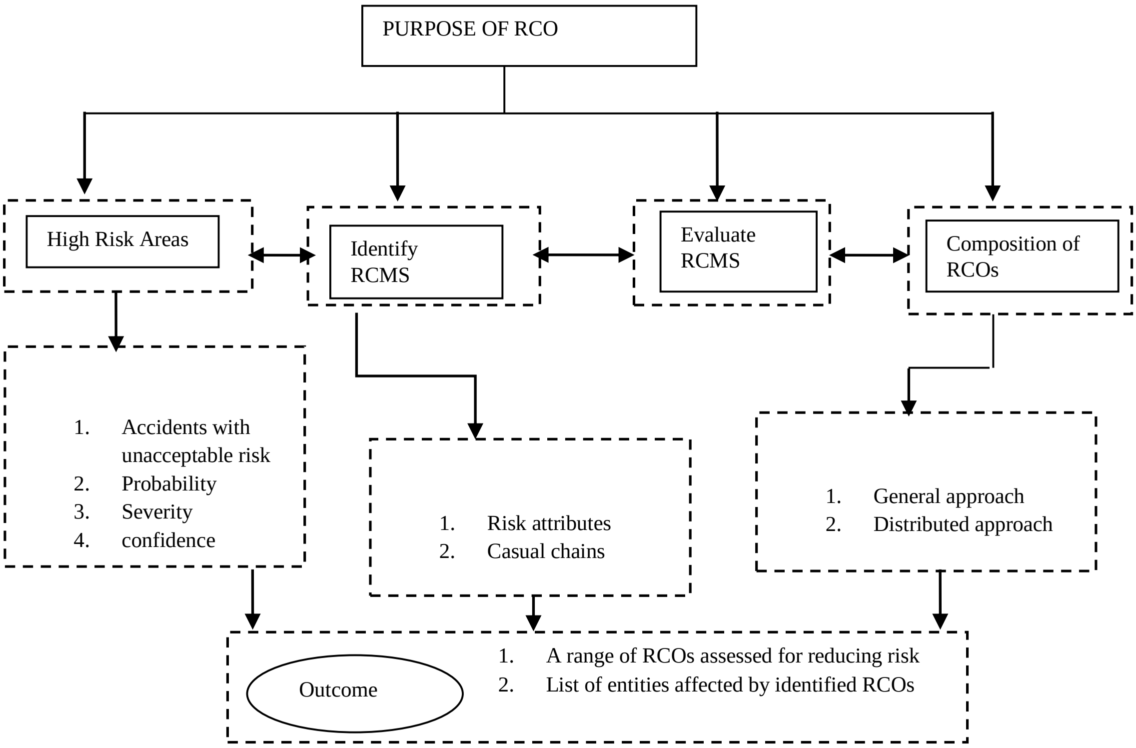


Figure 3.7: Application of RCO and outcome

3.3.3.5 Step 4: Cost benefit assessment

This step is aimed at identifying and quantifying the cost to be paid and benefit to be expected when each RCO developed in step 2 is implemented (Lee, 1999). Each RCO is evaluated in terms of implementation cost and then by deriving its associated cost per unit reduction in risk (CURR). The cost benefit assessment may consist of the following (MSC, 2002): (1) Consider the risks assessed in step 2; (3) arrange the RCOs, defined in step 3 in a way to facilitate understanding of the costs and benefits resulting from the adoption of an RCO; (4) Estimate the pertinent costs and benefits for all RCOs; (5) estimate and compare the cost effectiveness of each option, in terms of the cost per unit reduction by dividing the net-cost by the risk reduction achieved as a result of implementing option; (6) rank the RCOs from cost-benefits perspective in order to facilitate the decision-making recommendation in step 5. In general, the cost component consists of the one-time (initial) and running cost of an RCO, cumulating over the lifetime of the system. The benefit part is much more intricate. It can be a reduction in fatalities or a benefit to the environment, or an economic benefit for preventing a loss of a shipyard (Kontovas and Psaraftis, 2009). It is calculated using eqn. 3.3:

$$CAF = CURR = \sum_{t=0}^{n} \frac{(\mathrm{b\text{-}c})\left\{\frac{[1+\mathrm{i}]}{[1+\mathrm{r}]}\right\} \wedge \mathrm{t}}{1} \tag{3.3}$$

Where *b* and *c*, are benefit and cost respectively, *r* is the discount rate of 4%, *t* is the measure of time horizon from *0* to *n* years, and *i*, is the inflation or wage increase. Each RCO is evaluated in terms of implementation cost and then by deriving its associated cost per unit reduction in risk (CURR). However an extensively used index in FSA is the so called Cost of Averting a Fatality (CAF) and can be expressed in two forms:

$$\text{Gross Cost of Averting a Fatality (GCAF)} = \frac{\Delta C}{\Delta R} \tag{3.4}$$

$$\text{Net Cost of Averting a Fatality (NCAF)} = \frac{\Delta C - \Delta B}{\Delta R} \tag{3.5}$$

Where, ΔC is the cost per shipyard of the RCO under consideration, ΔB is the economic benefit per ship resulting from the implementation of the RCO, ΔR, the risk reduction per shipyard, in terms of the number of fatalities averted, implied by RCO. Cost-benefit analysis provides a consistent framework for option appraisal. This is achieved by attempting to quantify and where possible value, the costs and benefits associated with the various alternatives and to estimate the present value of their net benefits (Spiro, 1995). The results obtained from step 4 include (Maistralis, 2007): (1) cost and benefits for each RCO defined in step 3; (2) cost and benefit for interested entities and; (3) cost effectiveness expressed in terms of suitable indices as expressed in equation 3.4 and 3.5. Cost benefit analysis is the last step for any recommendation for decision making.

3.3.3.6 Step 5: Recommendation for Decision Making

Recommendations presented should be to the relevant decision makers in an auditable and traceable manner. These recommendations are based upon the comparison and ranking of all hazards and their underlying causes. The foregoing analysis provides a sound basis upon which decisions about safety improvement can be made. The systematic nature of the method not only ensures audit-ability and gives confidence in the results, but facilitates decision making (Peachey, 1995).

3.4 Accident Data Collection and Analysis

This chapter presents data collected from accidents which occurred in the shipyard industry over the years. The results obtained, are analysed to determine which accidents occurs frequently and their severity rate is noted. More attention is paid to fatal, nonfatal, and workplace injuries in the shipbuilding and repair industries. Occupational diseases in the shipbuilding and repair industry are not taken into account in this study.

The data presented, dates from 1990-2012 and are compiled from the following sources: (a) Occupational Safety and Health Division (OSHD) of the Ministry of Manpower (MOM), based on incidents reported under the Workplace Safety and Health (Incident Reporting) Regulations since its inception in March 2006; (b) Occupational and Health Safety (OSHA) USA, in collaboration with the Bureau of Statistics of Labour (BSL) USA and; (c) The Health and Safety Executive UK. Working in shipyards is seen as one of the riskiest occupations in United States as BSL records shows from 1990 to 2012.

Shipyard employees are at risk due to the nature of their work, which includes a wide variety of industrial operations, such as steel fabrication, welding, abrasive blasting, burning, electrical work, pipefitting, rigging and coating applications (OSHA, 2008). The occupational accidents are followed by costs; namely, injury, fatality, material and/or environmental damages. Common causes of occupational accidents are high elevation, toxic, flammable and explosive materials, fire, moving machinery, dangerous gases, work on/close to haphazard established heavy structures, misuse or failure of equipment, poor ergonomics, untidiness, poor illumination, exposure to general hazards including electricity, and inadequate protective clothing. Fatality rate refers to the number of occupational fatal accidents per 100,000 workers.

The fatality rate in the Turkish shipbuilding industry has been compared with all other industry groups in Turkey, and it has been found unacceptably high (Baris, 2012). Questionnaires from Baris (2012) shows that workers do not want to control the risk themselves, they want someone to check them. The workers want to be guided and supervised.

3.4.1 Data from Health and Safety Executive (HSE) UK

Reports from HSE UK shows that the injury rate in the shipbuilding and repair industry is double as compared to manufacturing industry, plus the three most prominent accidents in UK shipyards include, slip/trip, fall from height, and handling/lifting equipment injuries. Injury rates in shipbuilding and repair are comparably higher than the manufacturing industry. From the years 1997 to 2001, the injury rate doubled for shipbuilding and repair industry, compared to manufacturing industry in Table 3.4. This result gives a case to investigate the safety regime in shipbuilding and repair industry.

Table 3.4: Injury rate in UK SSR

Year	**Shipbuilding/ Repair**	**Manufacturing**
1996/97	1459.8	1210.5
1997/98	2193.2	1243.5
1998/99	2368.9	1213.0
1999/00	2603.8	1213.0
2000/01	2330.6	1194.1

HSE accident statistics for shipbuilding and ship repair (SSR) industry for the years 1999-2002 are summarised and presented in Table 3.5. The full detail is found in Appendix 3. It was not possible to differentiate between shipbuilding and repairing. Three kinds of accidents reported include: (a) Handling/lifting/carrying; (b) Slip/trip on the same level; and hit by an object. 65% of handling injuries are associated with the 3 main causes are; sprains/strains from body movement whether or not a load is involved-27%; injured through cuts from sharp/coarse material or equipment or from trapped fingers-21%; lifting or putting down loads-17%; 31% of slips/trips on the same level are associated with an obstruction .

Table 3.5: UK SSR incident statistics for period 1999-2002

KIND	**FATAL**			**MAJOR**			**3 DAY**			**TOTAL**		
	00	01	02	00	01	02	00	01	02	00	01	02
Machinery	0	0	0	6	3	5	18	13	10	24	16	15
Hit by object	0	0	0	23	32	15	114	99	77	137	131	92
Slip/trip	0	0	0	26	27	34	140	108	96	166	135	130
Fall	1	0	0	30	27	22	62	62	22	93	89	44
Exposure	0	0	0	3	1	1	19	16	7	22	17	8
Down asphyxiation	0	0	0	0	2	0	1	1	0	1	3	0
Handling	0	0	0	7	9	9	166	120	144	173	129	153

This statistic was taken to concentrate on prevention of the 3 most reported kinds of accident but particularly on their causes. This would therefore enable the industry to make its contribution to the Government's target in Revitalising Health and Safety issues in shipbuilding and repair industry by the year 2010 (HSE, 2006).

3.4.2 Data from bureau of labour statistics USA

Reports from USA shipyard accidents show that most of the accidents are due to fall from height, contact with electric current and caught in between equipment. The main agents that lead to these accidents are not clearly stated in this report, due to lack of data. In Table 3.6, falls (both low and high) resulted in the death of a number of shipyard employees. According to BLS data for 2002-2010, almost one-quarter of shipyard fatalities were associated with falls (both high and low fall). BLS CFOI data showed that at least 12 shipyard fatalities (6.7%) resulted from contact with electrical current and 37 fatalities (22%) occurred because of contact with objects.

Table 3.6: US Census for fatal occupational injuries from 2002-2010

Characteristics	**All industry**	**Shipbuilding and repairing**									
		2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**Total**
Total	5,920	11	18	15	10	15	15	25	23	11	
Contact with objects and equipment	**1,006**		**5**	**4**	**3**	**7**	**3**	**8**	**3**	**2**	**37**
Struck by object	571	1	3	3	3		2		4	2	18
Falls	**734**	**1**	**3**	**3**	**4**	**3**	**4**	**6**	**9**	**7**	**40**
Fall to lower	659				3	4	6	8	4		25
Fall from scaffold, staging	85	1		1		3			4		9
Transportation accident	2,573	2	5		3			3	2	4	19
Fires and explosions	177			1		1	2				3
Contact with electric current	256	4	1		1				3	3	12

BLS injury data showed that an even greater percentage of injuries were associated with new types of accidents. A detailed table showing the US Census for Fatal Occupational Injuries in shipyard industry registered between the years 2002 to 2010 shows the secondary nature of accidents, the injuries and part of the body affected by workers in SSR. Carelessness of the workers, insufficient safety training and education, unawareness of costs of accidents, erroneous series of human operations, and inadequate work site environment remain the key risk factors for occupational accidents (Baris, 2012).

3.4.3 Census of fatal occupational injuries in SSR USA (2010-2013)

In Table 3.7 the four most prominent accidents registered in shipyard in USA are drowning, exposure to harmful substance, multiple traumatic injuries, and hit by vehicle. All these accidents are registered in the year 2010. There exist an excellent record in slip/trip and fall from height from this statistic. No accidents were registered between the years 2010 and 2013. Nevertheless, the number of fatalities registered during this period was 30. From 2010 to July 2013, shipyard activities resulted in the death of 40 workers. The highest rates of accidents were found among welders, blasters, painters and substructure workers.

Table 3.7: Census of fatal occupational injuries, 2010-2013

Characteristics	**All industry**	**Shipbuilding and repairing**				
		2010	**2011**	**2012**	**2013**	**Total**
Total	7,630	5	5	7	10	27
Exposure to harmful substances	2,226	-	-	-	3	3
Drowning	623	-	-	-	3	3
Falls	934	-	-	-	-	-
Other traumatic injuries	1343	-	-	-	4	4
Vehicles	2112					
Contact with object	39	-	-	3	-	3
Slip/trip	-	-	-	-	-	-

3.4.4 Data collected from occupational safety and health division, Singapore

Data collected from OSHD Singapore, shows Accident Frequency Rate (AFR) in the shipyard industry remains high, at a rate of 1.3 per million man hours worked. Most accidents are due to fall from height from scaffold as detailed statistics are provided. Other accidents recorded include; caught in between objects and hit by a falling object. In the shipbuilding and repair industry the Accident Frequency Rate (AFR) which measures how often workplace accidents take place dropped from 2.2 in 2012 to 1.3 in 2013 as seen in Table 3.8. The Accident Severity Rate (ASR) dropped from 257 per million man-hours worked to 180 in Table 3.8. This result shows how much effort has been put in place to reduce accidents in SSR during these years, but the measures in place are not good enough.

Table 3.8: Accident severity rate 2012 and 2013

	Per million man-hours worked	
	2012	2013
All sectors	2.3	1.6
Construction	2.3	2.5
Manufacturing (SSR excluded)	1.8	2.1
Shipbuilding and Ship repair	**1.8**	**2.9**

3.4.5 Workplace fatality by type of accidents

In shipbuilding and repair, struck by falling objects remained as the dominant accident type, leading to 44%, or 4 out of 9 workplace deaths. The sector saw fatalities associated with new accident types, namely exposure to harmful substances (i.e. smoke), drowning and struck by moving objects in 2007 in Table 3.9.

Table 3.9: Accident by type of agent

Type of accident	**Workplace fatality**		**Permanent Disability**	
	Shipbuilding 2006-2007	Construction 2006-2007	Shipbuilding 2006-2007	Construction 2006-2007
Total	9(10)	24(24)	35(27)	18(16)
Falls from height	1(2)	14(15)		
Struck by falling object	3(4)	4(5)	5(3)	3(6)
Fires and explosions	1(0)			
Drowning	1(0)	1(0)		
Stepping on, striking	1(0)	0(1)	4(4)	14(7)
Exposure to harmful substances	2(0)			
Electrocution		2(0)		
Exposure to heat		1(0)		
Slipping and tripping				
Caught in or between objects	2(2)	1(2)	8(9)	17(11)

3.4.6 Temporary disablement in shipbuilding and repair

The top five accidents types common to temporary disablements in SSR include stepping/struck by object, caught in or between objects, falls from height, slipping and tripping as in Table 3.9. The top five agents of accidents from all industry include metal items, floors and level surfaces, hand tools, and transport equipment seen in Table 3.10.

Table 3.10: Accident types leading to temporary disablements in SSR

	% of temporary disablements in each sector	
Industry	**2007**	**2006**
Shipbuilding and ship repair		
1. Stepping on/striking/stuck by object	29.6	29.1
2. Caught in or between objects	23.1	17.7
3. Struck by falling objects	12.1	12.1
4. Falls from height	12.5	10.0
5. Slipping and tripping	5.8	6.7

3.4.7 Accident analysis in dry docking operation

FSA is a systematic risk based methodology aimed at considering the shipyard as a whole, including protection of life, property and the environment. However to become useful, the FSA needs a lot of work to implement all necessary information and tools. It is evident that such an exercise becomes effective if it is carried out on a wide and cooperative basis, with the support of all interested parties, e.g. owners, operators, insurers, administrations, classification societies, etc. Data interpretation is carried out with caution, as it is highly likely to find some degree of under reporting of incidents. This would entail that, the actual number of death, accidents and shipyard casualties would be higher than the figures presented. However the data gathered and analysed in this chapter show that there is a real problem in shipyard safety. The frequency of accidents and associated severity are considerably higher by maritime standards compared to other construction and manufacturing industry.

The following results are obtained (numbers in bracket represents fatality figure): *OSHAD (Singapore*) Fatality results - (a) Struck by falling object (7); (b) Caught in/or between object (6); (c) Falls from height (8). Permanent disability results – (a) Caught in or between objects (17); (b) Struck by falling object (9); (c) Stepping by falling objects (8). Temporary disablements – (a) Stepping or struck by objects; (b) Caught in or between objects; (c) Struck by falling objects; (d) Falls from height; (f) Slip/trip. *In OSHA (USA)* Fatality results – (a) Falls (45); (b) Contact with objects (24) and; (c) Electrical current (10). Injuries – (a) Exposure to harmful substances and; (b) Drowning. *In UK HSE* Fatality – Fatality; (a) Fall. Major injuries – (a) Slip/trip (87); (b) Fall from height (79); and (c) Hit by object (70).

3.4.7.1 Risk from Falling from Height

Risks of falling from a height can be divided into two main factors; workers unrelated and workers related. During the shipbuilding process various structures and scaffoldings are constructed in the shipyard. Various operations such as welding, cutting, blasting and painting are carried out on the vessel. Wiggles and sometimes crashes occurring in haphazard established unstable structures and scaffoldings may lead to accidents (Baris, 2012).

Framings (strength and support elements) used in the structures and scaffoldings material lack of appropriate materials and necessary conditions, unprotected scaffoldings, use of inexpert personnel during construction and installation phase of the scaffoldings, workers without the necessary safety equipment (safety harness, helmets, gloves, etc.) increase the risk potential of these accidents, and result in serious injury and even death. For the workers related factor, impaired posture control is one of the main reason for falling from a height. In general, about 40% of all accidents associated with falling and slipping are because of possible confounding effects of posture control (Moll Van Charante *et al.*, 1991). As a result, basis for falling from a height, slippage, loss of balance and posture control, distraction, loss of concentration, fatigue, apathy, inappropriate working positions, work during the conversation or fighting with someone else, scaffolding without handrails, may be considered (Baris, 2012).

3.4.7.2 Risk of Electric Shock

During welding operations, perspiration from the body becomes conductive and the occurrence of electric shock as a result of contact with electrical current during the accidents is high. In addition, removal and installation of electric motors and systems, electrical shock accidents occur. Accidents caused by electric shock with high current and voltage are largely fatal (Baris, 2012).

Shipyard safety management system in the absence of disorder, depending on the cables, and scattered areas of work of the presence of an open arc jump, electrical distribution panels to be exposed, not made available or no earthing systems, using elements such as leakage current relay raises the risk of electric shock accident. Simple accidents of electric shock, injury, death appears to vary from affected states (Baris, 2012).

Size effect of electric shock accidents, exposure to voltage, current resistance against the body, the current type (AC–DC), electrical contact with the time and depends on the path of electricity in the body. Victims of electric shock, had a loss of consciousness, respiratory arrest, cardiac arrest, the body burns, the effect of impinging on the victim from electrical injuries are growing as a result of jumping and falling. The main reason for the sudden deaths due to electrical shock is heart stroke (Baris, 2012).

3.4.7.3 Risks of Fire and/or Explosion

Shipyards frequently encountered fires caused by flammable and explosive gases. LPG, LNG, oxygen, hydrogen, acetylene and other gases can cause these types of fires. Explosion occurs because of a build-up of gas when there is lack of proper ventilation in closed areas (Baris, 2012). During welding operations, oxygen and acetylene hoses for welding gas incontinence and improper lay up of flammable and combustible materials can cause explosion and fire. The tanks would need to be ventilated during entry. Flammable gases cause explosion and fire accidents if the gas-free process is skipped (Baris, 2012). The electrical fires commonly happen during installation and repair of electrical systems. Besides, the most commonly encountered fire accidents are gasoline fires occurring during the repair of main and auxiliary engines (Baris, 2012).

3.4.7.4 Risks of being struck by or striking against objects

These types of accidents are sustained as a result of collision and contact made between the body of the workers and any objects. Workers are exposed to risks with falling materials from scaffoldings, and decks; the most fundamental reason for those type of accidents is, not wearing helmets. During welding processes, while electricity supply burrs and slag particles bounce out of control, it can collide with various parts of the body (Baris, 2012). Also, during oxygen and acetylene welding and cutting operations, the cut surface is heated to excess, and contact with the surface is dangerous. During repair of the piping, high pressure steam, or a variety of injuries occur as a result of contact with the fluid. In similar instances, accidents occur during blasting operations, as a result of not using protective clothing (Baris, 2012).

3.4.7.5 Risks of being caught in between objects

Ship blocks, ship plates and hatch covers can reach hundreds of tons weight of steel. Stocking and transport of material omission and during the hatch cover assembly and repair carelessness can lead to very serious accidents (Baris, 2012). During the transportation of heavy equipment, workers can get jam between structures or object leading to vehicles or crane load shifting or falling over causing crushing injuries (Baris, 2012).

The most common squeeze accidents are with hoisting crane accident risks, falling as a result of disconnection of load bearing elements of the crane wire under the load or the crane (Baris, 2012). Proper communication between the crane operator with a pointer to the process of removing the installed and available for crane ropes and eyebolts material due to breakage during lifting, breaking and falling, lifting rope during break, are risks of squeeze accidents.

Section 3.4.8 provides the basic framework for the application of Fault tree-Formal Safety Assessment (FSA) in enhancing dry docking operation. The application of FT-FSA helps to improve the safety of docking a vessel for repair, thereby avoiding the risks of these accidents occurring.

3.4.8 Steps in the application of FT-FSA in docking operation

3.4.8.1 Problem definition

The work definition in this Chapter is risk analysis in shipyard repair activities. This does not include the operation of bringing a ship out of water for repair or launching a newly built ship. The emphasis of these results and conclusions are on ship repairing or construction activities already on site.

3.4.8.2 Choose goals and set constraints

The goal is to identify shipyard fatalities. Goals are to expand research casualty data base, and accumulate results. Identify related work, and extract required information. Casualty data base is from Turkey, UK, USA, and Singapore. An example of the constraint in this study is, work in shipyards is carried out in normal weather conditions (e.g. good weather). Due to the large volume of data analysed from the period of 1990-2011, comprising of more than 100 shipyards, no generic shipyard is required to be developed.

3.4.8.3 Select risk analysis method

Expert grouping for brain-storming is by-passed in this study, due to available data and detailed reporting on accidents for selected illustrative examples. A generic case is developed on generic ranked hazards for detailed analysis. FTA is selected for use in Hazard identification and detailed risk analysis.

3.4.8.4 Draw FTA for hazard identified

FTA is constructed for 15 identified hazards from data collected. This step is quite tedious, but fault tree graphical representation makes sure nothing is missing during analysis.

3.4.8.5 Risk matrix of identified hazards

3x3 risk matrix developed in Section 3.3.3.2, is preferred in hazard identification study in shipyards as opposed to *7x4* matrices in the MSC guidelines. Accident analysis is important at this stage. The scenarios that can lead to every situation with potential to cause harm in dry docking operations are analysed from accident databases, or from brainstorming meetings with a unique goal to rank them according to consequence and severity rate.

3.4.8.6 Calculate equivalent total

This calculation is required in hazard identification step, so as to focus on those hazards above number 3, as illustrated in risk matrix in Section 3.3.3.2

3.4.8.7 Hazard ranking

The top ranked hazards are identified and noted for further analysis. In the ship repair industry, special attention however must be paid to the nature of constraints, and scopes of study defined in Section 3.3.1.

3.4.8.8 FTA quantification process

From hazard ranking carried out, a detailed quantified FTA is carried out on identified hazards with greatest risk. In other words, one accident might have 3 different scenarios. The greatest risk among these scenarios should be selected for detailed analysis. In some cases, where the equivalent total of each scenario is the same, then the quantification process highlights which is of greater risk. Results from the five (5) top hazards are ranked, and any can be selected for further analysis, depending on goals set in Sections 3.3.4.1 - 3.3.4.3 and time consideration.

3.4.8.9 Failure rate of top event

Engineering knowledge is acceptable here. In this study, basic events are provided with probabilities of failure, to compute the occurrence failure rate of the system under study. A Fault tree analysis software package (Isograph) computes the occurrence of top event, hence by-passing time-wasting hand calculations. This software provides the basis through which the popular '*minimum cuts sets analysis'* can be by-passed, due to RCM and CURR analysis for decision making.

3.4.8.10 Identify risk control option

The effectiveness of risk control options in any defined study within the scope of research in shipyard, are based on risk analysis. Questionnaires and literatures are reviewed on existing regulations or operation design to reduce specific risks in the area of study. All possible risk control options identified for each potential hazard are categorised with the aim to ease the grouping process.

3.4.8.11 Group risk options to risk measures

Grouping allows for risk control measures (RCM) to be applied appropriately. The detail application of this step is presented in Section 3.3.3.4. This step is vital for risk control measure analysis.

3.4.8.12 Risk control measures analysis

Improvement analysis is carried out by controlling failure events of FT in a quantifiable manner, and in every analysis, the top improvement of top event is noted. The risk control measures in this study have attributes such as: relating to fundamental type of risk reduction (preventive or mitigating), those related to action and costs required and finally those related to confidence that can be poured within active or passive limits within the study in ship repair.

3.4.8.13 Costs per unit risk reduction analysis

Cost benefit analysis is carried out by using equation 3.2 (see Section 3.3.3.2) and results from Section 3.3.3.5. CURR analysis requires the time horizon for this study to be on zero wage and inflation rate. A discount rate is recommended for analysis to be in the range of 3-6%.

3.4.8.14 Compare effective CURR and RCM

This step is to compare improvement in RCOs and values obtained from CURRs. This study shows that the benefit of a measure outweighs the approximated costs. A base case approach is usually encouraged to be used in ship repair industry, where available facts are published and obtainable.

3.4.15 Decision making

Select the best RCO which reduces risk to desired level. The desired level judgement is by results obtained from detailed FTA. Ranking of RCOs is required for effective management of resources where appropriate. Risk reduction to a desired level must be cost effective. Guidelines are required to be adopted from both the individual and societal type of risk perspective and should be considered for decision making in ship repair industry. To increase safety awareness among workers, safety culture must be somehow gained through an effective decision making process. The strength of supervision and adjustment of safety management policy are needed to decrease the occurrence rate of fatal accidents through FSA.

3.5 Application of FT-FSA in Dry-docking Operation: Fall from Height

3.5.1 Definition of work

The occurrence of occupational accidents in shipyards can be associated with risk factors from multiple perspectives such as workers, working environment, social environment, natural environment, and safety regulations. Because of the work force requirement under hard working conditions and the fatality frequency count for the employment group, the production process in shipyards can be identified as a hazardous occupation (dangerous job). Risks of occupational accidents in shipyards are given below (Baris, 2012).

3.5.2 Risk ranking

Data analysis shows three of these accidents occurs most frequently and causes major accident severity in shipyard. These accidents are: (a) Hit/stuck by object, (b) Fall from height and (c) Slip/fall. Lack of sufficient data, limited this study to "fall from height and slip/fall", to appreciate the application of formal safety assessment in a generic shipyard. "Hit/struck by object" not used, remains an area of interest to be considered in the nearest future. Table 3.11 shows the description of these accidents. It should be noted that, under major accident slip/trip, the subcategories of accidents include: on wet surface, dry surface, obstruction, and others. For accident fall from height, it could be subcategorised into either high or low fall.

Table 3.11: Accident categories and description

Categories/sub-categories	**Description**
1. Slipped, tripped or fall from same height	
1.1 wet surface	Due to spelt liquids, cargo residues, raining weather
1.2 dry surface	Cargo residue, dry surface
1.3 obstruction	Dummage, scrap metal, welding rods
1.4 uneven	-
1.5 other	Other sources of slipped/trip
1.6 unknown	-
2. Fell from height	**Description**
2.1 high fall	Height above 20m either scaffold, side of ship, gangway failure
2.2 low fall	Below 20m falls
2.3 unspecified	Unspecified to this subject

3.5.3 Risk matrix & generic locations

A risk matrix approach is used in the hazard screening process. For each appropriate combination, an assessment is made of the frequency (F) of the accident, and the severity (S) of the consequences in terms of human injuries/death, property damage and the degradation of the environment as in Tables 3.12 & 3.13. The area in the risk matrix, whereby risk is intolerable is with RRN number 4, 5 and 6. Areas with RRN less than 4 are regions where by risk can be ignored. This is shown in Table 3.3. Severity of identified hazards is classified as S1, S2, and S3. The rate of likelihood of hazard happening is ranked as F1, F2, F3 and F4. The corresponding risk ranking number (RRN) is then selected from the matrix table as in Table 3.2 (see Section 3.3.3.2). Generic locations are descriptions of typical areas in shipyard where most of operational activities take place. These areas are shown in Table 3.14. Risk matrix is required to calculate the equivalent total, which is used to evaluate the risk of identified hazards.

Table 3.12: Interpretation of the frequencies F1-F4

Likely to happen on the shipyard	**General interpretation**
F4 : 1- 12 months	Frequent
F3: 2-3 years	Likely to occur
F2: 5-10years	Remote
F1: over 10 years	Unlike to occur

Table 3.13: Shows the severity level in a typical shipyard industry

Severity value	**General interpretation**	**Generic shipyard**
S1	Minor injury	- Negligible lost time - Property damage or remedial cost <$5,000
S2	Major	- 60 days lost time - Property damage or remedial cost >$75,000 but < $100,000
S3	Fatality	- Property damage or remedial cost > 100,000

Table 3.14: Fall from height using risk matrix ranking

Accident	Generic Location			
Accident sub-category	**Above Deck**	**Shipside**	**Walkways/gangway**	**Below deck**
High fall	F3S2=4	F2S3=4	F4S3=6	F4S2= 5
Low fall	F4S2=5	F3S3=5	F2S2=3	F3S2=4
Unspecified	F1S2=2	-	F1S2=2	-

3.5.4 Calculating equivalent total - fall from height

The next step is to calculate the "equivalent total". This provides a means of integrating the risks evaluated for each hazard of the accident sub-category. It also provides a means of estimating each accident category to determine and justify the allocation of resources- to eliminate or reduce the risk (Wang, 2007). Table 3.15 is generated from 5 and this shows the number of times each RRN appears within an accident category. (Only values greater than 3 are considered).

Table 3.15: Number of occurrences of each ranking score for fall from height

RRN	**No of occurrences**
4	3
5	3
6	1

Equivalent total calculation makes use of the fact that both the frequency and severity bands of the risk matrix are approximate logarithmic (e.g. risk level of 6 is treated as 106). Using 3 as a base number then the following can be obtained from Table 3.14.

Equivalent total = 3 + log (300+30+1) = 5.62

Results obtained from step 1: A total of 5 hazards are identified to be associated with accident, fall from height (5); lack of training, improper design of scaffolding, poor communication, and gangway give up. The two most prominent hazards, identified from data collected include; obstruction in shipyard which leads to slip/fall and scaffold failure as presented in HAZID worksheet Table 3.16.

Table 3.16: Present HAZID worksheet for hazard due to scaffold failure

Hazard description	**Causes**	**Effects**	**Accident category**	**Frequency**	**Severity**	**Risk level**
Improper design of **scaffold**	Inexperience in design, lack of proper supervision.	Vulnerability to severe injury or potential death,	Fall from height	F3	S4	3

3.5.5 Risk estimation, fall from height due to scaffolding failure

Fault tree is used in risk engineering to analyse the frequency of system failure either qualitatively by logical and structural hierarchy presentation of failure events or quantitatively by the estimation of occurrence rate of the top event. The top event is fall from height due to scaffolding failure in shipyards and the frequency of occurrence as obtained from Program-Based Engagement for Scaffolding WSH, is 15 per shipyard year (WSH, 2006).The total risks summarised in this study include, structural damage, potential loss of life, and financial cost incurred if this hazards occurs. The potential risk caused by fall from height due to scaffold failure is estimated to about $159,350 in fines a year from statistics from OSHA reports:

“Improperly erected scaffolding and failure to train workers on the hazards of working with scaffolding which resulted in the deaths of five workers and injuries to ten more resulted in citations against three New York contractors - Nesa, Inc, Tri-State Scaffolding & Equipment Supplies, Inc., and New Millennium Restoration & Contracting Corp., - and $159,350 in penalties, according to the U.S Times report.”

The failure rates assigned to basic events in this study is an approximation due to lack of data. Nevertheless, the event table constructed in Table 3.17. Figure 3.8 presents the final result when using the fault tree analysis. Failure rates obtained from expert judgements.

Table 3.17: Basic event with failure rates assign

Events	**Failure Rate**	**Event**	**Failure Rate**	**Events**	**Failure Rate**	**Events**	**Failure Rate**
1	0.0015	5	0.003	9	0.07	13	0.08
2	0.009	6	0.004	10	0.001	14	0.01
3	0.002	7	0.001	11	0.02	15	0.005
4	0.008	8	0.006	12	0.002	16	0.015
						17	0.009

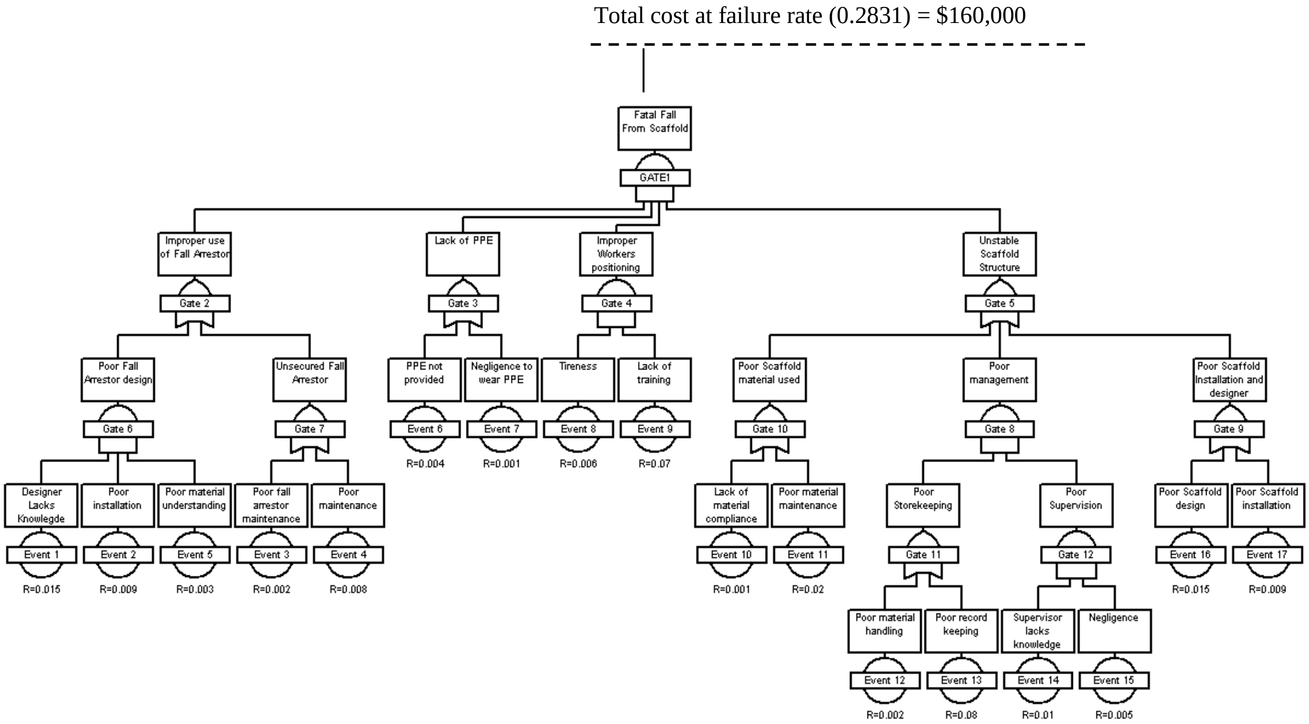
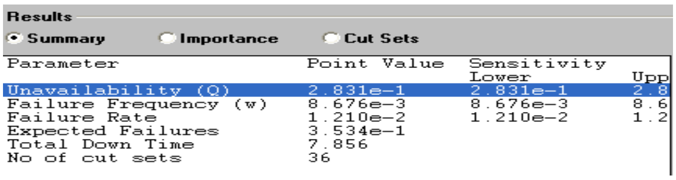


Figure 3.8: FTA results obtained from fall from height due to scaffold

This result indicates that, the failure rates of basic events leads to the occurrence probability of top event. Therefore, in further examination of this FTA, reducing or increasing the failure rates of basic events leads to reducing or increasing the occurrence probability of top event respectively. With this principle, risk control measures can be developed, and hence risk control options obtained as further discussed in step 3. Table 3.17 presents the risk control measures required to control these failure rates. The potential risk if these options are not implemented includes loss of life, loss in production cost/fines, and structural damage (requiring re-designer). Results obtained, shows the occurrence probability of top event (Fatal fall from scaffold) is 0.2831, and the number of cut sets is 36, t=100hrs. This is obtained by using the FTA software package, as hand calculation for such complex fault tree is difficult to obtain. Figure 3.9 shows the unavailability (Q) of event, fall from height.



```
Parameter                  Point Value   Sensitivity
                                         Lower         Upp
Unavailability (Q)         2.831e-1      2.831e-1      2.8
Failure Frequency (w)      8.676e-3      8.676e-3      8.6
Failure Rate               1.210e-2      1.210e-2      1.2
Expected Failures          3.534e-1
Total Down Time            7.856
No of cut sets             36
```

Figure 3.9: Results showing the unavailability (Q) of event fall from height

3.5.6 Risk control option-fall from scaffolding

In this step, the first goal is to provide evidence based on the results obtained in Section 3.4.6, whereby reducing the failure rate of basic events leads to reducing the occurrence probability of top events. Failure rates reduction can be carried out by using the appropriate risk control measures. From step 2, a total of 17 risk control measures can be obtained, and are grouped into four risk control options as shown in Table 3.18. In this step, each risk control option would be reduced by some percentage, and the reduction of top event occurrence probability.

Table 3.18: Risk control option log

RCO1	**Provision of PPE at all times**
Attribute	Preventative & mitigating
Stakeholders	Designers, supervisors, workers, shipyard owner, ship owner
RCO2	**Improvement of design**
Attribute	Preventive & mitigating
Stakeholders	Designers, supervisors, workers, shipyard owner, ship owner
RCO3	**Improvement of housekeeping/maintenance/inspection**
Attribute	Preventive & mitigating
Stakeholders	Designers, supervisors, workers, shipyard owner, ship owner
ROC4	**Training improvement for workers in height**
Attribute	Preventive & mitigating
Stakeholders	Designers, supervisors, workers, shipyard owner, ship owner

From Figure 3.9, the occurrence probability of top events is obtained (0.283), and areas of high risks to be addressed or control noted as in Table 3.19.

Table 3.19: Failure rates values for basic events

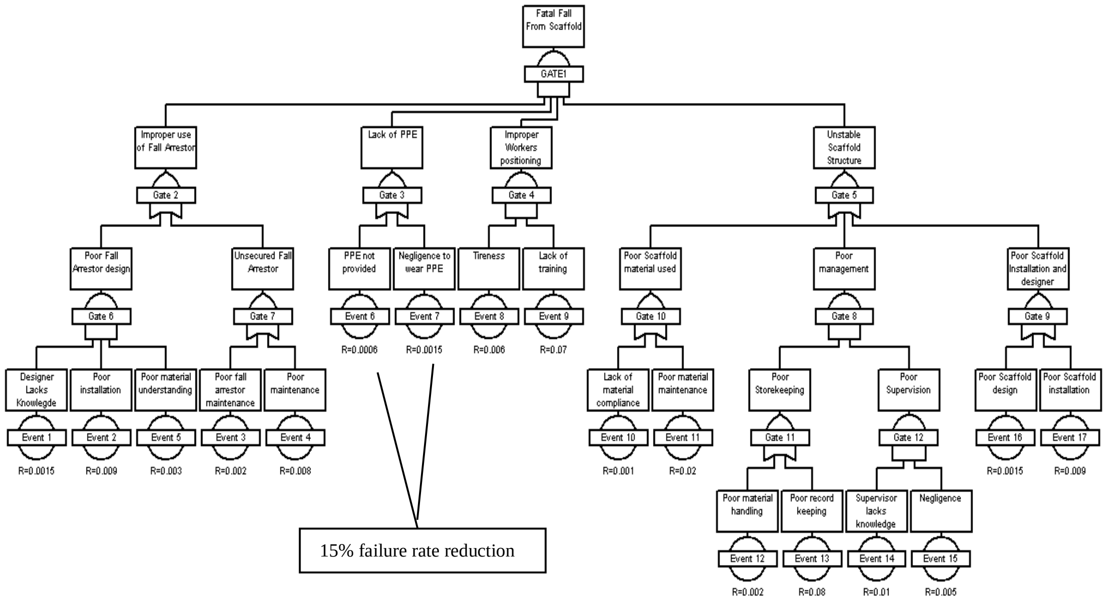
Basic Event and areas of risk control measures required	***Failure Rate***	***Risk Control measures grouping***	***Potential Risk***		
1.lack of scaffold designer knowledge	0.0015		Loss of life	Structural damage	Loss of production cost/fines
2. lack of fall arrestor designer knowledge	0.0015		-	-	-
3.Poor scaffold installation	0.009	RCO2	-	-	-
4. Poor fall arrestor installation	0.009		-	-	
5. PPE not provided	0.004	RCO1	-	-	-
6. Negligence put on PPE	0.001		-	-	
7. Poor scaffold material understanding	0.003	RCO3	-	-	
8. Poor Fall arrestor material handling	0.02		-	-	
9.lack of material compliance	0.001		-		-
10. Poor material inspection	0.02	RCO3		-	-
11. Poor material maintenance	0.02		-	-	-
12. Poor material house keeping	0.002		-		
13. Poor material record keeping	0.08	RCO3		-	
14. Tiredness	0.006				
15. Lack of Training	0.07	RCO2		--	
16. Negligence	0.005				
17. Supervisors lack training	0.01				

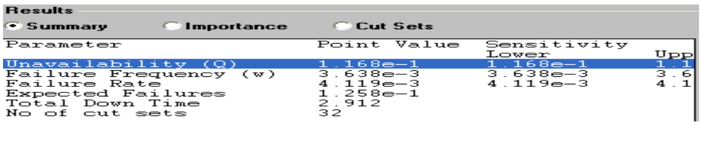
RCO1: 15% reduction in failure rates of basic events 6 & 7

Reducing the failure rate of some basic events would be vital to illustrate to the different stakeholders, owners and designers need for improving safety in shipyards. Therefore, reducing failure rate of events 6 & 7 indicates proper implementation of RCO1 as in Table 3.20. It should be noted that, the other basic events remain unchanged. The FTA is carried out as shown in Figure 3.10 and the results shows the occurrence probability is reduced from 0.283 to 0.116 (59% reduction).

Table 3.20: 15% RCO1 improvement

Risk control option	**Risk control measures**	**Initial basic event failure rate**	**Improve basic event failure rate**
RCO1	Improve provision of PPE Improve training on need of PPE	Event 6 = 0.004 Event 7 = 0.01	15% Event6 = 6.0e-4 15% Event7= 2.5e-3





```
Parameter                  Point Value   Sensitivity
                                         Lower        Upp
Unavailability (Q)         1.168e-1      1.168e-1     1.1
Failure Frequency (w)      3.638e-3      3.638e-3     3.6
Failure Rate               4.119e-3      4.119e-3     4.1
Expected Failures          1.258e-1
Total Down Time            2.912
No of cut sets             32
```

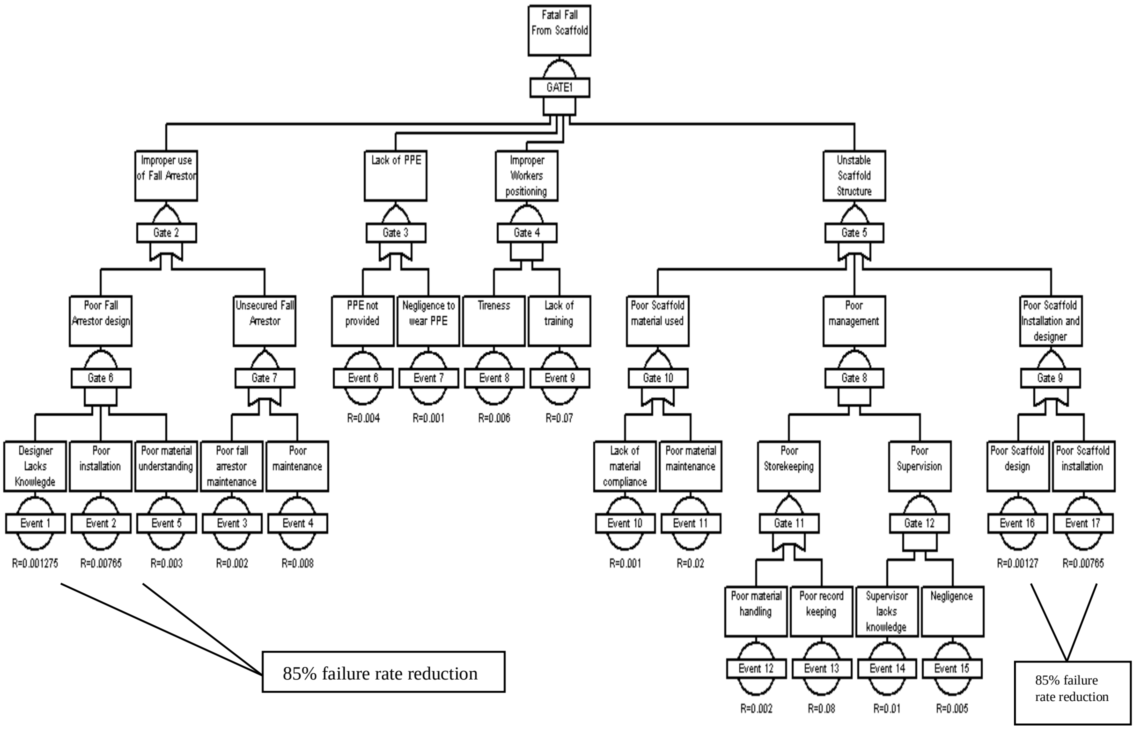
Fig 3.10: FTA of 15%RCO improvement

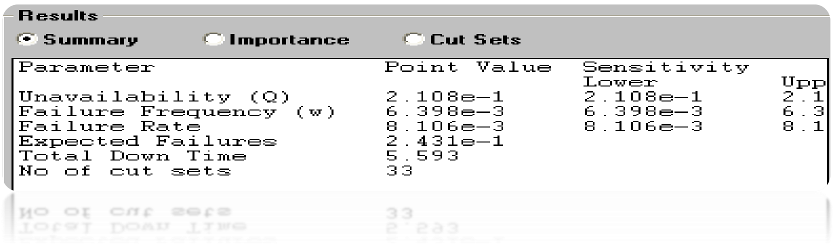
RCO2: 85% reduction in failure rates of basic events 1, 16, 17, & 2

In this light, in order to reduce the occurrence probability of top event, other failure rate of basic events must be reduced. In this case, reducing the failure rates of events 1, 16, 17 & 2, by 85%, would lead to implementation of risk control options 2 as in Table 3.21. The results obtained in Figure 3.11 show the occurrence probability of the top event is reduced from 0.2831 to 0.211 (25% reduction).

Table 3.21: 85%RCO2 improvement

Risk control option	**Risk control measures**	**Initial basic event failure rate**	**Improve basic event failure rate**
RCO2	Improve fall arrestor design Improve scaffold design Improve scaffold installation Improve fall arrestor installation	Event1 = 0.015 Event16 =0.015 Event 17= 0.009 Event 2= 0.009	85% Event 1 =1.2e-3 85% Event 16= 1.2e-3 85% Event17=7.5e-3 85% Event 2 = 7.5e-3





```
Parameter                    Point Value    Sensitivity
                                            Lower          Upp
Unavailability (Q)           2.108e-1       2.108e-1       2.1
Failure Frequency (w)        6.398e-3       6.398e-3       6.3
Failure Rate                 8.106e-3       8.106e-3       8.1
Expected Failures            2.431e-1
Total Down Time              5.593
No of cut sets               33
```

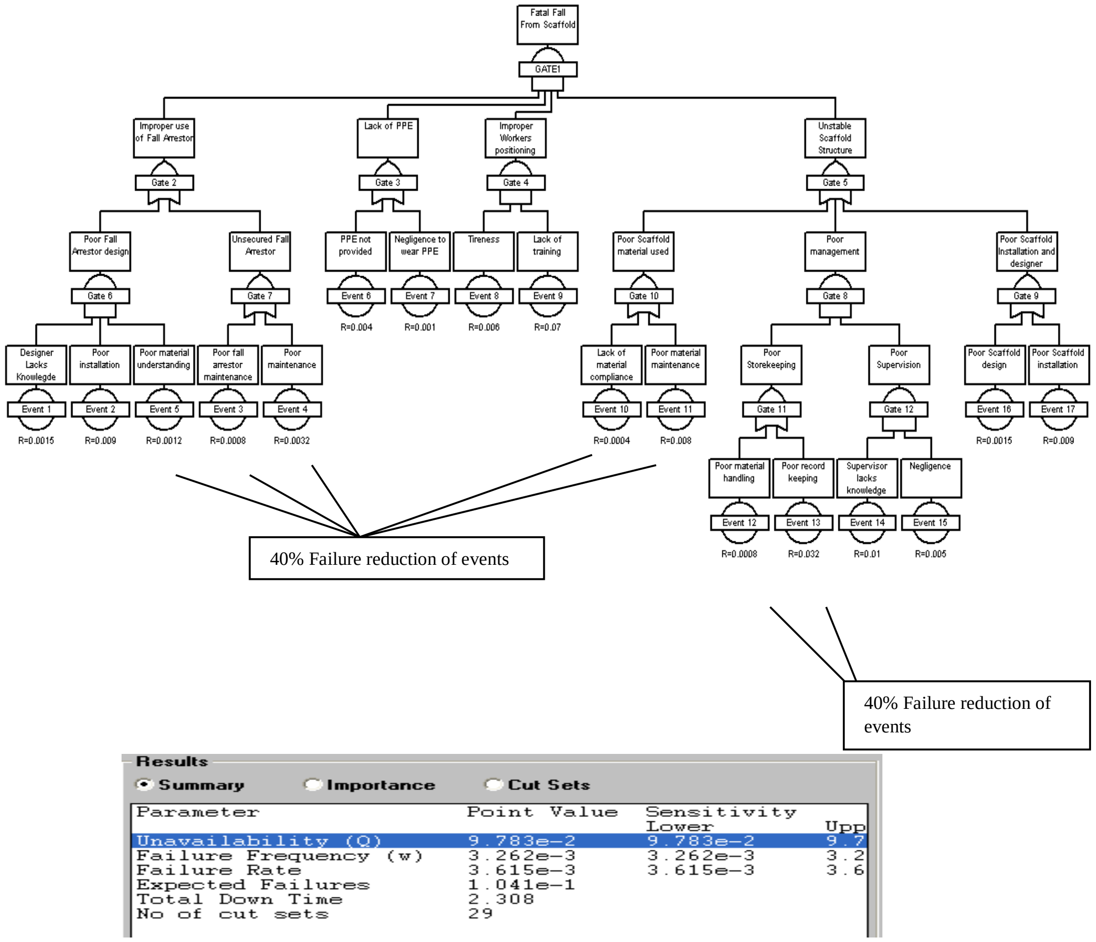
Figure 3.11: FTA of 85%RCO2 improvement

RCO3: 40 % Improvement in failure rate of basic event

Improving the failure rate of basic events 12, 5, 10, 11, 3, 4 and 13, by 40% means RCO3 is well implemented as in Table 3.12. The results obtained from Figure 3.1 shows the occurrence probability of the top event is reduced from 0.2831 to 0.097.

Table 3.12: 40%RCO3 improvement

Risk control option	**Risk control measures**	**Initial basic event failure rate**	**Improve basic event failure rate**
RCO3	Poor scaffold material handling Poor fall arrestor material handling Lack of material compliance Poor scaffold material handling Poor material handling Poor fall arrestor record keeping Poor scaffold record keeping	Event 12 = 0.002 Event 5 = 0.02 Event10=0.001 Event 11= 0.02 Event 3= 0.002 Event4= 0.008 Event 13=0.08	40% Event12= 8.0e-4 40% Event 5= 1.2e-3 40% Event10=4.0e-4 40% Event11=8.0e-3 40% Event 3= 8.0e-4 40% Event 4= 3.2e-3 40% Event13=3.2e-3



```
Parameter                  Point Value   Sensitivity
                                         Lower         Upp
Unavailability (Q)         9.783e-2      9.783e-2      9.7
Failure Frequency (w)      3.262e-3      3.262e-3      3.2
Failure Rate               3.615e-3      3.615e-3      3.6
Expected Failures          1.041e-1
Total Down Time            2.308
No of cut sets             29
```

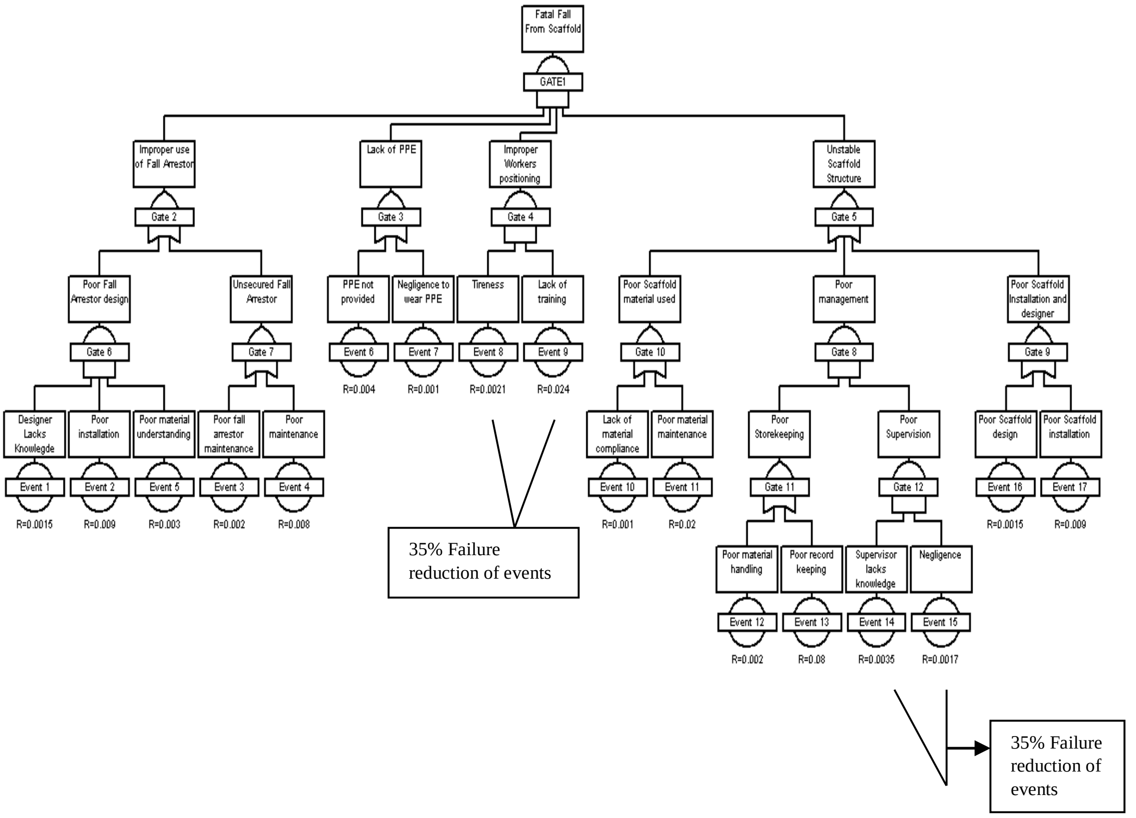
Figure 3.12: FTA of 40%RCO3 improvement

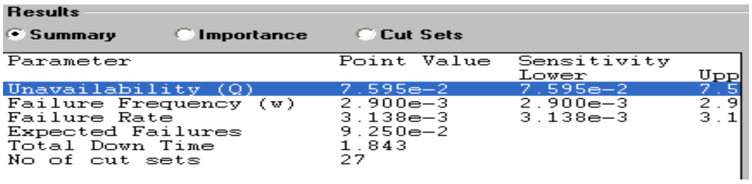
RCO4: 35% Improvement of some basic events

Improving the failure rate of basic events 8, 9, 15, and 14 by 35% means that, RCO4 is well implemented. This could be seen in Table 3.13. Results from Figure 3.13 shows the occurrence probability of top event is reduced from 0.2831 to 0.076.

Table 3.13: 35% RCO4 improvement

Risk control option	**Risk control measures**	**Initial basic event failure rate**	**Improve basic event failure rate**
RCO4	Improve awareness on tiredness Improve training at height Zero tolerance on negligence Improve supervisors knowledge	Event 8 = 0.006 Event 9 = 0.07 Event15= 0.005 Event14 = 0.01	35% Event 8 = 2.1e-3 35% Event 9= 2.4e-2 35% Event 15= 1.75e-3 35% Event14= 3.5e-3





```
Parameter                  Point Value   Sensitivity
                                         Lower          Upp
Unavailability (Q)         7.595e-2      7.595e-2       7.5
Failure Frequency (w)      2.900e-3      2.900e-3       2.9
Failure Rate               3.138e-3      3.138e-3       3.1
Expected Failures          9.250e-2
Total Down Time            1.843
No of cut sets             27
```

Figure 3.13: FTA of 35%RCO4 improvement

3.5.7 Cost benefit assessment

The results obtained from Step 3, shows a reduction of the occurrence probability of the top event is achieved by reducing failure basic rates of basic events. These risk control options are presented in Table 3.24.

Table 3.24: Results obtained from step 3

Risk Control Options	Initial Occurrence probability of top event (I)	Re- Calculated occurrence probability of top event (R)	Differences	% Reduction (I-R/I)*100
RCO1	0.283	0.116	0.167	59%
RCO2	0.283	0.211	0.072	25%
RCO3	0.283	0.097	0.186	65%
RCO4	0.283	0.076	0.207	73%

This step aims at identifying and quantifying the cost to be paid and benefit to be expected when each RCO developed in step 3 is implemented. Each RCO is evaluated in terms of implementation cost and benefits, and this is achieved by establishing the total implementation cost and then deriving its associated cost per unit reduction in risk (CURR). This could be seen calculated by equation below (Lee, 2002):

$$\text{NPV} \quad = \quad CURR = \sum_{t=0}^{n} (b-c) \left[\frac{1+i}{1+r} \right]^{t} \qquad (3.6)$$

where B and C are benefit and cost, respectively, r is discount rate of 3%, t is the measure of time horizon from 0 to n years, and *i* is inflation or wage increase. For the four RCOs selected to be analysed in this study, CURR could be calculated by the difference between the cost and benefit divided by the risk reduction. Table 3.24 shows the different implication of these RCOs.

For example, the cost proposed by OSHA for providing training to workers at height is $15,000 a year (RCO4). The benefit enjoyed from implementing these risk control option would reduce the occurrence probability, “for fall from height due to scaffold failure”, by 72% hence, ripping a benefit of 10, 800 (72% of 15,000) in Table 3.25.

Another example is presented with cost estimated for improving scaffold material, maintenance, housekeeping and record keeping (RCO3) to be $ 25,000 a year. The occurrence probability of the top event is reduced to 65% when RCO3 is implemented in step 3. In this light, the benefits obtained upon the implementation of RCO3 is $16,250 (65% of 25,000) presented in Table 3.25 from which CURR3 is calculated.

Table 3.25: Summary of cost-benefit assessment

Stakeholders	***RCO1***		***RCO2***		***RCO3***		***RCO4***	
	Cost(C1)	Benefit (59%C1)	Cost(C2)	Benefits (25%C2)	Cost(C3)	Benefit (65%C3)	Cost(C4)	Benefit (72%C4)
Shipyard owner/ operator/ Designer/Installer/regulators	5000	2,950	9500	2,375	25,000	16,250	15,000	10,800
Total in $	**5000**	**2,950**	**9500**	**2,375**	**25,000**	**16,250**	**15,000**	**10,800**
Risk reduction		1		2		3		4

Assuming that the time horizon for the safety assessment is for 10 years at a discount rate of 3%, and using equations1, the CURR calculation for each RCO is given as follows:

$$CURR1 = \sum_{t=0}^{10} \frac{(5000 - 2950)(1 + 0.03)^{-t}}{1} \quad = \underline{\$17{,}486}$$

$$CURR2 = \sum_{t=0}^{10} \frac{(9500 - 2375)(1 + 0.03)^{-t}}{2} \quad = \underline{\$30{,}385}$$

$$CURR3 = \sum_{t=0}^{10} \frac{(25000 - 16250)(1 + 0.03)^{-t}}{3} \quad = \underline{\$24{,}882}$$

$$CURR4 = \sum_{t=0}^{10} \frac{(15000 - 10800)(1 + 0.03)^{-t}}{4} \quad = \underline{\$8{,}956}$$

These results show RCO4 is the best option to implement. This may be recommended to for implementation, with RCO2 being the worst option.

3.5.8 Recommendation for decision making

It is noted clearly from the calculation that, if CURR is used as the only measure of effectiveness in the decision-making process, the most effective RCO would be RCO4. RCO1 would be the next and RCO2 the least effective according to the CURR calculations. However, initial benefits for implementing RCO3 are higher than those of RCO4 as in Table 3.25. This strongly indicates the shortcomings of using CURR as the sole tool for decision.

Chapter 4 – Use of a Fault Tree – Bayesian Network for Dry Dock Risk Analysis

Summary

Shipyards are complex systems with economic functions; they are subject to specific harsh environmental conditions and are built mainly in areas with increasingly corrosive activity. This chapter focuses on one particular dry dock type called 'relieving graving dock' reinforced with concrete. A detailed quantitative risk analysis with novel fault tree-Bayesian network mapping algorithm is used to rank the most dominant failure mechanisms in terms of risks. The results of this analysis will be a guide for the design, construction and maintenance phase of graving docks applicable to any critical component identified from a risk analysis perspective. The research results should be valuable in enabling industrial participants to manage large engineering risk projects and extending understanding of ship repairing.

4.1 Introduction

In recent years, safety analysis has played an important role in the verification of system safety and avoiding casualties and property losses. Actually it is difficult to verify dry dock safety using traditional computer software engineering analysis such as fault tree (FT) ++ given the dependency among the risk factors/events.

As an important way for verifying safety in graving dry docks, the fault tree-Bayesian network (FT-BN) has attracted more attention in practice (Cai *et al*., 2010). However, it is still an open question as to how marine safety analysts could make FT-BN more efficient. With the development of science and technology, modern ships have grown in size, while the relationships between upgrading graving docks' equipment and structures of these huge ships have also become more and more complex. The system safety, operational efficiency, life cycle cost control, and maintenance of docking systems have encountered a lot of challenges in terms of practical application (Cai *et al*., 2010).

Maintenance actions suggested from hazards identify that more detailed risk analysing techniques are required to avoid catastrophic failure in graving dry docks. Various parties (operators, shipyards, regulators, and government) in their respective working context are very often involved in a sequence of events leading to accidents in graving dry docks, such as the collapse of dry dock gates. This is the most critical issue in graving docks, thus there is a need to develop an effective risk or accident analysis to avoid future operator errors. For the past decades, risk analysts in dry docks have proposed techniques such as Fault Tree Analysis

(FTA), Failure Mode Effects and Critical Analysis (FMECA), and Fuzzy Set Theory (FST). In these methods and technologies, FTA, which generates the use cases by the minimal cut sets of fault trees, cannot determine the priorities of all the use cases and cannot utilise the finished test results (He and Tao, 2011). A more applicable approach to solve this problem is by transferring FT to BN (described in this chapter), expressing the information in fault tree and Bayesian networks together. The layout of this chapter is presented in Figure 4.1.

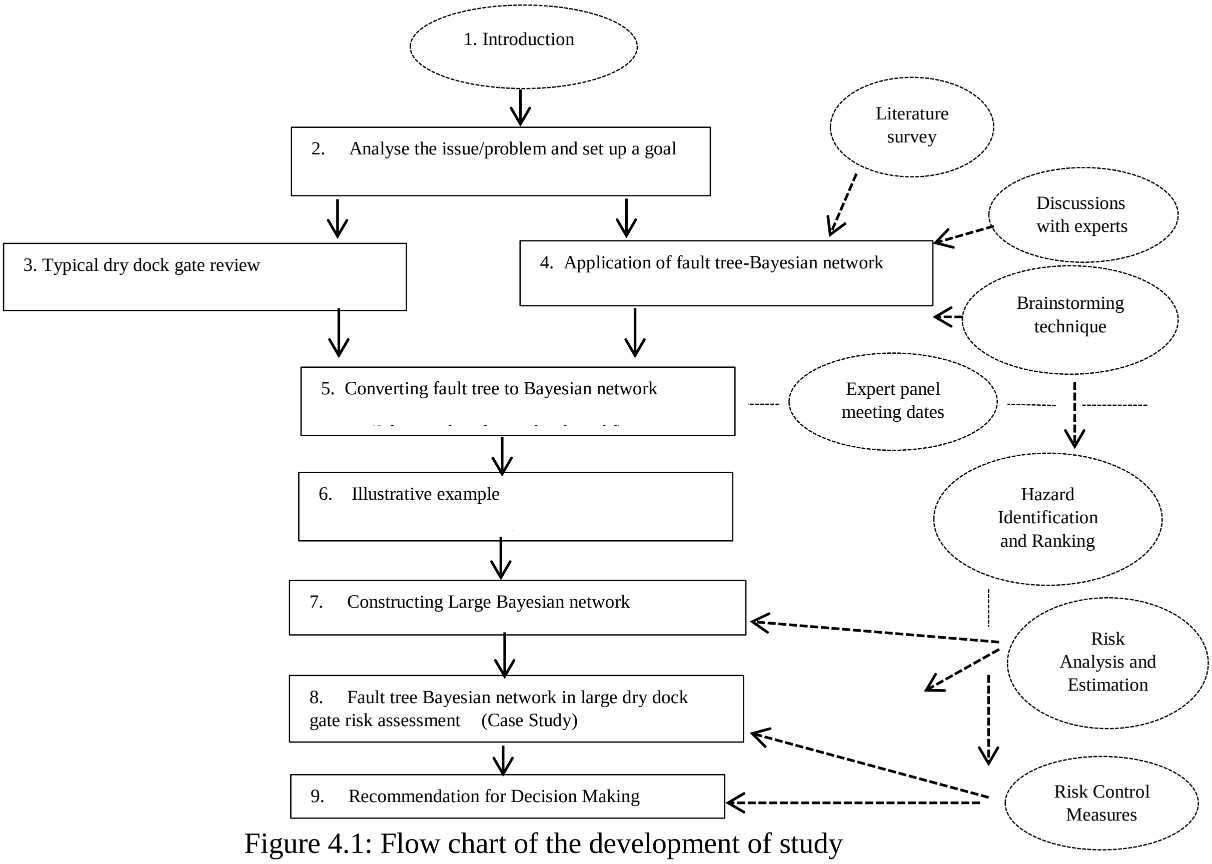


Figure 4.1: Flow chart of the development of study

In this chapter, a quantitative approach in the reliability evaluation method of the dry dock failure analysis of a caisson gate of a graving dock has been studied for the application of BN transferred from a fault tree. Section 2 presents the statement of the problem in the graving dock reliability analysis. Section 3 presents the two typical steel sliding gates used in this study. Section 4 is a review of FT-BN applications in engineering. Section 5 is an overview of converting a fault tree to its corresponding Bayesian network. Section 6 is the illustrative example of the failure analysis of a dry dock gate highlighting the system reliability. Section 7 is the framework of overcoming the problems of constructing conditional probability tables (CPTs) of a large Bayesian network. Section 8 presents a case study of applying a large BN analysis of a sliding dry dock gate at Birkenhead, Liverpool, UK. Section 9 provides the discussions and conclusions.

FTA is an important verification methodology for graving dock risk analysis. It is a top down technique used to analyse the origin of the failure, determine the graving dock safety requirements, detect the logic of errors, identify the multiple failure sequence involving different parts of the system (such as human and hardware). It provides an analytical tool to determine appropriate input data in graving dock analysis. FT can be used to analyse systems in the field of probabilistic risk assessment. However, traditional FT cannot handle sequential and functional dependencies between components (Shao *et al*., 2011).

BN is a directed acyclic graph used to represent uncertain knowledge in the field of graving dock risk analysis. This is defined to consist of qualitative and quantitative relations (Burton, 2001), and because of the advantages of uncertainty and conditional independence expression, the BN provides a comprehensive method of representing variable states and variable relationships. In addition, the BN presents these things by graphical diagrams of nodes and edges, BN can be understood more easily than many other techniques (Zhang and Guo, 2006).

Besides, an efficient method (Wojtek and Milford, 2006) can make the conversion of fault trees to Bayesian networks easy. In a BN, the nodes represent a random variable; the arcs signify the existence of direct causal influences between variables, and the strengths of these influences are expressed by forward conditional probabilities (Wang and Xie, 2004). Accordingly, this provides BNs with the ability to calculate posterior probabilities of unknown variables in graving dock failure analysis based on the variable evidence and conditional probability distributions. It is proved that the BN is suited for equipment failure prediction, especially for the complex equipment under uncertainty (Cai *et al*., 2010). The BN provides a promising framework for system reliability assessment (Angrig and Kohlas, 2005; Kral et al., 2005) in the ship repair industry. Based upon the analysis of BN by inputting prior information of the dry docking system failure, the probabilities of the fault occurences are effectively computed based on which proper preventive maintenance strategies can be established (Jong and Leu, 2013). This research however proposes a FT-BN risk analysis approach with the focus on dealing with uncertainty in data as a standalone characteristic of risk linked to each foreseen operation, applicable to any other critical component in graving dry dock highlighted to enhance safety certifications from a perspective of risk analysis. Lastly, due to the BN's powerful ability of modelling uncertainty propagation and updating through the nodes, it can overcome the disadvantage of earlier upgrading methods where information from the system level cannot be transformed to the component level.

4.2 Problem Definition

Risk analysis involves two basic types of uncertainty. The first is due to inherent randomness in the phenomenon and the variables chosen to model it. The second is due to inaccurate modelling, insufficient data, etc. This research is concerned mainly with this second, or epistemic, source of uncertainty, and its propagation through a risk analysis involving rare events such as the collapse of a dry dock gate (Castillo, 1999). In standard analysis, model parameters are assumed to be constant values, however, on many occasions these parameters are difficult to assess or are estimated. Thus, their initial deterministic character is considered to be inadequate and parameters are assumed to be random variables. When this occurs and the aim of the analysis is to monitor the effect of this randomness on a given target variable, we say that we are dealing with an uncertainty analysis (Castillo, 1999).

In the case of FT or BN models, the input uncertainties associated with the basic fault event or conditional probabilities (the parameters) are propagated through the model to obtain the corresponding uncertainty associated with the probability of the top event in dry dock gate failure. Since fault tree models are an integral part of FSA, the propagation of input parameter uncertainties through such models to arrive at the corresponding uncertainty in the probability of the top event, that is, the system unavailability, is of fundamental importance (Castillo, 1999). In traditional FTA the probabilities of basic events are treated as exact values, which could not reflect the situation of a dry dock gate system because of the ambiguity and imprecision of some basic events. In many circumstances, it is generally difficult to estimate the precise probabilities of basic events. Thus, it is often necessary to develop a new method to capture the imprecision of failure data. In this regard, it may be more appropriate to use BN (Yanfu and Min, 2012).

Marine works have been subjected more and more to risk analysis over the past few decades; for example, fishing vessels, ports, marine transportation, offshore support vessels, containerships, LNG ships, ship hull vibration, crushing ships, liner shipping, high-speed crafts, oil tanker, passenger roll on/roll off (roro), vessels with dangerous goods and bulk carriers (Nwaoha *et al.*, 2012). Costal structures like wind turbines (Sorensen *et al.*, 2004), optimisation of harbours (Billard *et al.*, 2007) and harbour monitoring (Yanez-Godoy *et al.*, 2006) for reliability are other creative areas of risk analysis carried out in marine areas beyond ships and offshore structures. However, the literature review reveals very little on risk analysis on structures used in bringing ships in and out of water for repair. An example of this type of structure is the graving dock. The graving dock is typical in that it is surrounded by earth on three sides and has a floatable caisson (or gate) at one end. The walls usually consist of two sections: thick walls and/or thin walls. An example of such a dock is the Charleston dry-dock in the USA, reinforced with concrete, which is particularly known as a relieved graving dock (Wu *et al.,* 1990). To support fleet operations, it is important to maintain the existing dry docks in a safe condition and to assure that the full capacity of the dry dock is maintained. Each dry dock needs to be initially certified for its safety and capacity for three to five years. To certify the safety of a graving dock, the stability analysis of the dry dock is performed using a finite element analysis. The content of this report is generally based on (Wu *et al.,* 1990):

- A material condition survey performed by a field investigation,
- structural analysis using a finite element analysis computer program, and
- the operation and maintenance procedures provided by the shipyard.

The safety certification of a graving dry dock comprises a structural analysis of geotechnical characteristics, structural parameters, soil structural interaction, and load cases. These safety certifications however have not prevented failure happening in graving shipyards. Typical accidents may include collapse of dock walls due to static lateral soil pressure and dynamic earthquake loads. A recent accident involving caisson gate failure on 27 March 2002, at Dubai Dock No 2, one of the world's largest ship repair facilities, caused uncontrolled flooding of the dock (Paul, 2011) leaving 21 people dead. Again, if the dry dock is not founded on deep foundations, such as piles, then a net uplift would result, causing the dry dock to float and tilt. However, according to Wu *et al*. (1981), this failure is not likely to occur.

From a risk analysis perspective, the analyst is required to gather enough data to classify a risk or failure unlikely to occur in a scientific manner, although Wu *et al*. (1981) analysed structural risk of graving docks based on their 20 years in the field. In the preparatory study preceding risk analysis, a detailed study is required to identify critical elements in dry docks. These critical elements are; dry dock gate, walls, piles, concretes, structural components, and ballast system control. In the maritime industry, it is necessary to address the issue as to why the industry normally reactively responds to an accident and then is motivated to modify the existing safety certification or propose new ones. The safety culture of anticipating hazards rather than waiting for accidents to occur is based on a detailed risk analysis. Faced by ageing of these structures, risk analysis faces some challenges. Most recent graving docks trace their origin back over 40 years, with rehabilitation and capacity upgrade to accommodate larger ships mid-way through this period. These indicators affect the condition diagnosis and ageing diagnosis of components and facilities in dry docks to adapt maintenance actions for larger fleets. Again, selecting critical elements for risk analysis becomes difficult since most components may be at high risk of collapse due to age. In this study, the risk analysis to support operation and maintenance of an ageing dock gate for the Port of Marseilles authority is re-visited. The dock gate identified as a critical component is further plagued by age. The previous study by Crouighneu *et al*. (2008) was based on FMECA with the methodology highlighted as follows: (1) to characterise the risk linked to each foreseen operation scenario; (2) identify the most appropriate actions to control these risks; (3) integrating operation constraints (e.g. the need to put the dock gate in dry dock); (4) rank actions regarding their cost/benefit ratio and; (5) building a maintenance plan.

4.3 Dock Entrances and Dock Gates

Dewatering of the dry dock takes place after setting the dock gate, which permits full closing at the highest predicted water level, and opening at least at the mean level. The gate as well as its support '*must safely withstand the largest water pressure from the water side'* was suggested by Crouighneu et al. (2008). Dock gates should fulfil the following objectives: (a) great tightness for all possible loading cases; (b) short opening and closing times; (c) easy servicing and maintenance; (d) mechanical reliability; (e) monitoring of the gate position during opening and closing; and (f) minimum operation and maintenance costs. Seals should correct any unevenness of the concrete surfaces which could not be eliminated by grinding. Another common problem with the gates is protection against corrosion, ice actions, and they must have sufficient buoyancy to allow them to be placed in their seating and removed for maintenance repair (Crouighneu *et al*. 2008). Again, the dock gate as a whole must be subjected to detailed complex static calculations in order to find the dimension of each structural element and also to establish interaction of the individual sections and the bearing elements. The tightness of the dock depends on these individual elements. Lastly, as water is added to the gate to sink it, the weight of the water causes the centre of gravity to alter as the gate takes on slight angles, raising stability issues. Many types of dock gates are in use nowadays. They are classified as floating, sliding, mitre, hinge, and flap gates but only the sliding gates of Dry dock No. 10 in Marseilles, France and in dry dock at Birkenhead, UK are considered in this research, where the latter serves as a benchmark study, and the former for detailed analysis (Mazurkiewicz, 1980).

4.3.1 Steel sliding gate, Birkenhead, UK

The gate is constructed on the arc of a circle with a centre line radius of 48.8 m. The radii through the outer gate subtend at an angle of 61^0, made of steel 49.1m long, 13.4 m high, and 4.3m wide. The gate has four decks lettered A, B, C and D. A is the Top Deck. On these decks are the driving winch, control panel, tank gauges, ladders for access at each end, and boxes for valve operation (Mazurkiewicz, 1980).

The gate is usually controlled from the desk in the control room, from which it is clearly visible. When the button is pressed, the gate commences to move at 1.4 m/s. The space between A and B deck is the Tidal Chamber. Tidal flaps, normally held open by wires, allow the water to flow in from the river and the ends of the gates are also open. When force is impounded in the dock these wires are released, the flap valves close and valves in the inner skin are opened. These arrangements prevent any buoyancy being obtained from the upper chamber (Mazurkiewicz, 1980). Figure 4.2 presents the general arrangement of a sliding gate in Birkenhead.

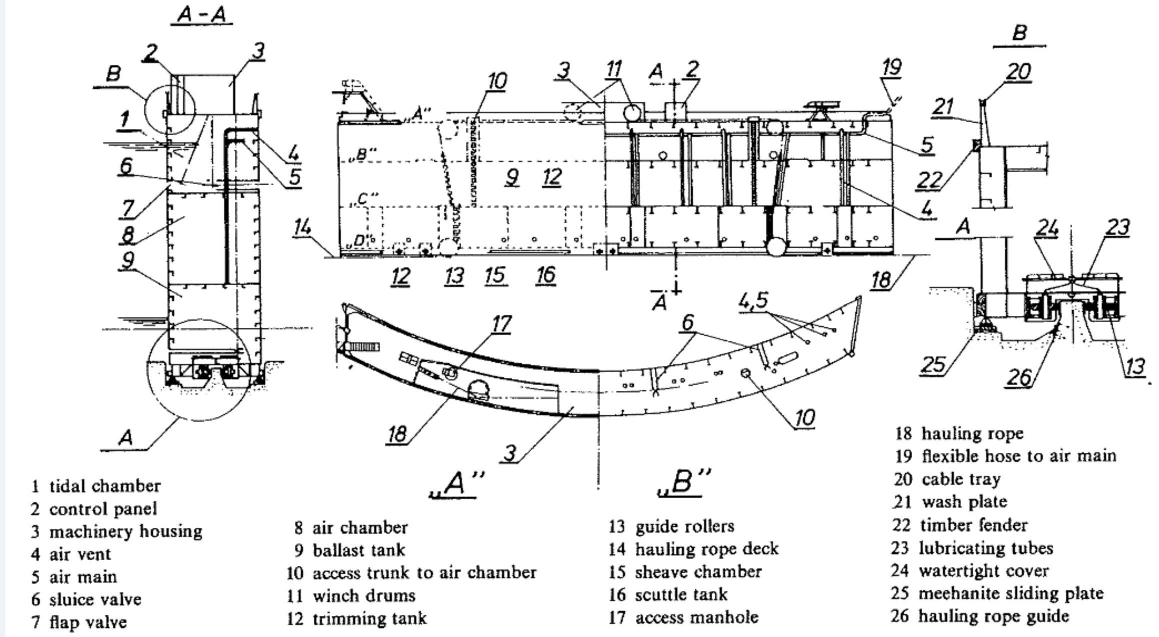


Figure 4.2: General arrangement of a sliding gate in Birkenhead, UK (Mazurkiewicz, 1980)

The space between B and C decks is an Air Chamber. By pressurising this chamber the covers to the sheave chambers below may be removed and maintenance to the rollers carried out while the gate is in its normal closed position. Between C and D decks are housed the trimming tanks, the scuttle, the ballast tanks and the sheave chambers. The trimming tanks were designed to enable the gate to be trimmed to an even draught. However, after the gate had been floated, readings were taken of the draught and permanent ballast was added to bring it to an even keel; there should not, therefore, be any further need to use the tanks (Mazurkiewicz, 1980). The two scuttle tanks are used to sink the gate in position and will normally be left full, only being emptied when it is desired to float the gate out of its position. When it is desired to empty the scuttle tanks the water can be blown out by air pressure. The two ballast tanks are flooded when the gate is in the closed position to increase its stability and prevent any movement due to wave action. Below D deck are the rollers to guide the gate on its circular path, one pair of rollers at one end, two pairs in the centre at 1.2m centres and two pairs near the other end at 2.4m centres (Mazurkiewicz, 1980).

During travel the rollers, running against meehanite plates on the central guide-wall, hold the gate in the centre of the recess, approximately 2.5mm off each meeting face. The gate rests on steel plates 305mm wide and 63mm thick which slide on meehanite plates set in the concrete. *Structurally* the gate consists of two skins and four deck plates. The upper skin between A and B decks is 3.8mm thick and the remainder 2.5mm thick (Mazurkiewicz, 1980). The quoins and sill are provided with greenheart faces which bear on granite faces on the inner stop, precast concrete faces on the impounding stop and a dressed concrete face on the upper stop. To ensure water tightness a rubber L-shaped strip was fixed to the outer edge of the green heart-facing pieces (Mazurkiewicz, 1980).

Operationally manoeuvring the dock gate involves pumping ballast out of the caisson until the dock gate is set afloat and moves into its chambers. The pumping operation is carried out with four submerged pumps, each of 2,220 m^3/h capacity, setting the dock gate afloat within about 15 minutes. The layout of the suction and delivery pipes of these pumps also makes it possible to draw water from the dock or to empty an adjacent ballast compartment.

The dock gate is shifted by a longitudinal sliding motion, brought about by: (1) a 2-pile system, sliding vertically within frames attached to the outside face of the structure, and sliding horizontally within the steel grove; (2) a hauling trolley actuated by a 2-stroke 250KN winch. When actuated this trolley is attached on one side to a rail horizontally affixed along the gate garage. When the gate is being closed, operations are reversed. Precise sitting when stranding the gate is obtained: (1) transversely, by projecting stops which are integral with the sill and designed for guiding metal ball fitted parts on the underside of the dock gate; (2) longitudinally by bumpers on the wall of the pumping station (Mazurkiewicz, 1980).

4.3.2 Dry dock No.10., Marseilles, France

Another type of dock in this study is the dry dock No 10, in Marseilles, France, with dimensions of gate chambers as shown in Figure 4.3. The chamber walls are made as reinforced concrete walls and reinforced concrete angular walls supported on piles. Stability was ensured by installing ground anchors. This pre-stressed concrete structure has the following dimensions: length 87.35m, width 15m, height 13.5 m (Figure 4.4), where 1 is the guiding post, 2 is the service road, 3 is the sealing system, and 4 the bearing-panel block. In elevation, the dock gate consists of 28 identical cells, of 5.82m x 6.64m inner size, grouped into four ballast chambers (Mazurkiewicz, 1980).

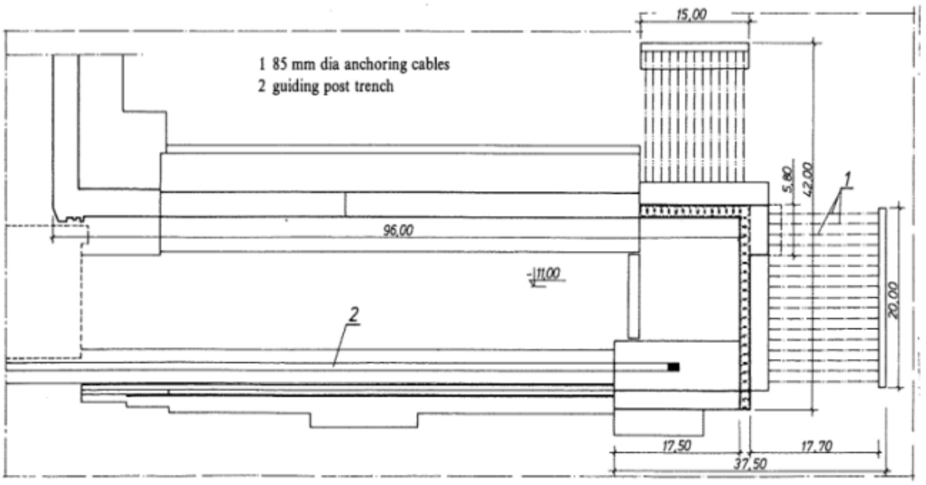


Figure 4.3: Dock gate chamber of the dry dock no. 10, Marseilles, France (Mazurkiewicz, 1980)

The dock gate is a self-stabilising pre-stressed concrete caisson that behaves like a gravity dam. When closed, the dock gate is supported along two lines: one on the seaward side conveying to the sill vertical reactions that compress the sealing system (Figure 4.5); the other on the dock side, transmitting the horizontal water pressure components in addition to the vertical reactions to the sill. Due to the sliding nature of these gates, the water pressure is transferred to the dry dock sidewalls and the sill. As a result of gate deformations, the greatest forces are transferred to the sidewalls at the water surface, and to the sill along the axis of the dock. This requires sealing on the side surface of the gate, which also influences the cross-section, which is generally rectangular (Mazurkiewicz, 1980).

To ensure the proper tightness it is advisable, in the light of the above remarks, to construct the sliding tracks so as to permit some side movement of the gate. During the sliding operation the gates are ballasted in such a way that their total reaction on the sliding tracks does not exceed 100 KN. They slide along rails on the dock sill on special wheels fastened to the bottom of the gate, or on rollers. They can also slide on smooth surfaces. In some cases the gate support is only a wooden or steel beam sliding on the smoothed bed surfaces or on loose rollers in special boxes (Mazurkiewicz, 1980).

Designs without rails will ensure better tightness of the gate because the gate, owing to its own weight and the ballast, will press towards the slide surfaces, thus creating additional horizontal tightness. The structure is entirely pre-stressed. The floor slab, the sidewalls and upper deck are pre-stressed in both directions (Mazurkiewicz, 1980). The cables employed are protected by rigid sheaths, the continuity of which is maintained by special sealed sleeves. The minimum draught of the dock gate (8m) permits it to be accommodated in any dry dock for repairs. Vertically, water-tightness is ensured by two metal vanes, rimmed with rubber and tightly squeezed flat by the water pressure. Water tightness at the base is ensured by a pre-stressed rubber seal, flanked and protected by pieces of azobe wood (Mazurkiewicz, 1980).

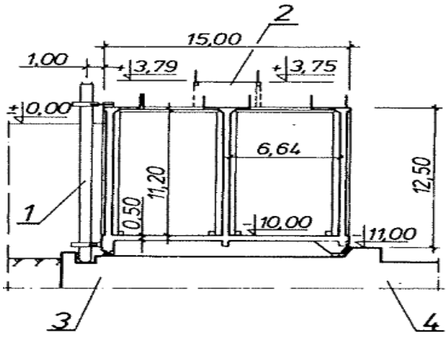


Figure 4.4: Cross-section of the dock gate

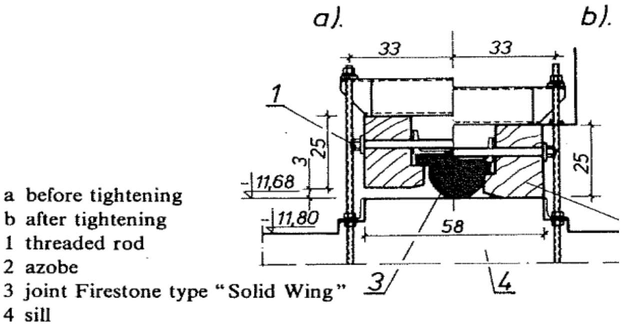


Figure 4.5: Sealing system (Mazurkiewicz, 1980)

4.4 The Application of a Fault Tree - Bayesian Network

4.4.1 Safety criticality software analysis

Hobbs and Developer (2012) of QNX software systems said, *'using Bayesian belief network to express fault tree, allows incorporation of both hard and soft evidence into analysis of a system in a quantifiable way.'* In applying the FT-Bayesian network to a neutrino microkernel a fault tree was developed guided by product history over the period 2002 to 2009. The top event was '*QNX Neutrino can fail'*. FT was mapped to Bayesian network to incorporate soft evidence about field failures rates, and calculate the resulting post-probabilities. Reports of failures in the field with field usage figures to estimate the failure rates were obtained and used in the fault tree. Sensitivity analysis was carried out to find the values to which the final result was most sensitive.

4.4.2 Feeding control system analysis

In 2011, Khakzad *et al*. (2011) compared Fault Tree and Bayesian Network approaches. Though this research took a 'comparing' approach, 'mapping' was the more efficient term to use. Using fault Tree and Bayesian Network as a failure analysis technique, the applicability of this approach to the performance of *'a feeding control system transferring propane'* from a propane evaporator to a scrubbing column was tested. All components were assumed binary (work/fail). Six basic events were identified and three intermediate events. Occurrence frequency data of primary events that would contribute to the occurrence of top events were assumed. Considering these probabilities, the prior probability of the top event was calculated as 0.270. '*Index improvement method*' was used to determine events with a higher index, by keeping some particular event absent. Again, mapping of Fault Tree to Bayesian Network was done to test FT-BN conversion approach. The prior probability was 0.270 using the '*Hugin Software*'. This improvement analysis showed the same results as FTA highlighted. In their work, Khakzad *et al*. (2011) further calculated the posterior probability to reflect the characteristics of an accident, claiming that '*posterior probability has advantages over prior probability*'. They further stated that '*posterior probability allows for updating using latest accidents information and abductive reasoning'*. Calculations to determine the posterior probability of root nodes were carried out and tabulated. In this same study, they made mention of '*posterior joint probability'*, and rounded up by indicating various modelling techniques in Bayesian networks such as multi-state variables and dependent approach with new variable. Finally, in comparison with other authors, this work was much detailed and gave solutions in dealing with expert opinions and other modelling techniques.

4.4.3 FPSO collision analysis

Carried out in the UK, this work was quantitative in nature with the use of FTA to calculate the occurrence of the top event and later mapped to the Bayesian Network for further analysis. A study was carried out by Eleye-Datuab (2005), where the transfer of oil from floating production storage and offloading (FPSO) oil tanker was examined. Collision rates were established relating to the varying ways a collision may occur. A fault tree was developed and frequency of collisions for FPSO was estimated. Using '*Hugin software'*, a Bayesian Network model was created, showing two influencing nodes, 'shuttle tanker' and 'support vessel', with one influencing node, 'collision-FPSO'. The model was run, giving 5% probability of impact and 95% probability of no-impact for 'collision-FPSO'. A scenario was then initiated in the model whereby the probability of impact was increased to 100%, and the probability of loss of shuttle tanker went up from 7% to 50%. From the point of view of using the software package, this research provided a detailed analysis.

The following are highlighted from the literature review: (1) the Hugin software and GeNieVer2.0 were applicable as reviewed, where the former is used for BN analysis, and the latter used as conversion algorithm software; (2) three authors were motivated to test the hypothesis that '*every fault tree can be converted to its corresponding BN'* for better analysis. The results studied proved successful. The use of the minimum cut set approach before conversion was observed. This was quite unusual, due to the fact that the model was not complex. This implies that a direct conversion algorithm may vary depending on the size of the model. The focus of all authors is mapping FT to a corresponding BN so that the advantages of using a BN can be further incorporated into the analysis.

4.5 Fault-Tree Bayesian Network Mapping Algorithm

A study on the conversion methodology is appropriate in understanding the building of the BN associated directly with the fault tree as seen in Figure 4.6 (Khakzad *et al*., 2011). In order to facilitate reasoning, two principles are suggested by Shao *et al*. (2011) as a 'MUST consider': (1) the nodes of the Bayesian network are associated with the events of fault trees; (2) the distribution of conditional probabilities in the Bayesian Network is the reflection of the logic gates in the fault tree. In mapping, detailed consideration should be given to the type of Boolean gate used. A simple representation Figure 4.7 presents the corresponding rule with nodes.

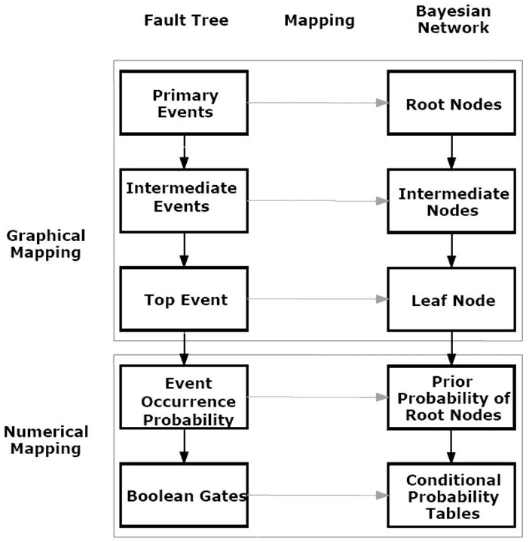


Figure 4.6: Mapping FT to BN

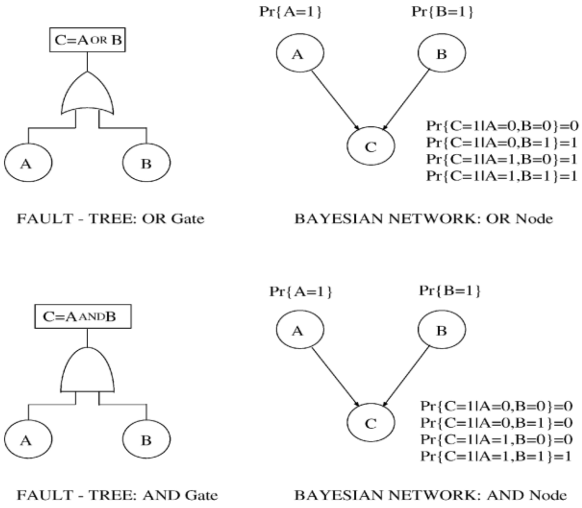


Figure 4.7: The 'OR' and 'AND' gate in FT and BN

With OR gates, P_r is [0, 1, 1, 1] and P_{r} [0, 0, 0, 1] for AND gates where P_r is probability of parent nodes' link to child. In reliability evaluation of a mechanical system, Bobbio *et al*. (2001) and Wojtek and Milford (2006) stated that building the Bayesian network is directly associated with its fault tree. Shao *et al*. (2011) further highlighted the difficulties in conversion process of large and complex systems. They stated, '*conversion needs to redraw the nodes and connect them while correctly enumerating their prior probabilities and conditional probabilities. Actually, it is not easy to accomplish this task in practice*.'

To overcome these difficulties, detailed work carried out by Wojtek and Milford (2006) titled '*An efficient framework for the conversion of fault trees to diagnostic Bayesian network models',* presented an observation list and fault tree. Fault trees, they said, '*deal[s] in truth'*, whereas diagnostic networks '*deal in observations of the truth.'* They further highlighted the need of a semantic checking and adjustment in the conversion process.

Wojtek and Milford (2006) are hailed as the masters of conversion from fault tree to Bayesian network, with the use of Graphical User Interface software with the aid of FT files created in "iGrafx" and BN files in ".xdsl". It is further claimed that this software, implemented entirely in C++ and running under Windows 2000 and XP, has been tested on a number of real-life FTs, ranging from small size nodes of 20 to 800 (Wojtek and Milford, 2006).

In brief, demonstrating how this software is utilised, '*the thermal control system'*, consisting of 23 nodes, was illustrated for conversion of fault tree to BN in their study. However, no researcher has implemented this software since its initiation in 2006, due to the fact that published FT-BN research has avoided the use of large nodes, hence using the available conversion algorithm based on basic conversion requirements.

First the FT is used to create the structure and parameters of the BN, then observation nodes from the observation list, which augments the domain knowledge contained in FT, are inserted into the BN on basis of the following: (a) the leaf nodes are independent of each other. Each node appears only once in the tree and two different nodes representing exclusive failure modes of the same component are connected with an XOR gate node, such as the states of valve: open and closed; (b) the FT nodes are interconnected by links, so that they form a directed tree.

Thus, for every two nodes there is a unique path connecting them – loops are not permitted; (c) the mapping algorithm study among the six researchers reviewed in this paper: one used four steps, two used five, and three used six steps in converting fault tree to corresponding

BN. The most elaborate of these for detailed reading and understanding is as referenced (Wojtek and Milford, 2006). It is however difficult to identify the originator of these steps. Four papers however reference Wojtek and Milford and dates from references point to them as authors. Though all drew inspiration from Wojtek and Milford's (2006) conversion algorithm, none used their proposed software. These steps include:

1. Create a corresponding node in the Bayesian network for each event in the fault tree.
2. Set the name and identifier of the corresponding node in the Bayesian network using those defined in the fault tree.
3. Assign to each node of the Bayesian network the corresponding different states, such as failure and success.
4. Connect those nodes of the Bayesian network as they are connected in the fault tree.
5. The root nodes of the Bayesian network correspond to the event nodes of the fault tree prior probabilities according to their respective states.
6. All the nodes that have parent nodes in the Bayesian network need conditional probability tables, which can be obtained from statistical data and expert experiences. This conversion algorithm however fails to stress the point where 'common failure' exist among nodes. Again, it fails to provide a re-numbering method when it comes to using its software to avoid getting wrong results and to construct the conditional probability table of posterior probability accordingly.

Step (7): a new step is introduced on nodes where FT-BN dependency is identified. If base event E8 and E9 are 'common failures', then its representation in BN is E8=E9 linked to the same node (either 'AND' or 'OR'), and a re-numbering system is suggested as 'E89', ensuing events unchanged as demonstrated in the illustrative example. This is very important, because the next numbering in the BN will remain unchanged hence keeping a constant correspondent in order to update information on the BN as data becomes more available.

The next section presents a simple conversion approach and the use of causal reasoning in the BN for risk modelling in dry dock gate failure, where the re-numbering system is seen with the term "E89". The next section presents an illustrative example of converting fault tree to Bayesian network and presents results under causal reasoning.

4.6 Illustrative Example

4.6.1 Dry dock gate failure analysis

In this illustrative study, FTA of a dry dock gate failure is constructed from the failure mode effect cause analysis (FMECA) of the original model established by Crougnieu *et al*. (2008) for detailed analysis. A dry dock gate seen under construction is shown in Figure 4.8, which reflects the size of this critical component in graving dry dock. The observation and functional lists of subcomponents of dry dock gate failure (DDGF) are seen in Figure 4.9. In risk analysis, a better understanding is given to designers and construction engineers regarding which subcomponents require more attention. Using FMECA methodology, the whole dock gate is assessed. This approach begins with a functional study of the system (integrating all its structural components and equipment), and covers a thorough identification and quantification of the potential failure modes. This process is called '*hazard identification'*, a first step of a formal safety assessment (FSA). The block diagram of DDGF highlighted in Figure 4.9 includes environment, solicitation, geometry or material. From the observation list, a total of 86 different potential failure modes taking into account all components and all expected functions were identified.

Figure 4.8: Dry dock gate construction

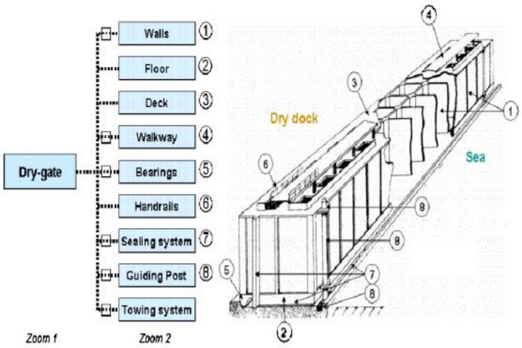


Figure 4.9: Functional analysis of gate failure

These are then quantified to find the critical ones. The most critical risks identified are (Bartllet *et al.*, 2009): (a) collapse of the dock gate caused by a resistance loss of passive re-enforcement, located in the wall on the dry dock side, and due to corrosion (mostly chloride attack); (b) collapse of the walkway caused by resistance loss of the main beams due to corrosion (chloride attack and carbonation); (c) dysfunctional bearings due to degrading properties. Constructing a fault tree from these observations, three failures: wall failure (*F3*), walkway failure (*F2*) and dysfunctional bearings (*F1*) are considered as sub-top events. Sub-event dysfunctional bearings can be caused by overheating (*Q1*) and lubrication failure (*Q2*).

The causes of overheating are spalling (normal fatigue failure) (*E1*) and resistance loss in hardness (*E2*). The causes of lubrication failure are restricted oil flow (*E3*) and degradation of lubricant properties (*E4*). This deductive process is carried out in a top down fashion for wall collapse and walkway, and a total of 13 basic events, ‘E6-13’ in Table 4.1, is presented. The corresponding Bayesian network is mapped from the fault tree constructed by using the conversion algorithm in section 4.5. A typical example of the conditional probability of node “Q” is presented in Table 4.2. Figure 4.10 and Figure 4.11 represent FT and BN respectively.

Table 4.1: The variable distribution and nodes of the DDGF network

Value	%	Node description		
Level of working condition		Description of nodes that can lead to the failure of the gate	Prior	Posterior
E1		Normal fatigue failure	27.00	28.23
E2		Resistance loss in hardness	27.00	27.38
E3		Restricted oil flow	27.00	27.45
E4		Degradation of lubricant property	27.00	27.45
E5		Wind load	54.00	55.15
E6		Hydrostatic load	27.00	27.61
E7		Carbonation attack of walk way	27.00	27.68
E8	89	Chloride ion attacks on walkway	54.00	56.00
E9	89	Chloride attack on walls	54.00	56.00
E10	10	Aggregated reactivity on walls	27.00	27.72
E11	11	Gradual formation of internal cracks on walls	27.00	27.61
E12	12	Efflorescence effects on wall	54.00	53.97
E13	13	Thermal effects	54.00	55.22
Q1		Overheating	43.50	44.42
Q2		Lubricant failure	43.50	44.13
Q3		Resistance loss of wall way main beam	57.22	59.38
Q4		Walkway corrosion	57.22	59.69
Q5		Wall corrosion	59.14	59.80
Q6		Resistance loss of passive re-enforcement of walls	54.00	61.25
F1		Dysfunctional bearing	22.14	24.02
F2		Walkway failure	72.00	76.54
F3		Wall failure	73.88	78.51
R		Dock gate failure	85.45	100

Table 4.2: Conditional probability table for Q1, E1 and E2

E1		**E2**	
F	30	f	30
W	70	w	70

	Q1			
E1	f		F	
E2	f	w	f	w
F	85	80	80	10
W	15	20	20	90

4.6.2 Probability of failure under no evidence

Assuming that the prior probabilities of all these events occurring are less than 23% and 54% when the dry dock gate operates at ground position, this means there is no fault produced by the level of working conditions. The happening probabilities of faults are listed in Table 4.1 under the condition of no evidence. The conditional probability table is constructed and figures entered into the *Hugin* software. An example of the conditional probability of node ‘Q1’ is seen in Table 4.2. All probabilities of the faults are lower than 55%. The occurrence probability of system fault P (R) is 85.5%, which means the ‘gate’ operates normally and no fault occurs. The results are the same as engineering experience.

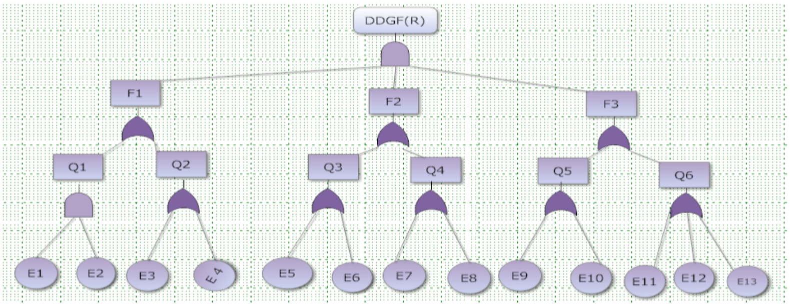


Figure 4.10: Fault tree of DDGF

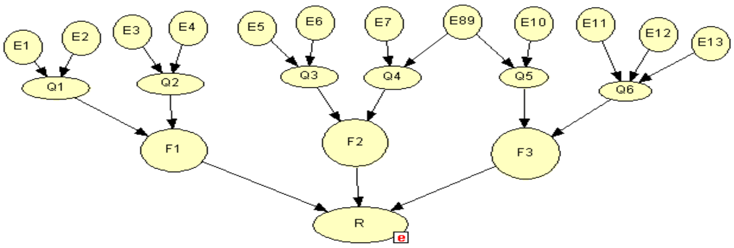


Figure 4.11: Bayesian conversion mapping diagram of DDGF

4.6.3 Probability of failure under given evidence

The reasoning and diagnostic ability of the DDGF network is checked under given evidence. Suppose that the system has a fault occur corresponding to ‘*P(R) = 100%’,* the new posterior probabilities results of working conditions are listed in the furthest column of Table 4.2. The posterior probability of E89 is 56.07%, which is the largest among those components’ failure probability under the condition of system failure. Therefore, in conclusion, E89 is the weakest part in the DDG system and needs to be strengthened in order to enhance the overall system reliability. The list from the second greatest to seventh is as follows: *E13*, *E5*, *E12*, *E1*, and E7, with values 55.22%, 55.15%, 53.97%, 28.23% and 27.68% respectively.

4.6.4 Probability calculation under causal reasoning

For causal reasoning, system failure probability is different in each component failure. In Table 4.1, we see that different components have different reliabilities in the DDG system and have their corresponding effects on the whole system reliability. Therefore, by the Bayesian network model, we can find the weak links of the system in order to provide the basis to improve the reliability of the whole system, by means of strengthening the reliability of the weak components in its design and constructing a process starting from the order E89, E13, E5, E12, E1 and E7. To demonstrate the reliability if E89 fails 100% then failure probability of top event DDGF is 89% and if E13 fails 100% then top event probability is 87.38%, as highlighted in Figure 4.12.

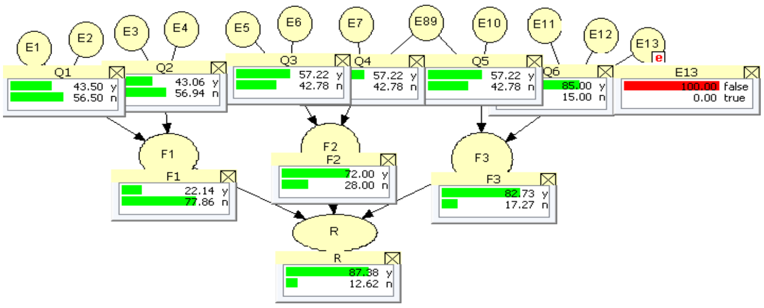


Figure 4.12: DDFE top event 85% when event E12 fails 100%

4.6.5 Recommendations

Recommendations based on the analytic results and experience of the three main ways to prevent failure of dry dock gates, when in a ground position and during the closing and opening operation are presented. To help prevent future failures and manage resources for construction and maintenance effectively, these critical failures can help build a maintenance pattern with financial estimation beginning with reinforcing corrosion attacks on walkways and walls (E89) during the construction phase of the project in Figure 4.11 as top priority (such as passive re-inforcement corrosion, pre-stressing cable corrosion and anti-carbonation and chloride prevention attacks). The next recommendation, as indicated from the analysis results, is to channel resources into improvement of inspections of all submerged areas and underwater inspections to identify effects of salt deposits on structures (E12). In the construction phase, it is better to consider these parameters and improve on pre-stressing conditions of walls. Again, focus should continue in ranking order E5, E12, E1 and E7 as obtained from analysis. These strategic decisions are based on concrete, objective and traceable detailed analysis as illustrated in this study. However, the limitations of this simple example are when dealing with a large model, and how to construct its corresponding CPTs.

4.6.6 Fault Tree-Bayesian Network framework

The construction of BN could be quite complicated and its network structure is problem specific. It is more advantageous to construct BN hierarchy following the concept of FTA and then transforming basic FT to BN framework. Finally, lateral links among BN nodes and conditional probability table (CPT) were introduced to incorporate expert's experiences. The two major steps for the proposed methodology are: (1) structure transformation from FT to BN; and (2) CPT determination.

4.6.6.1 Structure Transformation from FT to BN

Top event, intermediate events, and basic events are directly mapped into the nodes in BN. The arrows among BN nodes follow the definition of event relationships in FT. Furthermore, some meaningful auxiliary arrows can be inserted into fundamental BN based upon the experts. In summary, the transformation process of BN structure from FT is presented in Figure 4.13.

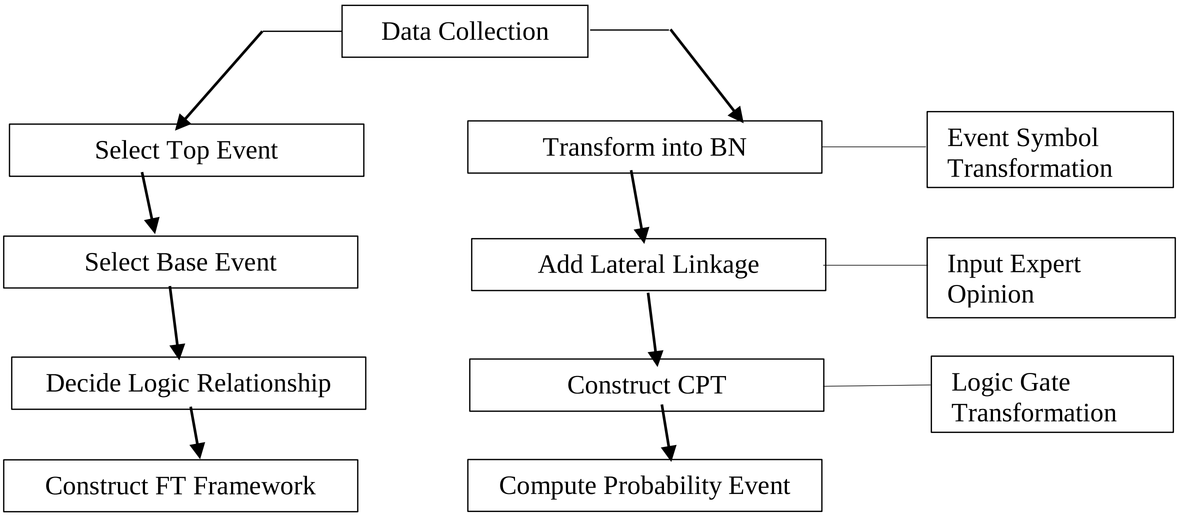


Figure 4.13: Flow Chart for FT-BN transformation

4.6.6.2 CPT Determination

In a BN framework, if the node has several parent nodes, or if each parent node and child node has several states, the CPT structure will become complicated. In addition, the values of CPT are generally defined by experts based on their experience, the probability values could be inconsistent especially under the condition of complicated CPT stated above. In this study the software, AgenaRisk, was used to eliminate the above mentioned difficulites (Agena, 2012). Through parameters defined in the software, coupled with weighting factors filled by experts among nodes, one can calculate probability values of the CPT rapidly.

4.7 Problems of Constructing a Large Bayesian Network in Risk Analysis

A typical task for the reliability analyst is to give input to a decision problem. An example in this study is to examine the effect that environmental conditions have on a dry dock gate's time to failure, and give this as input to a maintenance optimisation problem (Langseth and Portinale, 2007). The problem also includes the uncertainties or the random fluctuations of other quantities included in a dry dock gate failure model.

The model must be mathematically sound, and at the same time easy for the decision maker to understand. Furthermore, such models require a set of parameters to be fully specified, and either statistical data or expert judgement must be used to estimate them. Finally, the model must be represented such that the interested quantities can be calculated efficiently (Barlow, 1988). To overcome the challenges of representation, the FT-BN method is used and to overcome the challenges of better quantification, a method of ranking subjective nodes from experts' elicitation using WieghtedMin truncated normal distribution (TNormal) is adopted in BN to easily calculate and represent the priori probabilities and NPTs of corresponding nodes.

All these requirements have led to reduced focus on traditional frameworks like fault trees (FTs), and more flexible modelling frameworks such as Bayesian network (BN) models have gained popularity over the last decades (Langseth and Portinale, 2007). Nonetheless, there exist some challenges in building large-scale BN models when dealing with discrete variables. In discrete variables the conditional probability distributions (CPDs) can be presented as node probability tables (NPTs), which list the probability that the child node takes on each of its different values for each combination of values of its parents. Since a BN encodes all relevant qualitative and quantitative information contained in a full probability model, it is an excellent tool for many types of probabilistic inferences, where it is required to compute the posterior probability distribution of some variables of interest (Neil and Cabaliero, 2007).

In the applications of BN involving building extremely large-scale BN models, there are difficulties encountered in developing NPTs such as relying on purely "handcrafted" approaches, in which each variable and each NPT needs to be elicited exhaustively with domain experts (Neil and Cabaliero, 2007). The previous section in this study was to overcome the challenges of mapping fault tree to Bayesian network and presenting its advantage. Then causal reasoning was used in an illustrative case study with limited nodes to validate this approach. In large BNs however the main challenge is to produce prior probabilities and appropriate NPTs for each node that make the most of limited expert elicitation and limited statistical data. A new risk assessment model is built up on the basis of BNs shown in Figure 4.14, with some special merits in the context of risk assessment. A typical sequential process of a BN model contains six major stages from problem definition to validation of BN. After problem definition, the problem description fragments provided are matched by the expert against idioms. In this process the problem fragments are made concrete as idiom instantiations, which are then integrated into objects. The next step is to elicit and refine the NPTs for each of the nodes in each object. The objects are then integrated to form the complete BN and inferences made and tests run for validation purposes. Ideally, real test data/expert opinions not used in deriving the BN model (Neil and Fenton, 2012).

At each stage a verification step takes place to determine whether the output of the stage is consistent with the requirements of the previous stage and the original problem. Failure to pass a verification step results in the innovation of a feedback step that can return the process to any previous stage. For example, it might become obvious to the expert when building the NPT that the BN object may not be quite right. In such a case the idiom instantiations may be redefined. For verification and validation a number of tests are performed to determine whether the BN is a faithful model of the expertise and whether the expert's opinions match real data (Neil and Fenton, 2012).

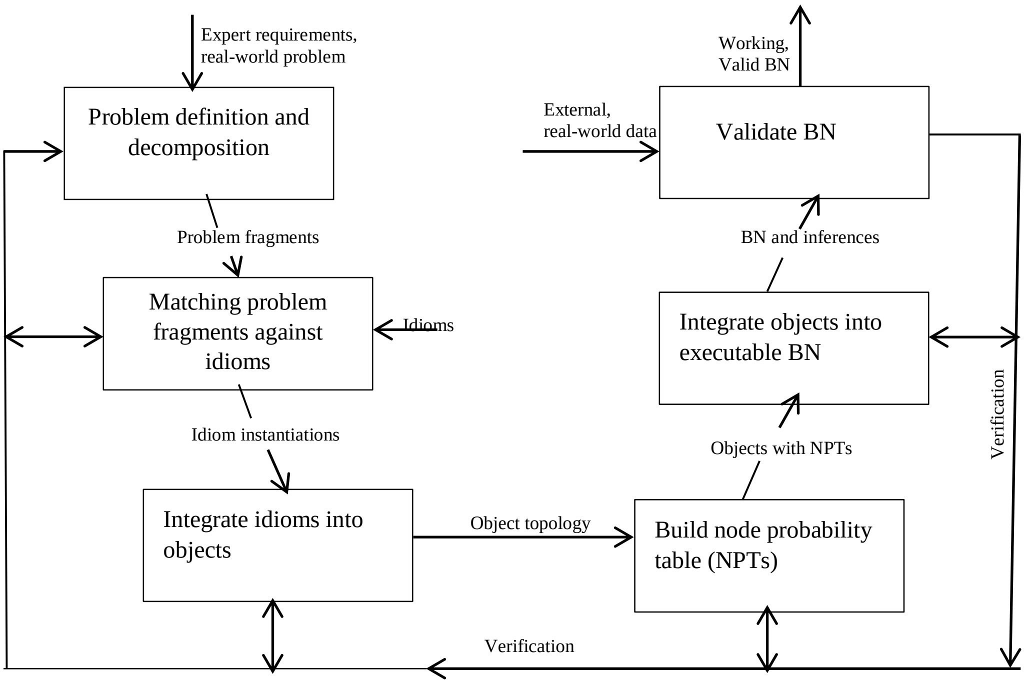


Figure 4.14: Typical BN risk assessment

4.7.1 Idioms

An idiom is defined by Webster's dictionary as 'The syntactical or structural form peculiar to any language; the language or cast of a language.' The term idiom is used to refer to specific BN fragments that represent very generic types of uncertainty reasoning. For idioms the interest is only on the graphical structure and not in any underlying probabilities. For this reason an idiom is not a BN as such but simply the graphical part of one. Four types of idioms have been used to speed up the BN development process: *cause consequence idiom*, *measurement idiom* and *definitional/synthesis idiom* and *the induction idiom* (which models the uncertainty related to inductive reasoning based on populations of similar or exchangeable members). Idioms act as a library of patterns for the BN development process. Experts simply compare the current problem, as described, with the idioms for dry dock gate failure. By re-using the idioms an advantage is gained of being able to identify objects that should be more cohesive and self-contained than objects that have been created without any underlying method (Neil and Fenton, 2012). Only the induction idiom (fault tree) is used to make some useful predictions in dry dock gate failure over using an observed population (study) taking account of differences in context. The key difference here is learning an unknown or partially known parameter of dry dock gate failure from some known data (expert elicitation).

4.7.2 Challenges of constructing a conditional probability table (CPT)

Consider a typical BN structure (Figure 4.15) characterised by the fact that node values are typically measurable only on a subjective scale like (lowest, very low, low, medium, high, very high, highest) and only extremely limited statistical data (if any) is available to inform the probabilistic relationship of U, given V_1 and V_2. However, there is significant expert subjective judgement that can be used.

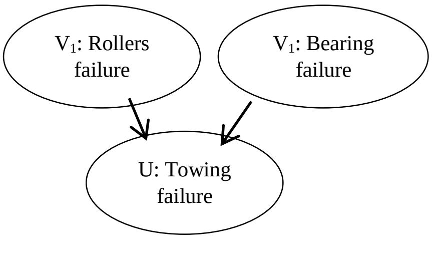


Figure 4.15: Typical qualitative BN fragment of a graving dock gate

Assuming that each of the nodes has seven states (in the many commercial studies experts are rarely satisfied with three), the NPT for node U has (7 x 7 x 7) 125 states. This is not an impossible number to elicit exhaustively, but some inconsistencies arise when experts attempt to do so, and if the node U has additional parents, then elicitation becomes infeasible and exhaustive especially as real-world models involve dozens of fragments (Fenton *et al*., 2007).

Hence the problem and challenge is to produce an appropriate NPT for the node U that makes the most of limited expert elicitation. This problem is certainly not new, since it has been addressed in Wellman (1990), Druzdzel and Gaag (1995) and Takikawa and D'Ambrosio (1999), and there have been serious studies on *specific elicitation techniques* (Maybeck, 1979; Laskey and Mahoney, 1998; and Gaag *et al*., 2002). Also, the Noisy-OR (Huang and Henrion, 1996) and Noisy MAX (Diez, 1993) methods are well established as a standard way of encoding expertise in large NPTs. Noisy-OR has the disadvantage that it applies only to Boolean nodes and implicitly ignores the interaction effects between variables. Noisy-MAX, despite the fact that it applies to ranked nodes with many states, does not model a certain range of relationships (Fenton *et al.,* 2007).

There is a large body of literature covering the psychological biases encountered during elicitation and use of probability values. Such biases often arise through an inappropriate or misleading question choice and depend on how the problem and question are framed. In BN literature, there are few relevant papers that describe experimental results gained from applying different probability elicitation. One paper by Zagorecki and Druzdel (2004) found that human experts produce better results when Noisy-OR parameters were elicited rather than complete NPTs. Also, Renooij (2000) gives a very good overview of a number of different methods that can be used for elicitation, including probability wheels and the verbal-numeric response scale. The role of elicitation in the whole model-building process and the inherent challenge encountered is not considered in this study due to size restrictions. So this study addresses only one type of probabilistic relationship that one might want to build into a BN. This approach is complementary to the elicitation methods, and for the purpose of quick comparison, the differences are given as follows (Fenton *et al.,* 2007): ranked nodes are useful when representing ranked relationships in NPTs involving nodes that are near continuous; Noisy-OR is useful in cases involving Boolean nodes; the verbal-numerical response scale is useful for relationships when nodes are labelled.

4.7.3 Ranked nodes approach

Ranked nodes represent discrete variables whose states are expressed on an ordinary scale that can be mapped onto a bounded numerical scale that is continuous and monotonically ordered. All ranked nodes are defined and labelled on an underlying unit interval [0, 1]. The crucial thing about ranked nodes is that they can make the BN construction and editing task much simpler than is otherwise possible. In particular, provided that they appear in the appropriate combinations described below, the normally complex task of constructing sensible associated NPTs is drastically simplified.

In some situations experts typically want to complete an NPT by using a '*simple averaging scheme'* to compute the maximum or minimum value as a guide to defining the 'central tendency' of the child node based on a set of casual parent node values. In other studies, in attempting to construct the NPT for node like U, an approach based on sampling values in expert elicitation assertions is presented as follows: when V_1 and V_2 are both 'very high' the distribution of U is heavily skewed towards 'very high'; when V_1 is 'very high' and V_2 is 'very low' the distribution of U is centred above medium (Fenton *et al*., 2007).

Since each node has an underlying numerical scale in the interval [0, 1], such assertions suggest intuitively that U is some kind of weighted average function. In fact, experts found it easier to understand and express relationships in such terms. Many so-called 'self-assessment' or 'scorecard' systems are based around little more than the weighted averages of attribute hierarchies. However, such systems are usually implemented in spread sheet-based programs that have associated with them a number of problems: difficulty in handling missing data, problems with assessing credibility of information sources, and difficulty in using different scales (Fenton *et al.*, 2007).

Since all of these problems are readily solved using BNs, the challenge is to provide the appropriate BN implementation that captures the explicit simplicity of the weighted average while also preserving the intuitive properties that the resulting distributions have to satisfy. For example, simply making U the (exact) weighted average of its parents does not work, since the only uncertainty in the distribution of U, given its parents, will be the result of discretisation inaccuracy rather than deliberate modelling. What is especially tricky to model properly are the intuitive beliefs about the causes, given certain child observations, that is, the so-called "*back propagated beliefs".*

For example, suppose we have observed U and V_1 and wish to infer the value of V_2 as follows: if U is 'very high' and V_1 is 'very low' then we would be almost certain that V_2 is 'very high' but not as confident as in the above case. In this light a straightforward solution for defining the NPT for P(U/V) (where V represents the set of parent variables V_1, V_2, ……V_n) in such a way that these various properties are all satisfied is provided by the Truncated Normal distribution, described next (Fenton *et al.*, 2007).

4.7.4 Using doubly truncated normal distribution for modelling ranked nodes

Formally, the ranked nodes' casual structure is characterised by a joint probability distribution with a set of causes V containing $i = 1, 2, \ldots..n$ ranked nodes V_i as the parents of U (Fenton et al., 2007):

$$P\ (V, U) = p\ (U/V) \prod_{i=1}^{n} P(Vi) \tag{4.5}$$

In general, the node V is considered to be a consequence of two or more cause nodes, where each of the cause nodes is assumed to be independent when calculating the NPT. The BN in Figure 4.15 is a very simple fragment of a large BN structure of dry dock gate failure. Drawing an analogy with linear regression, where $y_i = \beta x + \in$, with $\in$ approximating a Normal distribution of mean 0 and variance σ_Y^2 (written $N(0, \sigma_Y^2)$), and where the contribution to the variance of Y is σ_Y^2. The regression analogy is apt, since we are attempting to "*target*" the area of central tendency in U, given different values of V_i and then are adding a fixed amount of uncertainty around this. The only issue is to resolve the contribution of each cause to the effect, and a clear way to do this is to use the correlation between the cause and the effect as the appropriate measure (Fenton *et al.*, 2007). Rather than the Normal distribution commonly assumed in linear regression for ranked causal nodes, the doubly truncated Normal distribution (denoted *TNormal* hereafter) is used as defined by Cozman and Krotkov (1997) where all nodes are truncated in the [0,1] region.

Unlike the regular Normal distribution (which must be in the range – infinity to + infinity), the TNormal has finite end points. We denote the TNormal by TNormal $(\mu, \sigma^2, 0, 1)$ where μ is the mean, and σ^2 is the variance. The TNormal starts with a regular Normal distribution but "ignores" the probability mass to the left and right of the finite end points and then normalise the resulting distribution over the finite range [0, 1]. This enables us to model a variety of shapes, including a uniform distribution, achieved when the variance $\sigma^2 \rightarrow \infty$, and highly skewed distributions, achieved when $\sigma 2 \rightarrow 0$. A '*simple weighted sum model*' is used to measure the contribution of each U_i to explain V as a "credibility weight" w_i (it can also be elicited from an expert in this way) expressed as real values $w_i \geq 0$. The higher the '*credibility index'* the greater the correlation between U_i and V. Thus, in this method, the equivalent to the error variance σ^2_Y in the linear regression model is simply the inverse of the sum of the weights (Fenton *et al.*, 2007):

$$\sigma^2_Y = \frac{1}{\sum_{i=1}^{n} w_i} \tag{4.6}$$

Given that,

V lies within [0, 1], normalising the regression equation $E(V) = \sum_{i=1}^{n} w_i U_i$ by dividing with $\sum_{i=1}^{n} w_i$. Thus:

$$P\,(V/U) = \text{TNormal}\left(\frac{\sum_{i=1}^{n} wiXi}{\sum_{i=1}^{n} w_i}, \frac{1}{\sum_{i=1}^{n} w_i}, 0, 1\right)$$

Suppose, for example, that $n = 3$ and that the allocation of weights w_i for each V_i's contribution to explaining U is in the ratio 2:3:5, with variance $\sigma_Y^2 = 0.001$. The resulting distribution and BN model are shown in Figure 4.15 and the joint distribution generated will be:

$$P(U/V) = TNormal\left(\frac{200V_i + 300V_i + 500V_i}{200+300+500}, \frac{1}{200+300+500}, 0, 1\right)$$

$$= TNormal\left(\frac{2V_i + 3V_i + 5V_i}{10}, 0.001, 0, 1\right)$$

It should be noted that the resulting distribution for *p* (U) will not produce summary statistics exactly matching the function because the coarse discretisation is used in arriving at results. Given this, the mean values will tend to differ within the bin range specified. Specifically, for seven ranks defined on [0-1], the mean value may be out by up to 0.1. Figure 4.16 presents the Wieghted mean (WMEAN) function for U1. Also, the variance values observed will be considerably higher because of the coarse discretisation. However, neither of these are major problems since the aim is to produce a good fit to the experts' distribution rather than a good approximation to a TNormal distribution (Fenton *et al.*, 2007). This approach is only designed to cover unimodal probability distributions

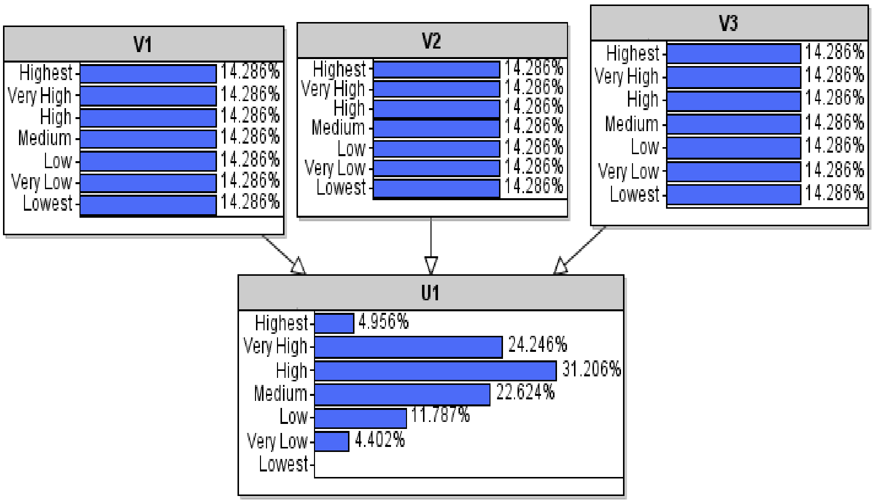


Figure 4.16: WMEAN function for U1, given V1, V2, and V3

4.7.5 Modelling ranked nodes using min and max

The weighted average is not the only natural function that could be used as a measure of central tendency in the ranked caused model. Suppose the BN fragment in Figure 4.16 is revisited. In this case we elicit the following information:

- When V_1 and V_2 are both “very high,” the distribution of U is heavily skewed toward “very high.”
- When V_1 and V_2 are both “very low,” the distribution of U is heavily skewed towards “very low.”
- When V_1 is heavily skewed toward “very low,” and V_2 is “very high,” the distribution of U is centred towards “very low.”
- When V_1 is heavily skewed toward “very high,” and V_2 is “very low,” the distribution of U is centred towards “low.”

A weighted sum for U will not produce an NPT to satisfy these elicited requirements. Formally, U’s mean is something like the minimum of the parents’alues, but with a small weighting in favour of V_1. The necessary function, which we call the weighted min function (*WMIN*), has the following general form:

$$WMIN = \min_{i = 1.....n} \left(\frac{w_i X_i + \sum_{i \neq j}^{n} X_j}{w_i + (n-1)} \right) \tag{4.7}$$

where $w_i \geq 0$ and n is the number of parent nodes, with a suitable variance σ^2_Y that quantifies our uncertainty about the result, thus giving P (U/V) = TNormal [*WMIN* (V), σ^2, 0, 1]. The *WMIN* function can be viewed as a generalised version of the normal *MIN* function. In fact, if all of the weights w_i are large, then *WMIN* is close to *MIN*. At the other extreme, if all the weight $w_i = 1$, then *WMIN* is simply the average of the X_i’s. Mixing the magnitude of the weights gives a result between a *MIN* and an *AVERAGE*. In the above example, taking $w_1 = 3$ and $w_2 = 1$ (with a variance $\sigma^2_Y = 0.01$) yields the results as shown in Figure 4.20. The analogous *WMAX* function can also be used:

$$WMAX = \max_{\forall i=1...n} . \left(\frac{w_i X_i + \sum_{i \neq j}^{n} X_j}{w_i + (n-1)} \right) \text{where } w_i > 0 \tag{4.8}$$

Finally, the function *MIXMINMAX*, which is a mixture of the classic MIN and MAZ functions:

$$\text{MIXMINMAX}= \frac{w_{min} MIN(\text{V}) + w_{max} Max(\text{V})}{w_{min} + w_{max}} \text{ where } w_{min} \text{ and } w_{max} > 0 \tag{4.9}$$

In each case, the experts need to only supply the parameters to generate the NPT. This set of functions has been sufficient to generate almost the entire ranked node NPTs elicited in practice. The efficiency savings are considerable: if there are *m* ranked cause nodes, each with *n* states, then the experts need to only supply $(m + 1)^n$ values for full elicitation. It should be noted that ranked nodes can be further partitioned by declaring additional labelled, Boolean or numeric parents that can be used to condition the type of weighted expression that one might wish on the child node. Figure 4.17 presents the WMIN function for U1.

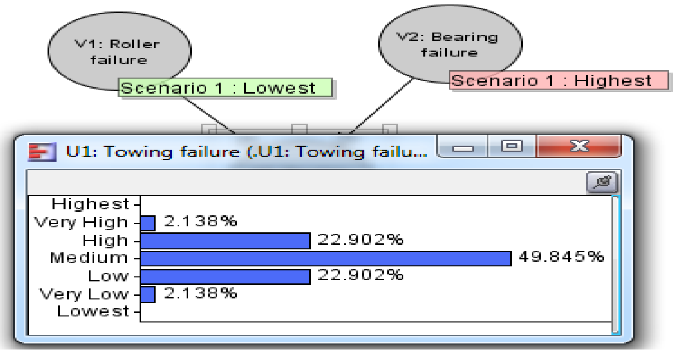
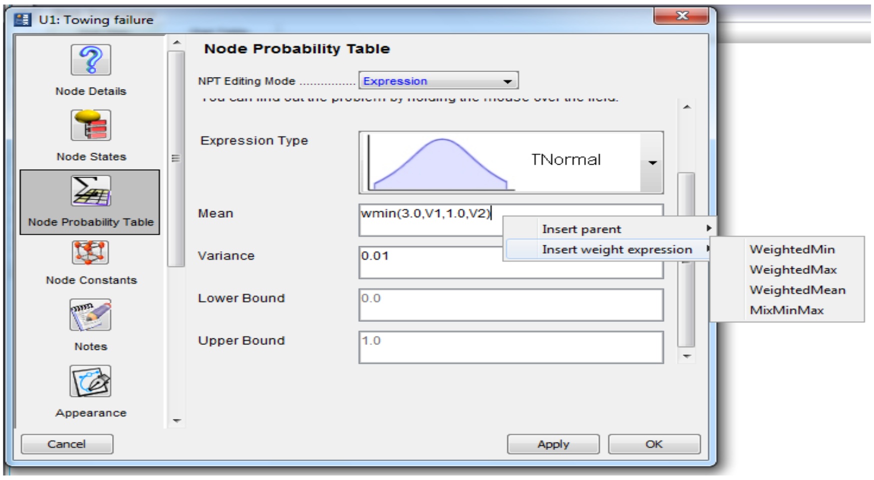


Figure 4.17: WMIN function for U1

4.7.6 Creating ranked nodes using AgenaRisk software

The AgenaRisk software comes with an easy to use graphical user interface (GUI) and provides applicable programmer's interface (API). It can be used as a robust BN programming environment for modelling and interference (Fenton *et al*., 2007). While AgenaRisk software makes it easy to key the input and read the output of the network by providing a graphical representation of the properties of each node as a bar graph, there is usually a general strategy of using AgenaRisk with TNormal applications to rank nodes. A weight declaration in AgenaRisk is presented in Figure 4.18.



NPT Editing Mode .... Expression

Expression Type TNormal

Mean wmin(3.0,V1,1.0,V2)

Variance 0.01

Lower Bound 0.0

Upper Bound 1.0

Figure 4.18: Declaring a rank weight expression for a node in AgenaRisk

For the purpose of building realistic NPTs that adequately capture expert judgement, the existence of a good theoretical approach is insufficient. Good tool support is also needed, and successful use of ranked nodes must be supported by a reliable tool that (Fenton *et al*., 2007): (1) enables domain experts without any statistical knowledge to quickly and easily generate distributions and; (2) provides instant visual feedback to check that the NPT is working as expected. The AgenaRisk software satisfies these requirements. Constructing the necessary NPT requires experts only to go through the following simple steps in AgenaRisk (supported by the dialogue shown in Figure 4.17):

1. Select the NPT property for a given node and declare that the NPT is defined by an expression. The TNormal distribution is automatically selected.
2. Either type in the full weighted expression or access the Dialog by a simple right mouse click, as shown in Figure 4.17.
3. Complete the appropriate weights via the dialog presented by selecting the parent nodes by using a slider bar to define the weight’s values and the certainty.

4.8 Risk Analysis of a Large Dry Dock Gate failure Model (Case Study)

The proposed methodology is a combination of different techniques already used. Proposals of different authors and several techniques are combined to compose the methodology, which resulted in the formation of the four-step process: familiarisation, qualitative and quantitative analysis (inteference), complementary analysis and verification. Table 4.3 presents an overview of the methodology steps.

Table 4.3: BN comprehensive framework

Step 1 Familiarisation	Step 2 Qualitative analysis	Step 3 Quantitative analysis	Step 4 Complementary analysis	
Understanding the system. Identify possible scenes that the system will be submitted to	Represent the system Physically and Functionally, Represent the Relationship between System elements	Completing the Construction with Quantitative data Probabilities (CPT) Estimating the Probability of system Failure and reliability	Analysing the criticality Analysing different Scenarios Analysing the Conditional reliability	Tasks
Data reviews: Interview with experts	Functional tree: Fault tree Bayesian network	Bayesian network (Inference)	Bayesian network (Posterior probability)	Means

Table 4.4 is divided into two parts, the first in which all the tasks to be performed at each step are listed and the second which lists the means suggested for these tasks. In the first step, familiarisation, all the information available about the sliding dry dock gate failure must be collected. The second step, qualitative analysis, is the step at which the relationship among the system and components is identified from the induction idiom to build the appropriate fault tree. In the quantitative analysis, the priori probabilities of the root nodes and the conditional probabilities tables for non-root nodes are defined allowing the evaluation of the joint probability of a set of variables. Finally, a complementary analysis must be performed by evaluating the posterior probabilities, criticality analysis, the analysis of different scenarios of interest and the conditional reliability analysis. These analyses allow improving the reliability analysis through an evaluation that is not possible through traditional tools. The criticality analysis means to find the set of components or subsystems that have greater influence in the system behaviour; the analysis of different scenarios can be used to model any situation of interest, such as the impact of including redundancies, the impact of a component fault or any other conditions that affects the system reliability; and the conditional reliability analysis provides information about the system's behaviour over time

4.8.1 Application to sliding dry dock gate at Birkenhead, UK

In this section, the reliability analysis of a 'sliding dry dock gate failure' is performed by using the methodology presented. First, information collected about the system is presented. Then, the qualitative analysis is performed. Subsequently, a quantitative analysis will be conducted, in which the limitations of using *failure probability density* and the *system reliability are estimated for a given mission time of the system* are overcome by using readily available subjective data from expert judgement. The AgenaRisk (Desktop Agena Risk, 2011) was used to build the BN and to make the inferences about the system. Finally, the complementary analysis is presented to validate the results as appropriate.

4.8.2 Familiarisation- sliding dry dock gate failure at Birkenhead, UK

Usually the dry dock gates are used for opening and closing the graving dock for docking a vessel for repair purposes. The ageing structure of these gates increases the hazards due to an unforeseen operation scenario. Accident in this process may lead to uncontrolled flooding of the dock causing very severe consequences. In the dry dock gate studied, a 'sliding gate' must be subject to detailed complex static calculations in order to check the *structural elements* and *interactions of various elements* during design to ensure proper gate installation. The tightness of a sliding gate in Birkenhead Shipyard depends on individual elements presented, yet is not limited to those highlighted in Figure 4.19 for this study. It must be noted that some of these components operate in the same environment while others have the same causes and effects on the system. A detailed description is discussed in section 4.3.1. The Birkenhead sliding dry dock gate operates to fulfil the following objectives: (a) great tightness for all loading causes; (b) short opening and closing times; (c) easy servicing and maintenance; (d) mechanical reliability; (e) monitoring of the gate position during opening and closing; (f) minimum operation and maintenance costs in a minimum life span of twenty (20) years. The induction idiom (fault tree diagnostic idiom) is used in this study, because none of the reasoning in the induction idiom is explicitly causal. Specifically, the idiom has two components (Fenton and Neil, 2012): (1) it models Bayesian updating to infer the parameters of the study where the entities are assumed to be exchangeable; (2) it allows the experts to adjust the estimates produced if the entity under consideration is expected to differ from a real-life situation. The aim of this functional list is to provide guidance in the development of various events that can lead to a sliding dry dock failure. Understanding the risk model can lead to effective risk control measure hence improving mechanical reliability, maintenance and operation cost, easing servicing, and monitoring gate tightness for all possible loading cases.

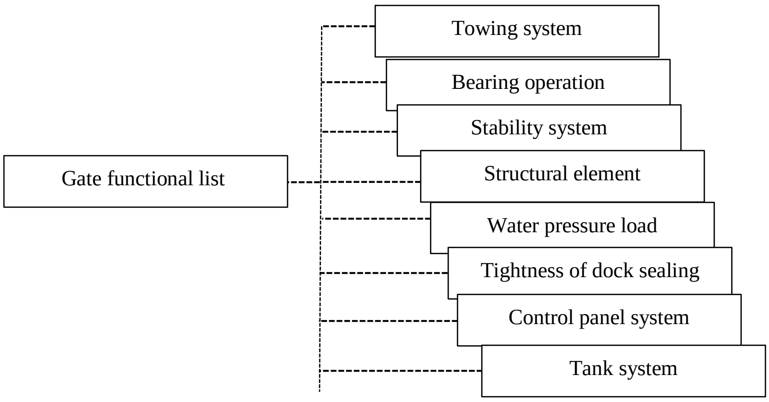


Figure 4.19: Functional list for sliding dry dock gate failure mode

Outside the dry dock gate system, the top deck contains the driving winch, control panel, tank gauges, and ladders. The *control system* in the dry dock might fail, leading to breakdown time. Likewise, there could be a failure of the *driving winch*, and *tank gauges*. Failure of *tidal flaps* can be caused by failure of wires or flap valves. This can lead to increased buoyancy in the upper chamber. In the air chamber, are the *rollers*, which can fail due to lack of proper maintenance. The tanks' failures include: *trimming tanks* might leak leading to improper even dock trimming, the t*wo scuttle tanks* might leak leading to the gate not being able to seat in position when normally full. When it is desired that these two tanks are empty the water in the scuttle tanks can be blown out by air pressure. If not well flooded, these tanks *can reduce dock gate stability* leading to *increased movement of the dock due to wave action.* Also, *pumps* might fail, and there could be a *blockage in the delivery pipes* of the system. This system must have sufficient strength during operation to avoid unexpected water pressure outside or a failure of any individual component which could result in possible rupture of the structure. The next step is to develop a fault tree to represent a typical sliding dry dock gate failure model.

FTA involves quantifying risk from knowledge of how risk events (faults or failures) in the dry dock systems propagate to cause accidents or hazards. The idea is that the functional specification of the sliding graving dock gate can be decomposed into intermediate components/functions that, should they fail, whether individually or together, would lead to the hazard occurring. Fault trees are therefore composed from events with relationships that connect the events together, reflecting what we know about how faults are likely to interact and propagate. In classic FT diagrammatic notation, special shapes are adopted to visually indicate the type of Boolean logic to express the model. The scenarios are those combinations of primary events expressed in 'AND' or 'OR' logic gates as comparative statements involving Boolean logical test. Because BN tools like *AgenaRisk or Hugin* implement expressions for the Boolean operators, it is simple to perform FTA analysis using a BN.

In the gate failure functional list, there are eight (8) immediate causes (U) that can lead to its failure. These are: towing system failure (U1), bearing failures (U2), stability issues (U3), structural element failure (U4), loads from water pressure (U5), tightness of dock sealing joints (U6), control panel failure (U7), and tank issues (U8). The primary events that can lead to immediate towing system failure are: rolling rails (V1), rollers (V2) and system failure (V3); the bearings failures (U2) include air chamber inaccessibility (V4) and roller failure (V5); causes of stability issues (U3) include flap valves failure (V6), ballast tanks (V7) and wires (V8). The causes of structural element failures (U4) are: floor failures (V9), walls failure (10), handrails failure (V11), and ladder failure (V11). The causes of increased load from water pressure (U5) are: increased sea state (V13), high tide (V14), and hurricane *(*V15). The causes of improper dock tightness (U6) are: failure of rubber L-shape (V16), increased sea state (V17), and hurricane (V18). The causes of control panel failure (U7) are: level water (V19), control system (V20), and undetectability (V21). The causes of tank failures are: trimming tanks (22) scuttle tanks (23) and scrum tank (24). Multiple experts (Appendix 4) are consulted in this study. Only one scenario is modelled for five experts. Firstly, single expert opinions are provided for each base event or parent events (V1-24) and five different independent/dependent experts are used. It is ascertained that the results are better than when multiple experts are asked to judge the risk of parents occurring. If we have a strong reason to believe experts are not independent of each other, e.g. they may have attended the same university, or work for the same organisation, then they become dependent. Five dependent experts provide subjective judgements on the risk of base events on the sliding gate failure model (V1-V24), using ranking nodes on seven scale nodes. The five experts are denoted in the study as E1, E2, E3, E4, and E5 (dependent on each other), i.e. they are all working as operators in the sliding graving shipyard industry with sliding dock gates. The weights of experts E1, E2, E3, E4, and E5 on the scale of *1* to *5* are 5, 3, 3, 2 and 1 respectively.

The seven linguistic language rank nodes used in this study are: lowest (LT), very low (VL), low (L), medium (M), high (H), very high (VH) and highest (HT), where each expert gives his opinion on how parent V affects child U for this study. The underlying numerical equivalent mapping of a 7-point rank scale is provided in the Bayesian interference engine of software (AgenaRisk). It is usually not required to construct mappings in BN, because for every respective linguistic description of the sates there is an underlying model working with a numerical scale. In this light, every underlying numerical scale can be expressed in a numerical statistical distribution. In practice it is often necessary to rely on subjective probabilities provided by expert judgements as a rational expression of an individual's degree of belief in relation to the failure of a sliding dry dock gate working under certain conditions.

4.8.3 Converting fault tree to Bayesian network

There are a number of specific compelling reasons for performing FTA in terms of BNs rather than using the classic FT approach (Fenton and Neil, 2012): (1) calculations in discrete BNs are exact, whereas classic fault trees provide only an approximate method, called 'cut sets', to calculate the probability of occurrence of the top event. This involves algebraically expanding the Boolean event space of the model, inevitably leading to a combinatorial expansion leading to inaccuracy; (2) unlike classic FTs a BN can be executed to diagnostic as well as predictive mode. Therefore, given evidence of failure at the top or intermediate events, we can diagnose which of the primary, or other, events is the most likely cause of this failure. This is useful in fault finding and accident investigations in dry docking system; (3) classic FTA assumes a Boolean specification for the states of all variables but in BN we need not, resulting in a richer, more realistic model; (4) classic FTA assumes that the primary events are independent. This is seldom the case, especially in the presence of common causes of failures and also where components suffer from shared design faults. Using the conversion algorithm, the fault tree is mapped to its corresponding BN, as presented in Figure 4.20.

4.8.4 Qualitative analysis

Qualitative analysis should provide a clear view of the system and the relationships between system elements; this representation is first produced in this study by building a fault tree and then converting it into a BN. The idea of directly producing a large BN for system analysis is usually not advisable. In a dry dock classical risk assessment problem, the task of the risk analyst and domain expert is to accept or reject the system. One of the key acceptance criteria is the safety of the dry dock. This might, for example, be measured in terms of the predicted number of safety-related failures in a 10- or 20-year life span. The FT-BN model provides a better framework to ask appropriate questions, make decisions and justify them.

The challenges of coming up with quantified figures in a BN has led to combining evidence of very different types in the past. The evidence might range from subjective judgements about the quality of the supplier and component complexity, through to more objective data like number of defects discovered in independent testing. In some situations there might be extensive historical data on previous similar components, whereas in other cases there might not be any. In this study, the trust in the accuracy of any test data will depend on the trust in the providence of the testers. Having little or no test data at all will not absolve the responsibility for making a decision and having to justify it.

A decision based only on gut feel will generally be unacceptable and, in any case, disastrous in the event of subsequent safety incidents with all the legal ramifications. The aim to build a scientific model, so open, factual, and honest for discussing risks and our beliefs (i.e. theories) about how they interrelate, and what the probabilities are, is of the utmost importance. The risk analyst (the modeller) and the elicitee (the sliding dry dock gates’ subject matter expert) must have an understanding of each other’s professionalism, skills and objectives.

The goal is to understand sliding gate operation (design, construction, installation and operation) sufficiently to probe and challenge discussion in order to allow experts to sharpen and refine thinking; this in turn leads to more accurate probabilities. The use of a BN structure in this study is because it supplies some or all of this, thus making this easier than when asking for probabilities alone

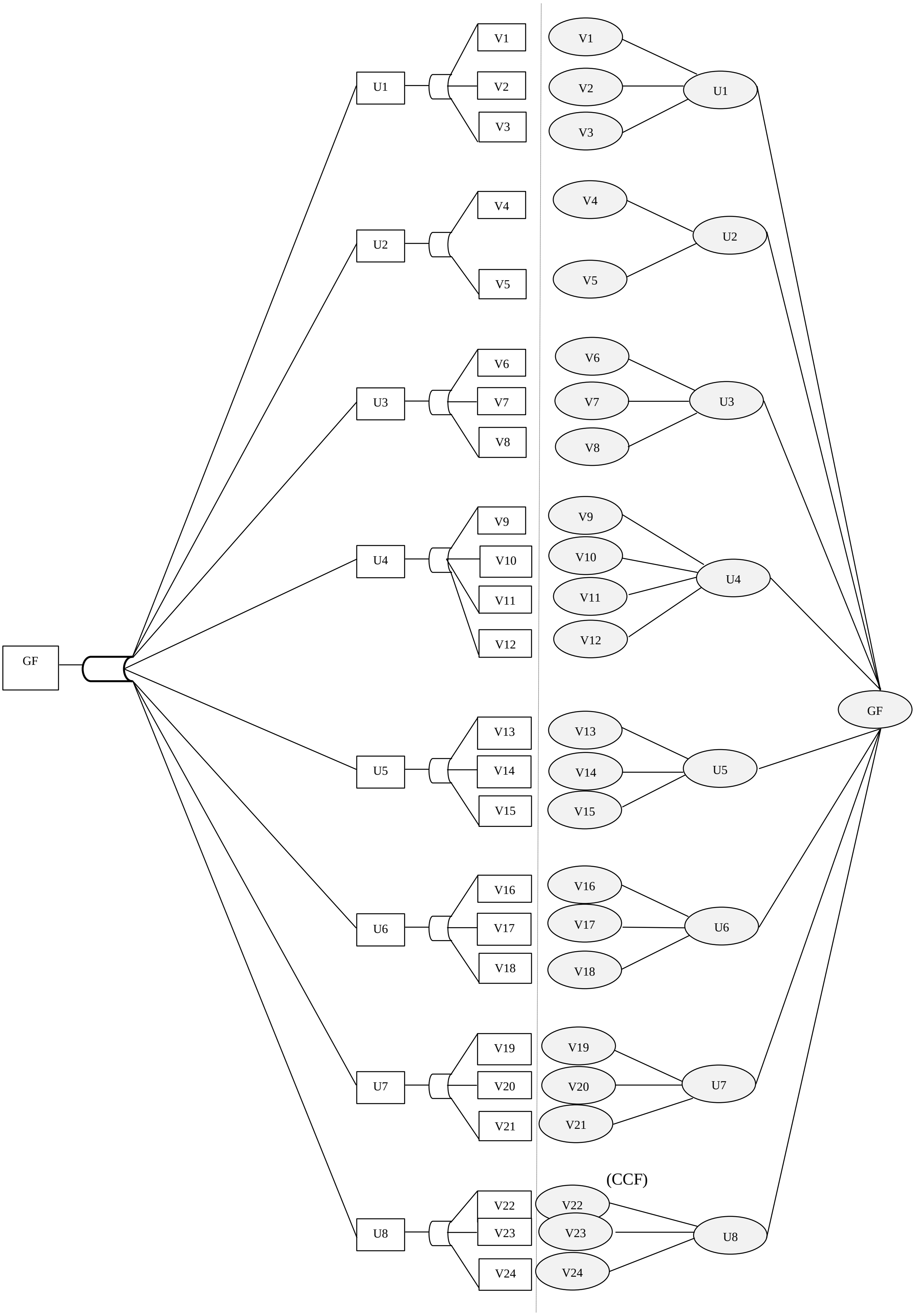


Figure 4.20: FT-BN sliding dry dock gate failure mode

Determining whether any two nodes in BN are *dependent* is well taken care of in the FT-BN. In the three types of connection (serial, divergent, and convergent) in a typical BN structure, defining the conditions under which pair nodes dependent (formally this was a notion of d-connected) is required. The dry dock gate system has local dependences between walls and floors. Walls and floors change if there is increased load on the system. Load increase leads to increase of walls failure probability. This variable has conditional dependence that is not possible to address with traditional FT. To include this dependence in the BN model, an arc was built between the nodes. With this approach, it is possible to model how the malfunction of any equipment affects the other equipment. Although it is not required in determining such general dependencies in any practical model building, this notion is important to understand the detailed BN algorithm.

Finally, to complete the qualitative analysis, the common cause failure (CCF) must be included. This dry dock gate system has a redundant subsystem in which a CCF may occur; a parallel system provides failure to sealing system and guiding post. The CCFs are important contributors to system unreliability and typically exist among redundant units. CCF in this dry dock gate system directly affects the reliability of the whole system. In the BN, one node is included for each group of redundant components to verify the CCF effects; each node is a representation of the CCF associated with groups of similar component: CCF1 (bearing), CCF2 and CCF3.

4.8.5 Modelling using AgenaRisk

Building a BN to solve a risk assessment problem involves the following steps: (1) *identify the set of variables that are relevant for the problem;* (2) *in AgenaRisk create a node corresponding to each of the variables identified* in the fault tree, hence mapping fault tree to BN; (3) *identify the set of states for each variable*. Again this depends on your perspective and issues related to complexity; (4) *in AgenaRisk specify the states for each node*; (4) *identify the variables that require direct links*. This must have been taken care of by the fault tree diagram; (5) *for each node in the BN specify the NPT*. (This is usually the hardest part of the modelling process and that is why much effort is devoted to providing guidelines and help for this part.) In this study all variables involved have a finite discrete set of states then the NPT requires us to specify the probability of each state of the node given each combination of states of the parent's nodes. Executing a model in AgenaRisk, click on the appropriate toolbar button. This will result in all the marginal probability values being calculated; the point of interest is entering observations and recalculating the model to see the updated probability values.

Entering an observation (also called evidence) for a variable means specifying a particular state value for that variable, called hard evidence, in contrast to an uncertain evidence. Once any type of evidence is entered the model needs to be recalculated so that you can see the revised probability values.

Dealing with inconsistent evidence, it is important to understand that sometimes evidence entered in a BN will be impossible. Sometimes, too, when attempting to run the model with certain observations a message comes on screen indicating inconsistent evidence. What happens is that the underlying inference algorithm first takes one of the observations and recomputes the other node probability values using Bayesian propagation. One of the most common confusions when using BNs in practice occurs when entering evidence in large complex BNs. It is often the case that entering particular combinations of evidence will have extensive ripple effects on nodes throughout the model. In some cases this will result in certain states of certain nodes having zero probability; in other words they are now impossible. These nodes might be directly connected to the nodes where evidence was entered. If, in these circumstances, the user subsequently enters evidence that one of the impossible states is ‘true’ the model, when computed, will produce an inconsistent evidence message that may surprise the user (who may wrongly assume that the algorithm has failed). In such circumstances the user also has the tricky task of identifying which particular observation caused the inconsistent evidence.

4.8.6 Quantitative analysis

Quantitative analysis begins with the inclusion in the BN of the priori probabilities of root nodes; these probabilities can be provided by statistical data or be estimated by experts. Next, the relationships between nodes must be specified. And finally the joint probability of the network is obtained, which, in this case will serve to obtain the system reliability for a given mission time or using a ranked node as in the case of this study. The root nodes that represent the basic components are completed by probability density functions representing the time to failure (TTF) of the basic components. The relationships between components are presented by basic constructs such as AND and OR gates, used in fault trees. The AND gate, where the output will fail when all input components fail, has a probability of failure of its output in the time interval [0, t], given by: $P(\ell_{AND} \leq t) = P(\ell_1 \leq t, \ldots \ell n \leq t) = P(\max\{\ell_i\} \leq t)$ where $\ell_{AND:}$ time to failure of AND gate, ℓ_1 time to failure of component *i*. The OR gate, where the output will fail if at least one input component fails, has a probability of failure of its output, in the time interval [0, t], given by: P ($\ell_{OR} \leq t$) =1- P ($\ell_1 \leq t, \ldots \ell n \leq t$) = P (max $\{\ell_i\} \leq t$), where $\ell_{OR:}$ time to failure of OR gate, ℓ_1 time to failure of component *i*. Although the BN is able to deal with any kind of prior distribution, some studies consider the components to have constant failure rates (λ) which means that the time-to failure distributions were assumed to be *exponential*. Thus, the probability of a component to fail at time T within a given mission time t is calculated as P (T<t) = $1\text{-}e^{-\lambda t}$, except for insulation. Statistical data about the probability of the towing failures were not found along this investigation, but these distributions may be estimated by expert judgement. BN builders ask relevant questions to a group of specialists and explain the assumptions that are encoded in the model, and the domain experts supply their knowledge to the BN builder demonstrated in this process. Understanding the limitation of a normal distribution, and overcoming the limitation of Boolean gate expressions for a large BN, one especially useful distribution to express expert numerical statistical distribution is the truncated Normal (or *TNormal*). It is convenient to generate both prior probabilities of nodes with parents, and to generate satisfactory NPTs for almost all BN fragments involving ranked node with ranked parents. Not only are the parents and experts' nodes ranked, they are also weighted.

Using the "*Weighted Ranked Nodes TNormal distribution"* the computation of prior probability is readily done in large studies, while the weighted parents' TNormal distributions are used to generate satisfactory NPTs. Once the BN structure is constructed using AgenaRisk, the first step is to identify the set of states for each node as ranked nodes for the entire structure. For each parent node V1, five experts provide a truth table of occurrence of parents, as presented in Figure 4.21.

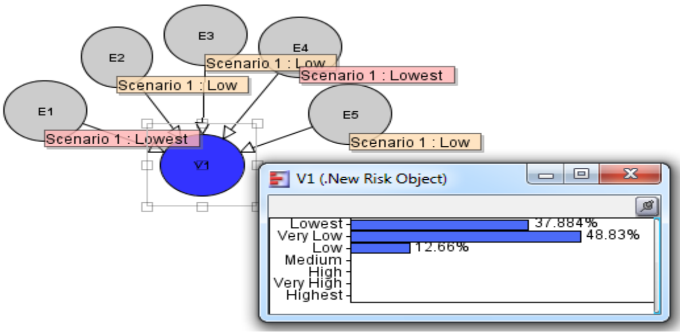
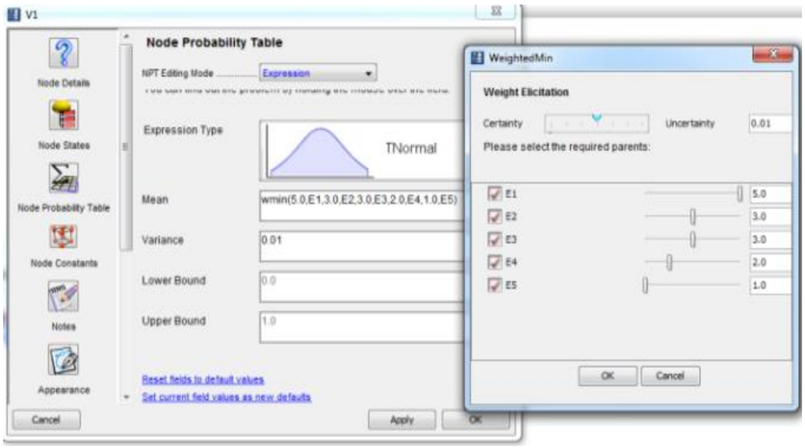


Figure 4.21: Expert input evidence for parent node V1

Unlike the regular Normal distribution (which must be in a range –infinity to + infinity) the TNormal has *finite end points*. For ranked nodes these points are 0 and 1, respectively. Like the Normal distribution, the TNormal is characterised by two parameters: the *mean* and *variance*. A range of TNormal distributions with different means and variances is shown. The notation TNormal (a, b) stands for mean and variance respectively. The ranked node functions in AgenaRisk are generated using TNormal distributions from a sample taken from the parent nodes so as to generate 'mixtures' of TNormal distributions.Generating prior probabilities using Weighted min function (WMIN) for each parent node, V in AgenaRisk, an example using node V1 ranked on a scale {lowest, very low, low, medium, high, very high, and highest} is specified. Defining the prior probability of node (V1) using AgenaRisk, the five experts consulted in this study were provided with values as E1-lowest, E2- low, E3-low, E4-lowest, and E5-low. The next step is to specify their relative weights using the Weighted rank nodes incorporated in the wizard of experts and uncertainty shown in Figure 4.22.



Node Probability Table

NPT Editing Mode: Expression

Expression Type: TNormal

Mean: wmin(5.0,E1,3.0,E2,3.0,E3,2.0,E4,1.0,E5)

Variance: 0.01

Lower Bound: 0.0

Upper Bound: 1.0

Weight Elicitation

Certainty | Uncertainty: 0.01

☑ E1: 5.0

☑ E2: 3.0

☑ E3: 3.0

☑ E4: 2.0

☑ E5: 1.0

Figure 4.22: The wizard to insert weight of experts and uncertainty

Suppose we wish to define the prior probability of node (V1), then we need to specify the individual truth table of each expert and their relative weights using weighted rank nodes. Instead of specifying the individual node entries for the seven states manually, simply define the prior probability as an approximate TNormal expression (the mean would be below 0.5 to ensure skew towards low, if this were the case). The real power of the TNormal distribution comes when we define the NPTs for V1 with five experts' judgements ranked in 7-scale mapping; here the mean is a weightedMean expression of the expert nodes E1, E2, E3, E4, and E5 (with weights 5, 3, 3, 2 and 1 respetively) and variance of 0.01. Clicking on the appropriate button, the prior probability of V1 is obtained, seen in Figure 4.21 as {37.884% lowest, 48.83% very low, 12.66% low, 0% medium, 0% high, 0% very high, 0% highest}. The truth table for all parents' nodes (V1-V24) provided by five experts is presented in Table 4.4. Likewise, generating NPTs for the entire system using WMIN domain experts provide the importance of each parent over its corresponding child node. For example, using the BN model where V1, V2 and V3 are parents to child node U1, the relative weights of V1, V2 and V3 are suggested to be 3, 4, and 1 respectively.

Table 4.4: The linguistic expression for five experts for each parent V1- V24

	V1	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**	**V10**	**V11**	**V12**
E1	LT	L	LT	M	LT	H	H	M	H	H	H	L
E2	L	M	LT	M	L	H	H	M	M	H	L	L
E3	L	L	LT	L	M	H	H	L	VH	L	H	H
E4	LT	M	M	H	M	L	M	M	M	VH	L	H
E5	L	LT	L	L	L	M	M	L	H	H	H	H
	V13	**V14**	**V15**	**V16**	**V17**	**V18**	**V19**	**V20**	**V21**	**V22**	**V23**	**V24**
E1	M	L	VH	H	VH	H	LT	LT	M	LT	LT	M
E2	M	M	L	M	L	M	L	L	L	L	LT	L
E3	L	L	H	L	VH	M	LT	L	L	LT	VL	M
E4	H	M	H	H	L	H	M	L	VL	L	L	M
E5	VL	M	L	VH	H	M	LT	LT	VL	LT	L	LT

The resulting prior probabilities of each parents (V1-V24) and each corresponding weight is presented in Table 4.5. The example presented for node V1 is highlighted.

Table 4.5: Resulting prior probabilities and suggested weights of V1-V24

	W	**LT**	**VL**	**L**	**M**	**H**	**VH**	**HT**
V1	3	**37.884**	**48.83**	**12.66**	**0**	**0**	**0**	**0**
V2	4	2.447	25.875	50.809	19.393	1.38	0	0
V3	1	44.692	45.78	9.186	0	0	0	0
V4	1	0	6.743	39.22	43.924	9.527	0	0
V5	5	19.147	50.775	27.981	2.844	0	0	0
V6	4	0	0	11.802	46.814	35.596	5.118	0
V7	2	0	0	7.998	41.871	41.696	7.896	0
V8	1	0	9.599	44.007	39.11	6.698	0	0
V9	5	0	0	6.996	39.724	43.561	9.21	0
V10	2	0	0	13.196	47.772	33.696	4.55	0
V11	2	0	3.014	28.269	50.177	17.356	1.115	0
V12	1	0	5.534	36.06	46.014	11.678	0	0
V13	4	0	9.599	44.007	39.11	6.696	0	0
V14	2	0	12.992	47.44	34.037	4.754	0	0
V15	1	0	1.876	25.573	51.048	22.573	1.876	0
V16	5	0	1.142	17.557	50.209	28.049	2.974	0
V17	5	0	1.146	17.603	50.238	27.98	2.956	0
V18	1	0	0	14.803	49.084	31.394	3.819	0
V19	2	44.15	46.003	9.48	0	0	0	0
V20	1	37.877	48.833	12.663	0	0	0	0
V21	1	5.157	35.76	46.818	11.727	0	0	0
V22	1	49.85	42.731	7.194	0	0	0	0
V23	1	44.15	46.003	9.481	0	0	0	0
V24	1	1.188	18.029	50.486	27.431	2.814	0	0

The NPT of child node U1 (*bearing failures*) can be likewise defined to be TNormal with mean and variances. Here, the mean is a weighted mean expression (using AgenaRisk as distribution can be entered directly as an expression for the node U1 or via the simple wizard shown in Figure 4.23 and Figure 4.24 since the tool has a built-in WeightedMean expression).

In this study, the prior probability of V1, V2 and V3 is entered manually in a 7-ranked scale mapping. Also, the relative importance of each V1, V2, and V3 is 3, 4, and 1 respectively, as seen in Table 4.4, and the corresponding prior probabilities of V1, V2 and V3 as seen in Table 4.4 are: V1 {37% lowest, 48.83% very low, 12.66% low, 0% medium, 0% high, 0% very high, and 0% highest}, V2 {2.447% lowest, 25.875% very low, 50.809% low, 19.393% medium, 1.38% high, 0% very high, and 0% highest}, V3 {44.692% lowest, 45.78% very low, 9.186% low, 0% medium, 0% high, 0% very high, and 0% highest}. Entering the evidence for parents V1-V3 and their relative importance reflected in the weighting scheme used is also evident when calculating the cause given evidence about the effects. The nodes with higher weights will be identified as the most likely causes of the consequence. Should the probability of U1 be expressed, it can be obtained from the software as: U1 {1% lowest, 55.986% very low, 40.629% low, 12.115% medium, 1.23% high, 0% very high, and 0% highest}. The results of the all the children U1-U8 with respective parents V1-V24 are provided in Table 4.6.

Table 4.6: Effects of parents V1-V24 on children U1-U8

	W	**LT**	**VL**	**L**	**M**	**H**	**VH**	**HT**
U1	1	55.986	40.629	12.115	1.23	0	0	0
U2	3	0	4.07	24.586	43.789	23.466	3.736	0
U3	4	17.987	37.808	32.016	10.777	1.357	0	0
U4	2	0	4.011	26.026	45.37	21.589	2.756	0
U5	3	1.782	15.643	40.901	31.914	8.146	0	0
U6	5	0	5.985	27.685	42.026	20.588	3.156	0
U7	1	29.459	46.625	21.09	2.728	0	0	0
U8	5	21.441	46.092	27.622	4.631	0	0	0

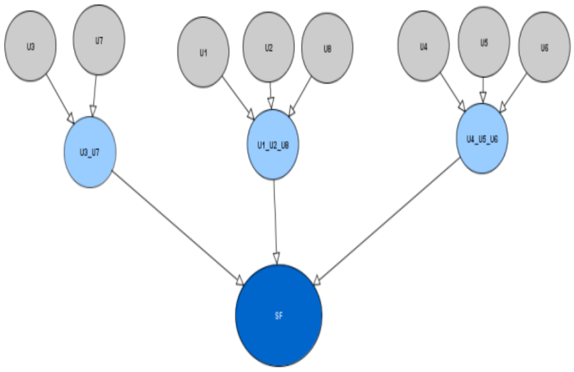


Figure 4.23: BN model for Parent U1-U8

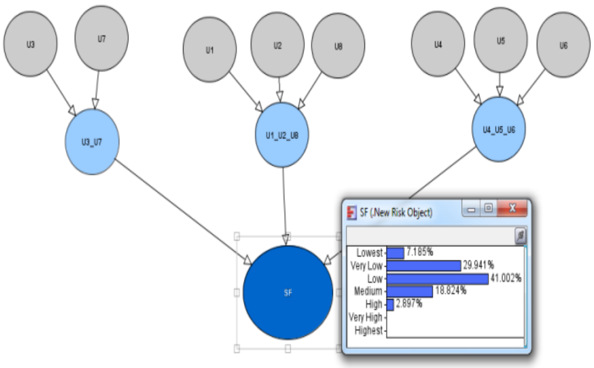


Figure 4.24: System failure (SF) probability

For diagnostic analysis, the entire BN is reduced to a resultant model with parents U1-U8. In the AgenaRisk the parent nodes can be regrouped in order of importance and function as presented "*U3-U7*", "*U1-U2-U8*", and lastly "*U4-U5-U6*". Using the prior probabilities of parents U1-U8 as calculated in Table 4.5, the resultant failure SF of the system is calculated as {lowest-7.185%, very low-29.941%, low 41.002%, high-2.897%, 0%-very high, 0%-highest}. Diagnostic analysis can therefore be carried out using various scenarios, and the goal to represent a complex structure to as few variables as possible for traceable results is presented. Next, when the system failure is highest, the most affected node is U3. Entering evidence that the dry dock gate at Birkenhead fails (when SF is highest), the diagnostic results shows that U3 affects the system the most as presented in Figure 4.25.

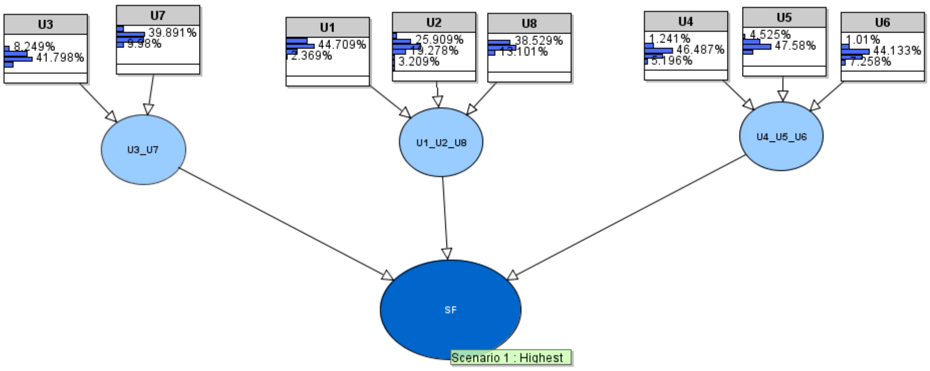


Figure 4.25: Result when dry dock gate fails

4.8.7 Sensitivity

An extremely useful way to check the validity of an expert built model is to perform sensitivity analysis, whereby it is possible to see diagrammatically which nodes have the greatest impact on any selected (target) node, in this case SF, signifying system failure of dry dock. Considering the model, it would clearly be interesting to know, based on the overall definition, which nodes have the greatest impact on SF. Setting SF as the target node, the tornado graph in Figure 4.26 is generated.

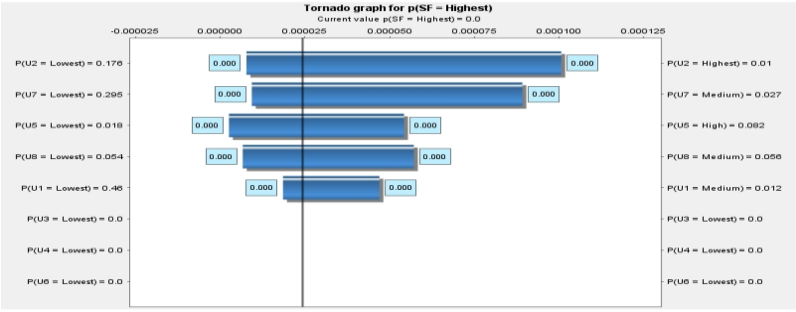


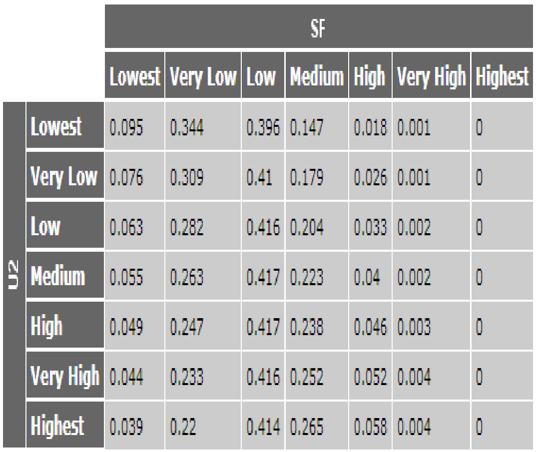
Figure 4.26: Tornado graph showing sensitivity analysis

In theory, this can be manually done by running through various scenarios of the model setting different combinations of scenario definition for system failure (SF). Fortunately, AgenaRisk does this automatically by allowing us to select a target node and any number of other nodes (called sensitivity analysis).

From a purely visual perspective the length of the bars corresponding to each sensitivity node in the tornado graph is a measure of the impact of that node on the target node. Thus, the node U2 has most impact on system failure, followed by the nodes U7, U5, U8, U1, U3, U4, and U6. The formal interpretation is that the probability of SF given the result of U2 goes from 0.176 (when U is lowest) to 0.01 (when U2 is highest). This range (0.176 to 0.01) is exactly the bar that is plotted for the tornado graph. The vertical bar on the graph is the marginal probability for system failure (SF) being 'highest' (0.000025).

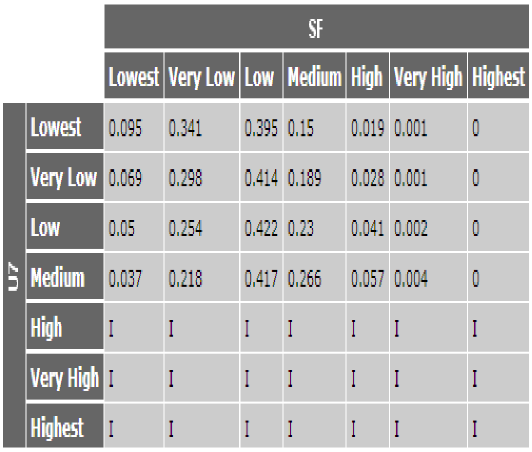
In validating these results, there are many types of sensitivity analysis, some of which are extremely complex to describe and implement. AgenaRisk has a sensitivity analysis tool that provides a range of automated analyses and graphs. In this study, only the simplest type of sensitivity analysis with discrete nodes, tornado graph, is used, validated by generating the incremental influence table for U2 and U7.

Table 4.7: U2 vs SF incremental influence



		SF						
		Lowest	Very Low	Low	Medium	High	Very High	Highest
U2	Lowest	0.095	0.344	0.396	0.147	0.018	0.001	0
	Very Low	0.076	0.309	0.41	0.179	0.026	0.001	0
	Low	0.063	0.282	0.416	0.204	0.033	0.002	0
	Medium	0.055	0.263	0.417	0.223	0.04	0.002	0
	High	0.049	0.247	0.417	0.238	0.046	0.003	0
	Very High	0.044	0.233	0.416	0.252	0.052	0.004	0
	Highest	0.039	0.22	0.414	0.265	0.058	0.004	0

Table 4.8: U7 vs SF incremental influence



		SF						
		Lowest	Very Low	Low	Medium	High	Very High	Highest
U7	Lowest	0.095	0.341	0.395	0.15	0.019	0.001	0
	Very Low	0.069	0.298	0.414	0.189	0.028	0.001	0
	Low	0.05	0.254	0.422	0.23	0.041	0.002	0
	Medium	0.037	0.218	0.417	0.266	0.057	0.004	0
	High	I	I	I	I	I	I	I
	Very High	I	I	I	I	I	I	I
	Highest	I	I	I	I	I	I	I

4.9 Discussions and Conclusion

In this chapter the main challenge encountered when building a BN and attempting to complete the conditional probability tables (CPTs) in the BN are: that the number of probability values needed from experts can be unfeasibly large. In this study, a new node types has been introduced to make clear which types are compatible with what functions and for ranked nodes. The idea of expert elicitation is avoided in this chapter; however the concept of transforming fault tree to Bayesian network is expanded. Where data is available, the validation or recalibration of expert predictions is best suited as proposed in this study. The outcome of this study is the application of effective risk control measures as listed in hierarchy order: RCO 2- *Preventing any buoyancy obtained from the upper chamber,* these include improved inspection in Tidal Chamber, focusing on Tidal flaps connected by wires, and tidal valves. RCO 7- *Preventing failures of control system*, these include maintenance of driving winch, control panels and control tank gauges. RCO 5- *Loads from water pressure – rolling and holding gate in centre of recess* – roller guide gates using a pair of rollers, into a central guide-wall, holding the gate in the centre of the recess. RCO 8- *Tank operation issues,* putting in permanent ballast to *bring the gate to an even keel,* two scuttle tanks, used to *sink the gate into position,* how the two ballast tanks are flooded when the gate is closed to increase stability and prevent any movement due to wave action. RCO 1- *Maintenance on towing system*, these include removal and maintenance of the rollers in air chambers, gate-shifting system inspection (A 2-pile system, and hydraulic trolley). RCO 3-C*onstantly controlling an even draught* (stability concerns) by using trimming tanks. RCO 4- *Improve structural element inspection* – walls, floors, decks, walkway, handrails, guiding post. RCO 6- M*aintain gate water tightness* – a roller L-shaped strip was fixed to the outer edge of the green heart-facing pieces, which must be constantly maintained and checked.

This chapter presented an effective and flexible event-based FT-BN framework for dry dock risk analysis. The framework is mathematically sound and at the same time simple enough to allow interaction with domain experts and decision makers. This chapter has demonstrated the approach using a simple illustrative example and a case study to achieve results that are in the simple case almost as good as analytical results.

Further improvements is however required in technical aspects of this approach including coping effectively with situations in which evidence lies. In future work, the reliability analysis applied in this study may be expanded to the entire dry dock system failure. Also, the impact of a failure in this system may reach other areas of the docking process, which may lead to more severe consequences; hence a more detailed consequence analysis is required.

Chapter 5 – A Fuzzy Rule-Based Approach for Risk Analysis in Dry Docking Operation

Summary

In this chapter, a fuzzy rule-based system with final evidential aggregation is proposed for risk analysis in a floating dry dock. Accidents involving transverse bending failures of dry dock pontoons are presented. The proposed fuzzy evidential rule-based (FERB) system is used to deal with uncertainty in experts' knowledge on how a pontoon deck's plate might buckle while lifting vessels well within the overall rated capacity of the docks. The fuzzy evidential reasoning framework is introduced to model epistemic uncertainties including nonspecificity and vagueness. A computational efficient formulation of the FERB system using an uncertain IF-THEN rule is presented. Inference is performed through determining the fired rules followed by fuzzy Dempster-Shafer combination of activated belief structures. The advantages of the proposed FERB system are demonstrated using simple numerical examples and the risk analysis of a floating dock pontoon deck failure.

5.1 Introduction

Up until recently, structural failures of floating dry dock pontoons due to excessive transverse bending stresses were thought to be relatively rare occurrences. However, there have been three accidents involving transverse bending failures of pontoons within the last few decades (Heger, 2003). All three accidents provide knowledge on what can lead to accidents although some uncertainties exist due to complex environments and multicriteria information. Multicriteria information fusion is an extremely active field of research due to the need to improve frameworks to support decision making in this complex environment (Wallenius *et al.*, 2008).

Fuzzy rule-based systems are one of the most popular approaches for representing the knowledge because of some of their unique characteristics. The simplicity of analysis of complex systems and the ability to model the nonlinear relationships of the input-output in the realm of fuzzy inferences system (FIS) are some of the promising features (Aminravan *et al.*, 2011). Belief rule-based (BRB) systems refer to a class of expert systems that extend the traditional IF-THEN rules to represent uncertainty knowledge about complex systems. To model the knowledge based on the BRB system, only a partial and imprecise input-output relationship is required. The knowledge can be vague and incomplete, either obtained from expert, data or both (Aminravan *et al.*, 2012). Belief structures are popular in knowledge representation systems as they can model various facets of knowledge of uncertainty (Yager, 2008). A general structure of rule-based belief functions for represented knowledge was presented in Eddy and Pei (1986). Most of the suggested belief rule-based systems use evidential reasoning algorithms to aggregate the uncertain knowledge presented on belief structures (Aminravan *et al*., 2011). Among all evidential reasoning methods, the Dempster-Shafer theory (DST) (Dempster, 1967 and Shafer, 1976) provides a framework for handling granularity, non-specificity and conflict and has been successfully used in different applications. To date, several evidential reasoning algorithms using a distributed modelling framework based on DST have been introduced (Yang and Singh, 1994 and Smets, 2007). A more recently well-known method realisable in both analytical and recursive formulations called the evidential reasoning (ER) approach was proposed for multiple attribute decision analysis under uncertainty (Yang and Xu, 2002 and Wang *et al*., 2006). The belief rule base concept and its inference methodology as proposed based, on the evidential reasoning approach, provide better results when compared to a traditional rule base (Yang *et al.*, 2006, Yang, and Xu, 2002). In the belief rule base, each possible consequence of a rule is associated with a belief degree. Such a rule base is capable of capturing more complicated and continuous causal relationships between different factors. When applying the belief rule base, the input of an antecedent is transformed into a belief distribution over the reverential values of an antecedent. The distribution is then used to calculate the activation weights of the rules in the rule base. Subsequently, inference in the belief rule base is through the aggregation of all the activated rules using the evidential reasoning approach (Ehaheh *et al*., 2013).

Fuzzy rule-based systems (FRBSs) have the capability to model and interpret vague information in a linguistic environment. FRBS have found a wide variety of applications in various engineering problems. For instance, an application in detection and also defect type analysis of flat steel productions using image processing and FRBS has been investigated (Carbajal and Sanchez, 2008). Cho and Park (2000) showed another application of FRBS in assessing water quality in shrimp ponds. In this application the defuzzified output of FRBS is interpreted as a quality index. In another application, a two-stage FRBS is employed in the traffic signal controller (Nikili and Kuhu, 1999). FRBSs have been employed for risk assessment in environmental risk analysis problems (Aminravan *et al*., 2011, Sadiq and Rodriguez, 2005). They have been applied to the safety analysis of offshore systems (Liu *et al*., 2005), pipeline leak detection (Xu *et al*., 2007; Zhou *et al*., 2009; Chen *et al*., 2011), clinical decision support systems (Kong *et al*., 2009) and stock trading expert systems (Dymova *et al*., 2010). Also, they have been used in graphite detection (Yang *et al*., 2006), inventory control (Liu *et al*., 2009), consumer preference prediction (Wang *et al*., 2009), new product development (Tang et al., 2011)), system reliability prediction (Hu *et al*., 2010), gyroscopic drift predictions (Si *et al*., 2011), delayed coking unit (Yu *et al*., 2012) and aggregate production planning under uncertainty (Li *et al*., 2012). In the context of structural failures of pontoons due to excessive transverse stress in floating dry docks, the risk assessment grades are expressed using linguistic variables. In this study, FRBS with final fuzzy evidential reasoning has been proposed to incorporate ambiguity and uncertainty involved in structural failure of the pontoon within the linguistic environment. The main advantage of the proposed method is the ability to deal with uncertainty risk assessment parameters and to model nonlinear relationships.

The rest of the chapter is structured as follows (Figure 5.1). Section 5.2 is the problem statement. Section 5.3 introduces the structure of the classic rule-based system and proposed FRBS with final evidential reasoning to assess the relative risk assessment parameters. Section 5.4 presents the properties and definition of typical FRBS. Section 5.5 is review of FRBS framework adopted for this study. Section 5.6 explains about structural failures of pontoon due to excessive transverse stress in a generic floating dock. Section 5.7 illustrates the performance of the proposed framework using a typical floating dry dock pontoon failure. Section 5.8 summarises the concluding remarks of this chapter.

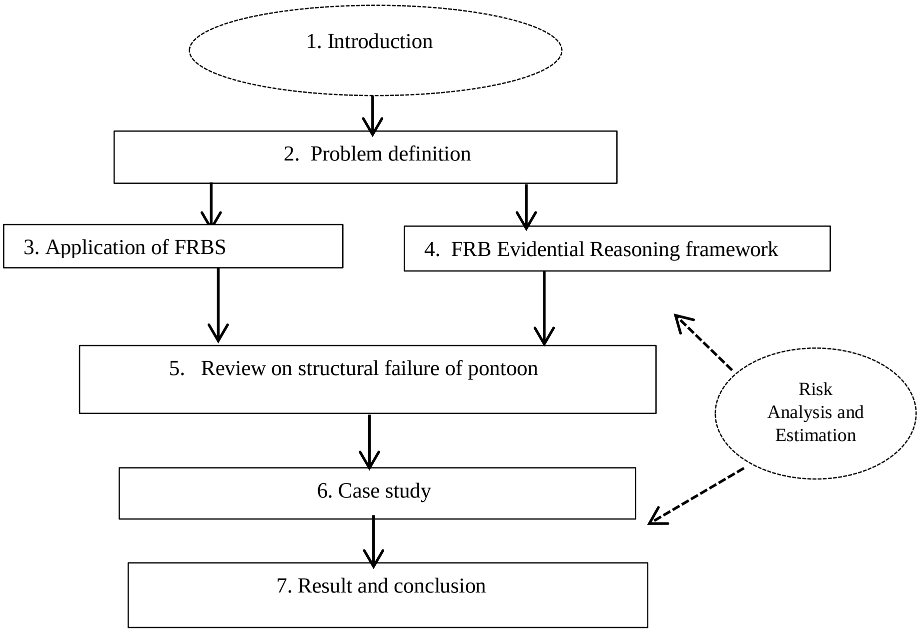


Figure 5.1: Flow chart of the development of the study

5.2 Problem Definition

This monograph chapter has two objectives. First, but not foremost, it is intended as a manifesto for the use of subjective reasoning approaches with imperfect information, which argues '*that they are useful and well-developed'*. Secondly, it is intended as a manifesto for an eclectic approach. The eclectic approach is a natural way of modelling the various forms of imperfection that may be present in the models of a real floating dry dock (Parsons, 2001). The monograph research approach is to overcome the challenges of this chapter which are: (1) Lack of data collection, accident and near miss reports in floating dry dock systems; (2) Developing a floating dry dock model to capture industrial applicability; (3) Definition of experts' participation and response to the system model; (4) Justification of results output of using FRBS; and; (5) Uncertainty analysis validation approach. Every floating dry dock has its own personality. This personality is a function of its operation, and differs with the size of dock. A moment of thought is sufficient to reveal the extent to which imperfect information is present in daily life, as Morgan and Herion (1990) point out, *'We have evolved cognitive heuristics and developed strategies, technologies and institutions such as weather reports, pocket-sized raincoats, and insurance to accommodate or compensate for the effects of uncertainty*.'

It is exactly because information about the world is imperfect that floating dry dock systems in the real world have been able to represent and reason with imperfect information. To overcome these limitations, the floating dry dock model captures essential features of reality, whilst being reasonably cheap to construct and operate (Fellows and Liu, 2008). Relationships between variables and boundaries are identified prior to quantification. The resulting model therefore reflects both the education and training of the risk analyst in the floating dry dock system. FRBS is a method of reasoning under uncertainty in a precise mathematical way. As a result it is possible to precisely determine the meaning of the derived measure. It is also possible to precisely determine the conditions under which the measure is valid (Morgan and Herion, 1990). Indeed, a large amount of survey on the application of FRBS which already exists, is introduce in large amount so as to cover a large amount of material that is never used in theoretical parts. This is focused on eclecticism in handling imperfect information and the need to integrate different approaches.

The disadvantage, however, with FRBS is that it requires specific types of information to be known, and places specific conditions on how the measures are to be allocated – for instance, the use of one method might require the attachment of a measure to be at least one. Such conditions on the measure lead to quite stringent constraints on the situations in which models may be built using these methods (Morgan and Herion, 1990). This, in turn, means that it is often the case that, when modelling a specific situation in a floating dry dock, no method exactly fits the data that is available. Three such models are *certainty factors* (Shortliff, 1979), *fuzzy sets* (Zadeh, 1965) and *the theory of evidence* (Shafer, 1976). Different methods are often designed to model different aspects of imperfect information, different preconditions, and provide different types of solutions. Different methods are completely exclusive in dry dock subjective risk analysis. These issues can be overcome by adopting the eclectic position, such that where there is a floating dry dock scenario in which no single method will be able to handle the imperfect information that is present, the best possible treatment of imperfect information is using several formalisms in combination. The next question to answer is: *what must be done when subjective data nexpressed in a particular formalism has missing values?* Assumptions are required to be made when relevant data is collected. The solution is to take whatever information is available and see what can be deduced from it, usually sacrificing some of the precision of the original methods. In-depth knowledge and detailed brainstorming exercises are required by both operators and risk analysts (Morgan and Herion, 1990). Ultimately, an estimate of risk should be accompanied by a *statement of the degrees of confidence in the estimate*, hence the term fuzzy rule-based system with belief degrees (Hartford and Baecher, 2004). This statement of degree of confidence describes the extent to which the result of the analysis can be relied upon in the decision-making process.

Expert systems are subject to various patterns of uncertainty that may exist in information (Yang *et al*., 2006). One source of uncertainty is non-specificity in assessing the impact of an antecedent attributed to distributed assessment of the consequent terms. The other source is the conflict which arises by judgements acquired from multiple attributes. Other uncertainty knowledge representation parameters are rule and attribute weights. All these cases can exist when the expert cannot make strong judgements due to lack of historical data or uncertain knowledge (Aminravan *et al*., 2012). Besides, imprecise and incomplete date may be used to make the rule base. The FRBS allows the capturing of a nonlinear input-output relationship when the information is not highly assured (Xu *et al*., 2007).

Traditional FRBS systems claim to be able to model non-specificity, ignorance and conflict (Yang *et al*., 2006). Non-specificity in the BRB systems is related to imprecise cardinalities of the sets of consequent grades. The mathematical framework used to represent these patterns of uncertainty is based on the evidential reasoning (ER) approach or Dempster-Shafer. The BRB inference methodology using evidential reasoning (RIMER) has been used in various applications but has some limitations especially when considering vagueness (Yang *et al.*, 2006). Vagueness is an important facet of uncertainty faced in the applications where linguistic assessment is a better presentation than numerical values. Both antecedent and consequent parts of IF-THEN rules in fuzzy logic approaches can have linguistic variables. In classic FRBS systems vagueness is considered only for the linguistic variables of antecedent attributes. Considering the different forms of uncertainty knowledge about complex system the use of FRBS to aforementioned patterns of uncertainty (Aminravan *et al.*, 2012).

This chapter shall establish the difference between sensitivity studies and uncertainty analysis. *Uncertainty analysis* is an extension of sensitivity analysis where probability distribution is associated with the various parameters or models being varied. Thus, the output is in the form of a probability distribution which specifies the likelihood of each possible result across the full range of possible results. Analysis of uncertainties associated with data, methods, and FER used to estimate risks posed by floating dry docks is important. Uncertainty analysis involves determining the variation or imprecision in the risk model resulting from collective variation in the parameters used to define the floating dry docks system. Estimation of uncertainty is done by translating the uncertainty in the analysis models and in the crucial model parameters into uncertainty in the outputs of the risk model (Hartford and Baecher, 2004).

5.3 Application of FRBS in Risk Assessment

This section reviews the application of two recent studies of FRBS in risk assessment. The results of these applications show that the generalised pignistic probability is insufficient to carry certain information provided by fuzzy evidence in the fuzzy evidential reasoning, and the improvements over traditional non-fuzzy evidential reasoning are quite limited (Elaheh *et al.*, 2013). However, the hybrid decision rule-based system applied in these studies makes the proposed FRBS with evidential reasoning, in terms of the classification accuracy and robustness to the variation of reliability of fuzzy evidence and probability evidence (Zhu and Basir, 2013). The researches herein mention to support these hypotheses are Aminravan *et al.*, (2011) and Da *et al.*, (2009). Aminravan *et al.* (2011) used an interval belief structure rule-based system with extended fuzzy Dempster-Shafer inference to investigate microbial water quality risk assessment. In this new belief structure fuzzy inference system (FIS) the interval belief structure is introduced to define the rules of an FIS and build uncertain knowledge. Their study conducted an extensive review just giving the interval belief structure fuzzy inference system using the classic FRBS represented by membership value and belief degree assigned to each fuzzy proposition. In order to model the interval uncertainty in belief degree assignment (i.e. non-specificity in belief degree), the fuzzy interval belief structure is proposed. The belief structure is said to be normalised, while the non-normalised belief structure in the consequence of all rules provided by experts is normalised. After normalisation the true internal belief degrees associated with all normalised fuzzy propositions (i.e. basic and intersection fuzzy propositions) are incorporated into the FIS engine. After establishing the rule based FIS using the interval belief structure where the fuzzy composition is transformed to its extended fuzzy Dempster-Shafer theory (FDST) combination, the proposed FIS engine uses the Mamdani inference procedure to determine the firing strength of each rule. In this study, different weights for each antecedent attribute and each rule are considered. T-norms are used to account for the importance of each attribute. The output of each rule is an interval belief structure with subnormal fuzzy focal elements after accounting for the firing strength. To show the utility of the proposed belief structure FIS, the risk assessment of drinking water was carried out. By interpreting the obtained results at a lower level using the hypothesis preference ranking method (Wang *et al.*, 2006) the hypothesis about the risk of drinking water was estimated as ‘very low’.

The belief rule-based inference methodology to improve nuclear safeguards information evaluation was presented by Da *et al*. (2009). After a hierarchical analysis of states’ nuclear activities on the basis of the International Atomic Energy Agency (IAEA) Physical Model, a framework for modelling, analysing and synthesising nuclear safeguards information with various uncertainties was proposed by using a newly developed belief rule base inference method (RIMER). A belief rule base system which provides a better way used to characterise the indicator strength in a more rational and realistic way is presented and the input transformation and activation weight for each rule considered and normalised. The rule based combination using the evidential reasoning (ER) approach is applied directly to combine the rules and generate final conclusions.

In particular, the ER recursive algorithm (Yang and Xu, 2002 and Yang et *al*., 2006) has been equivalently transformed into the analytical ER algorithm (Yang *et al*., 2007). Using the analytical ER algorithm, the overall combined degree of belief is generated. As an example, a specific evaluation on the possibility degree of ‘No conducting specific process Gaseous diffusion enrichment’ within the evaluation of production of highly enriched uranium (HEU) was used to validate the method. The result of scenario output OP was (H, 0.5194, M, 0.2672, and L, 0.2134), which means that the authors were 51.94% sure that process P exists with high confidence, 26.72% sure that process P exists with medium confidence, 21.31% (low confidence with process P) they noticed that the results reflect well the real cases because a strong indicator played a more important role in the evaluation than the weak indicators.

In conclusion, the whole framework aims at modelling, analysing and synthesising information that may be of a very different nature under uncertainty and for which the traditional quantitative approach does not give an adequate answer. This methodology can provide the risk analyst with a convenient tool that can be used at various stages of the design, construction and operational phases of investigating failures in floating dry dock systems for risk analysis. In this light, a fuzzy evidential rule-based (FERB) system has been proven to provide better fusion for multicriteria information compared to traditional FRBS as herein discussed.

5.4 Rule Based System with Fuzzy Evidential Aggregation

This section introduces a fuzzy inference system (FIS) that allows knowledge with various types of uncertainty to be represented in a rule based FIS. One type of uncertainty in the FIS is vagueness which refers to the linguistic imprecision in the propositions used to build the rule base. Another source of uncertainty is ambiguity which represents the condition that non-specificity and strife coexist in the information used to build the rule base. Non-specificity is related to imprecise cardinalities of the sets of alternatives while strife expresses conflict among various sets of alternatives (Aminravan *et al*., 2011). Crucial information, necessary for building a realistic model, is usually hidden in historical data (Kilic *et al*., 2007).

There is also the empirical evidence that past management behaviours in dry docking a vessel are important. Motivated by the operational aspect of docking a vessel in a floating dry dock with uncertainty, this chapter proposes a hierarchical belief rule based inference (BRBI) methodology using evidential reasoning (RIMER) (Yang *et al*., 2006), which is derived from the basis of the evidential reasoning approach (ER) (Yang and Sen, 1994, Yang and Singh, 1994, Yang, 2001, and Yang and Xu, 2002) and rule based expert systems. RIMER provides a modelling and inference framework that enables operators to intervene in the floating dry docking process and updating of the belief rule base (BRB) using judgemental knowledge and operational data. The method is easy to understand and implement, and it requires little computational effort (Li *et al*., 2012). The concepts of fuzzy sets (Zadeh, 1965, Zimmermann, 1991) and D-S theory (Dempster, 1967, Shafer, 1976) can be further studied as reference. This section briefly introduces the concept of a fuzzy rule base.

5.4.1 The fuzzy belief structure

To properly represent real-world knowledge, fuzzy production rules have been used for knowledge representation to process uncertain, imprecise and ambiguous knowledge (Chen, 1988, Liu *et al*., 2012). However, in the literature fuzzy production rules have been criticised because of the fact that the 'consequent' may sometimes not be able to reflect slight changes of linguistic variables occurring in the antecedent (Yang *et al*., 2006). Another kind of uncertainty exists when a strong correlation between premise and conclusion cannot be established. That condition means the evidence available is not adequate, or experts do not support a hypothesis totally but only to a degree of belief (Liu, *et al*., 2013). With the purpose of modelling more general, complex decision-making problems under uncertainty, the belief rule idea was proposed by considering a belief distribution in a conclusion (belief degree), the relative weight of the rule (rule weight) and the relative weight of an antecedent attribute (attribute weight). Mathematically, a belief rule base (BRB) which captures the dynamics of a system consists of a collection of belief rules defined as follows (Yang *et al*., 2006):

$$R_k : \text{IF } x_1 \text{ is } A_1^k \wedge x_2 \text{ is } A_2^k \ldots\ldots\ldots x_{Tk} \text{ is } A_{Tk}^k \text{ THEN } \{(D_1, \beta_{1k}), (D_2, \beta_{2k}), \ldots (D_N, \beta_{Nk})\} \qquad (5.1)$$

With a rule weight θ_k and attribute weight $\delta_{k1}, \delta_{k2}, \ldots\ldots \delta_{KTk}$, where $x_1, x_2, \ldots\ldots x_{Tk}$ represents the antecedent attributes in the *kth* rule R_k, A_i^k ($i = 1,2\ldots, T_k$, $k = 1,2\ldots L$) is the referential value of the k*th* rule R_k, $A_i^k \in A_i$, $A_i = \{ A_{ij}, j = 1,2,\ldots J_i\}$ is a set of referential values, θ_k ($\in R^+$, $k = 1,2,\ldots L$) is the relative weight of the *k*th rule R_k,, $\delta_{k1}, \delta_{k2}, \ldots \delta_{KTk}$ are the relative weights of the T_k antecedent attributes used in the *k*th rule R_k, and β_{ik} (i=1,2…,N, k = 1,2….,L) is the belief degree assessed to *Dj* which denotes the *j*th consequent. If $\sum_{i=1}^{T_k} . \beta_{ik} = 1$, the *k*th rule R_K is said to be complete; otherwise, it is incomplete. Note that "∧" is a logical connective to represent the "AND" relationship. In addition, assume that T is the total number of antecedent attributes used in the rule base.

5.4.2 Belief rule-based inference methodology using the evidential reasoning approach

Given an input to the system, $U(t) = \{U_i(t), i = 1,2\ldots, T_K\}$, how can the rule-base be used to infer and generate the output? As mentioned earlier, T_k is the total number of antecedents, which can be one of the following types (Yang *et al*., 2006): continuous, discrete, symbolic and ordered symbolic. Before the start of an inference process, the matching degree of input to each referential value in the antecedents of a rule needs to be determined so that an activation weight for each rule can be generated. This is equivalent to transforming an input into a distribution on referential values using belief degrees and can be accomplished using different techniques such as the rule or utility-based equivalence transforming techniques (Yang, 2001, and Yang *et al*., 2007). Using the notations provided above, the activation weight of the *k*th rule R_k, w_k, is calculated as (Yang *et al*., 2006): $W_k = \frac{\theta_k a_k}{\sum_{i=1}^{L} \theta_i a_i}$, where a_k is called the normalised combine matching degree. This reflects the individual matching degree to which the input matches its referential value A_i^k of the packet antecedent A^k in the *k*th rule R_k and $a^k_i \geq 0$ and $\sum_{i=1}^{T_k} a^k_i \leq 1$. In RIMER it can be generated using various ways depending on the different types of input information. In Yang's (2001) paper, the important technique of rule based information transformation was proposed, to deal with the input information that includes qualitative assessment and quantitative data. This chapter gives a detailed overview for quantitative data.

5.4.3 Fuzzy rule base with belief degree

This new safety model is the so-called belief degree methodology, and each step is outlined with a detailed description of fuzzy mathematical and logic principles as used in fuzzy logic systems. A more developed framework is presented Figure 5.2.

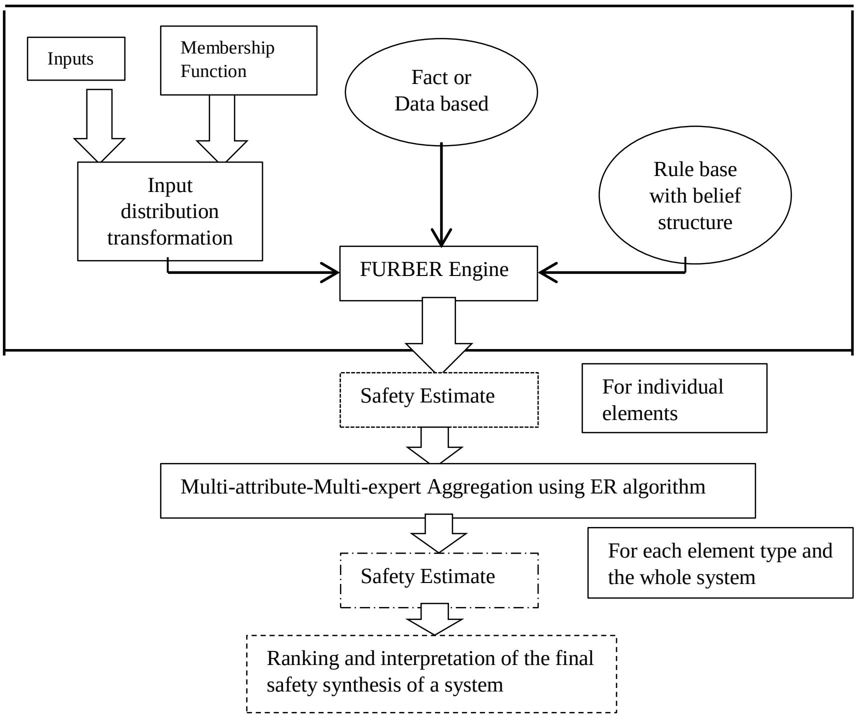


Figure 5.2: A generic dry dock safety assessment and synthesis framework

5.5 The Proposed Fuzzy Evidential Reasoning Rule Base with Belief Degree

In the decision-making process, one may need to introduce intelligent computing techniques in order to capture the structure and behaviour of a floating dry dock system that is highly nonlinear and uncertain (Kilic *et al*., 2007). From our point of view, the following principles should be adhered to when selecting a decision model for risk analysis/accident models for a floating dry dock (Li *et al*., 2012): (a) the sophistication of models should match the complexity of a specific decision situation; (b) the techniques should emphasise practical importance rather than just theoretical merit; (c) the models should be adaptable to different risk analysis scenarios; and (d) the models should be able to deal with different forms of uncertainties. The fuzzy rule base approach is generally presented as seen in Figure 5.3. It is well known as the best solution to real-world problems obtained using the synthesis of some powerful methods.

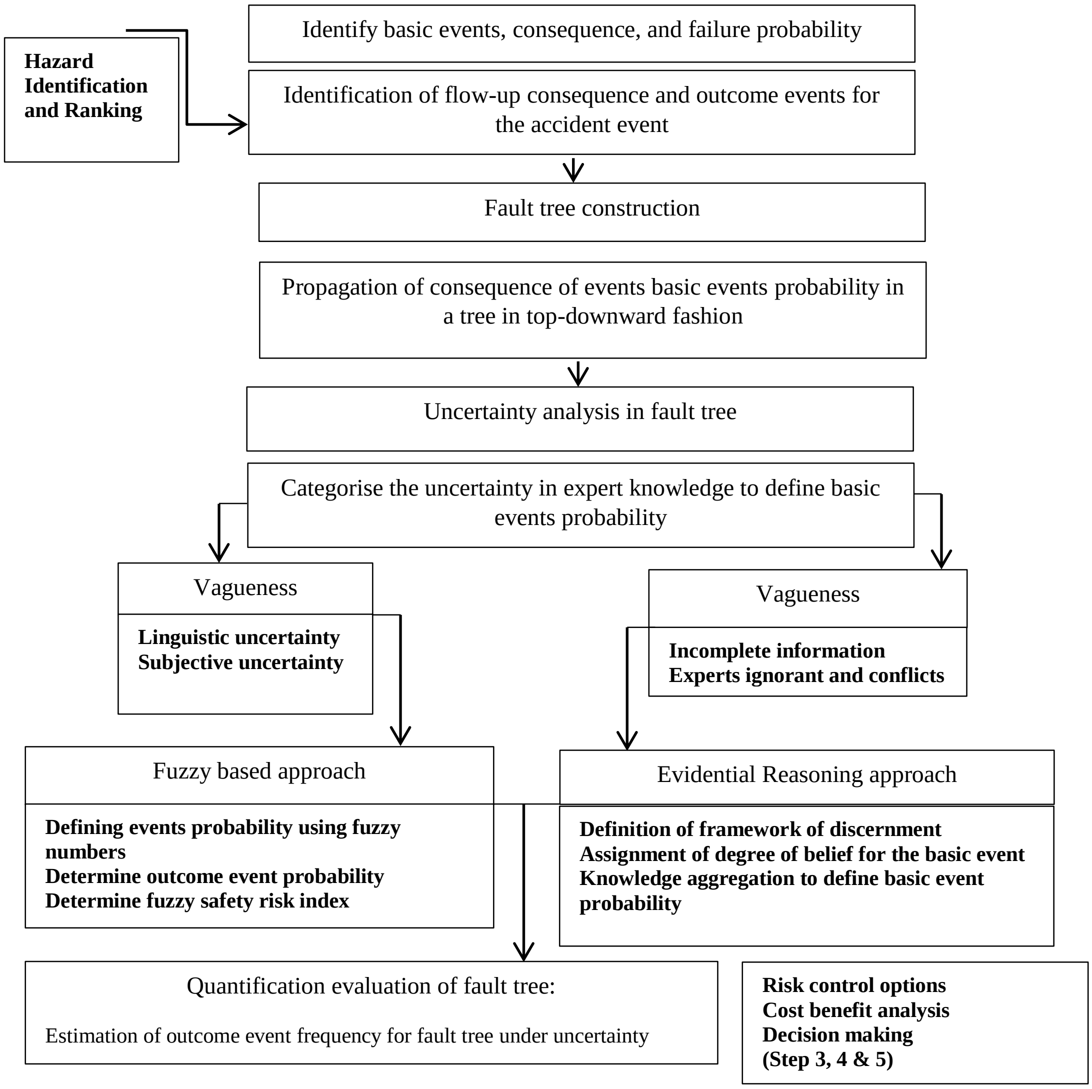


Figure 5.3: Fuzzy rule base approach

The FRBS combine Fuzzy Set Theory and Dempster-Shafer Theory methods in a synergic way, preserving their strengths while avoiding the disadvantages they present when used as monostragegy approaches: a capacity for the representation of fuzzy classifiers is enhanced by introducing the measure of ambiguity; a limitation of the Dempster-Shafer theory is providing effective procedures to draw inferences from belief functions is softened by a rule of propagation (Dymova *et al*., 2010). The flowchart of the proposed FRBS with belief degree modelling methodology is presented in Figure 5.4.

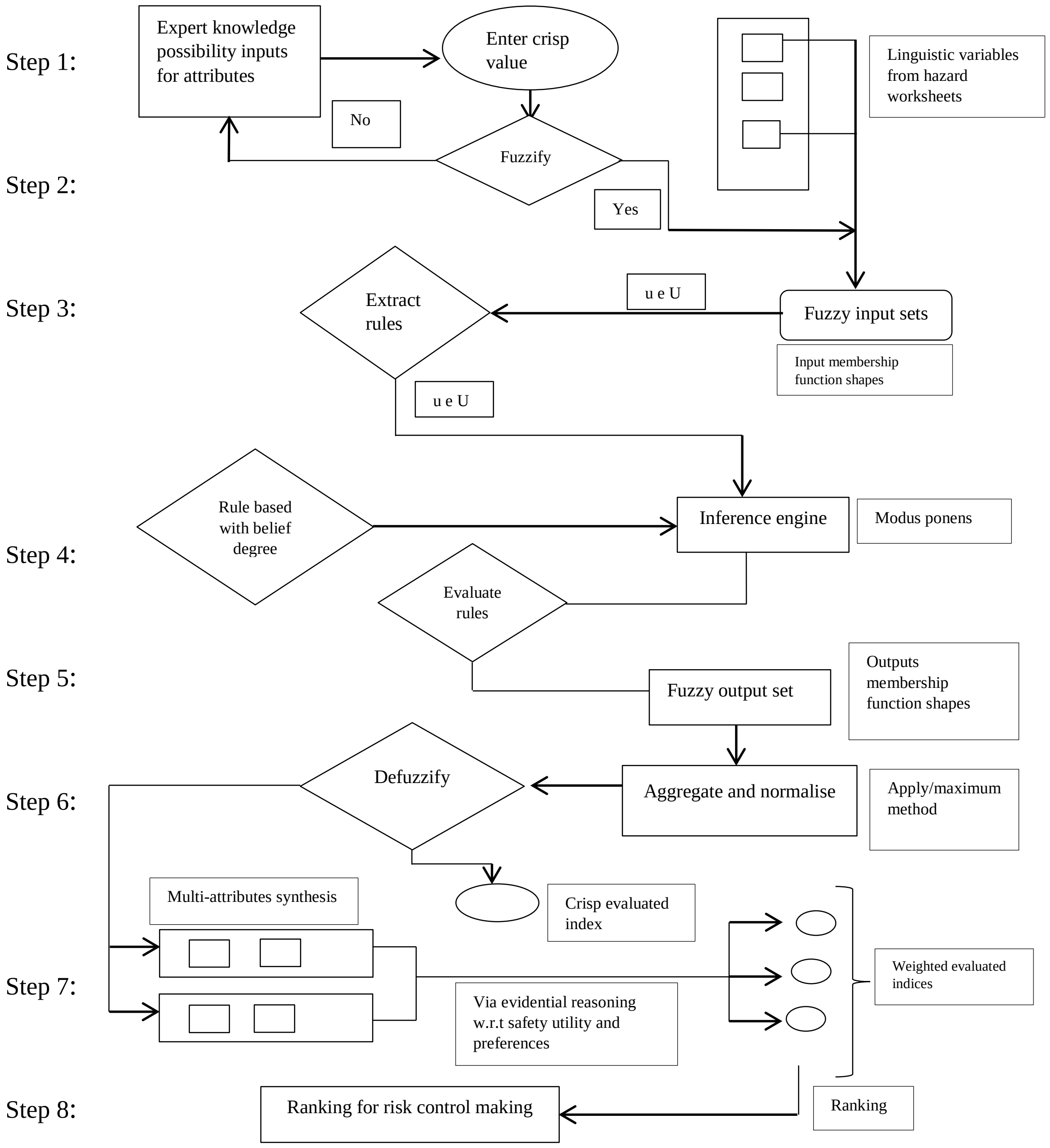


Figure 5.4: Flowchart of proposed fuzzy rule base safety modelling methodology

5.5.1 Hazard identification and fault tree

Preceding hazard identification is the preparatory study which includes identification of experts, selection of model, and choice of approach, questionnaires and conference meeting. In this methodology, hazard identification is carried out using fault tree analysis. The base events of failure analysis are linked to middle events using AND/OR gates. For risk estimation purposes in floating dock operation, three safety parameters are used to define the risk of base events in the fault tee. These safety parameters are *failure likelihood* (F^L) *consequence severity* (C^S) and *failure consequence probability* (F^{CP}). Once accident analysis has been carried out on the worksheet, the corresponding fault tree is constructed and the next step is to use linguistic variables collected from the expert's worksheet to start the belief rule base inference (BRBI).

The safety level (S) is expressed as the conclusion attribute. Subjective belief degrees are assigned to the linguistic variable used to express the conclusion attribute S for modelling the incompleteness of expert judgement. The linguistic variables for describing each base event attribute are decided according to the situation of the case of interest in floating dock risk analysis. To estimate F^L, for example, one may often use such variables as (F^L, j = 1,...,5), very low, low, average, frequent and highly frequent. To estimate C^S, one may choose to use such linguistic terms (C^S, j = 1,...,5) such as negligible, marginal, moderate, critical, and catastrophic.

To estimate F^{CP}, one may use such variables (F^{CP}, k = 1,…,5) as highly unlikely, unlikely, likely, highly likely, and definite. Similarly, the safety level of the particular base event can be described using such linguistic variables (S_h, h = 1, …, 4) such as good, average, fair and poor. All the criteria of base events in the hierarchical structure are given assessment grades from five experts. Consequently, belief rule based inference (BRBI) can be established, and the advantages of using belief functions can be appropriately appreciated.

5.5.2 Belief rule based inference (BRBI)

BRBI is a hybrid modelling and inference scheme in which subjective knowledge or system behaviour can be described using belief rule base natural language. Belief rule has been proposed recently as an efficient tool for uncertain and nonlinear modelling with reasonable precision while allowing linguistic interpretability (Yang *et al.*, 2007), and has been successfully utilised in many complex decision-making domains where traditional analytical methods do not work well (Li *et al.*, 2012).

5.5.3 The development of a fuzzy rule base

The starting point of constructing a rule-based system is to collect if-then rules from human experts or based on domain knowledge. A knowledge base and an inference engine are then designed to infer useful conclusions from the rules and observation facts provided by users (Yang *et al.*, 2006). Formally, a rule based mode is represented as R = (U, A, D, F), where U is the set of antecedent attributes, with each of them taking values (or propositions) from an array of finite sets A which is a referential set of values for attribute U. The values or propositions in A were mentioned in Section 5.4. The array U defines a list of finite conditions, representing the elementary states of a problem domain, which may be linked by some logical connectivity. D is the set of consequents, which can either be conclusions or actions. F is a logical function, reflecting the relationship between conditions and their associated conclusions (Yang *et al*., 2006). Several sources can be used to derive the fuzzy rules. These approaches are mutually supporting each other, and a combination of them is often the most effective way to determine the rule base.

In the statistical data and information analysis the fuzzy rules may be derived based on statistical studies of the information in previous incident and accident reports or database systems. An in-depth literature search may also be helpful. Skilled human analysts often have a good, intuitive knowledge of the behaviour of the system and the risks involved in various types of failure without having any quantitative model in mind. Fuzzy rules provide a natural platform for abstracting information based on expert judgements and engineering knowledge since they are expressed in linguistic form rather than numerical variables. Therefore, experts often find fuzzy rules to be a convenient way to express their knowledge of a situation in a floating dry dock. Note that in a rule base a referential set can be a set of meaningful and distinctive evaluation standards for describing an attribute by subjective linguistic terms. To establish a rule base, one has to determine which referential set of each antecedent attributes needs to be used and how many referential values should be used (Yang *et al*., 2006). In practical applications the fuzziness of the antecedents eliminates the need for a precise match with the inputs. All the rules that have any truth in their premise will fire and contribute to the fuzzy conclusion, i.e. RL expression. Each rule is fired to a degree that is a function of the degree to which its antecedent matches the input. This imprecise matching provides a basis for interpolation between possible input states and serves to minimise the number of rules needed to describe the input-output relation. The rules developed in this research framework are presented in Table 5.1. The continuation of this rule is presented in Appendix 5.

R	Table 5.1: Rule base development							
	F^L	C^S	F^{CP}	P	F	A	G	VG
1	Very low	Negligible	Highly U					1
2	Very low	Negligible	Unlikely				0.25	0.75
3	Very low	Negligible	Likely			0.25		0.75
4	Very low	Negligible	Highly L		0.25			0.75
5	Very low	Negligible	Definite	0.25				0.75
6	Very low	Marginal	Highly U				0.4	0.6
7	Very low	Marginal	Unlikely				0.65	0.35
8	Very low	Marginal	Likely			0.25	0.4	0.35
9	Very low	Marginal	Highly L		0.25		0.4	0.35
10	Very low	Marginal	Definite	0.25			0.4	0.35
11	Very low	Moderate	Highly U			0.4		0.6
12	Very low	Moderate	Unlikely			0.4	0.25	0.35
13	Very low	Moderate	Likely			0.65		0.35
14	Very low	Moderate	Highly L		0.25	0.4		0.35
15	Very low	Moderate	Definite	0.25		0.4		0.35
16	Very low	Critical	Highly U		0.4			0.6
17	Very low	Critical	Unlikely		0.4		0.25	0.35
18	Very low	Critical	Likely		0.4	0.25		0.35
19	Very low	Critical	Highly L		0.65			0.35
20	Very low	Critical	Definite	0.25	0.4			0.35
21	Very low	Catastrophic	Highly L	0.4				0.6
22	Very low	Catastrophic	Unlikely	0.4			0.25	0.35
23	Very low	Catastrophic	Likely	0.4		0.25		0.35
24	Very low	Catastrophic	Highly L	0.4	0.25			0.35
25	Very low	Catastrophic	Definite	0.65				0.35
26	Low	Negligible	Highly U				0.35	0.65
27	Low	Negligible	Unlikely				0.6	0.4
28	Low	Negligible	Likely			0.25	0.35	0.4
29	Low	Negligible	Highly L		0.25		0.35	0.4
30	Low	Negligible	Definite	0.25			0.35	0.4
31	Low	Marginal	Highly U				0.65	0.25
32	Low	Marginal	Unlikely				1	
33	Low	Marginal	Likely			0.25	0.75	
34	Low	Marginal	Highly L		0.25		0.75	
35	Low	Marginal	Definite	0.25			0.75	
36	Low	Moderate	Highly U			0.4	0.35	0.25
37	Low	Moderate	Unlikely			0.4	0.6	
38	Low	Moderate	Likely			0.65	0.35	
39	Low	Moderate	Highly L		0.25	0.4	0.35	
40	Low	Moderate	Definite	0.25		0.4	0.35	
41	Low	Critical	Highly U		0.4		0.35	0.25
42	Low	Critical	Unlikely		**0.4**		0.6	
43	Low	Critical	Likely		0.4	0.25	0.35	
44	Low	Critical	Highly L		0.65		0.35	
45	Low	Critical	Definite	0.25	0.4		0.35	
46	Low	Catastrophic	Highly U	0.4			0.35	0.25
47	Low	Catastrophic	Unlikely	0.4			0.6	
48	Low	Catastrophic	Likely	0.4		0.25	0.35	
49	Low	Catastrophic	Highly L	0.4	0.25		0.35	
50	Low	Catastrophic	Definite	0.65			0.35	
51	Average	Negligible	Highly U			0.35		0.65
52	Average	Negligible	Unlikely			0.35	0.25	0.4
53	Average	Negligible	Likely			0.6		0.4
54	Average	Negligible	Highly L		0.25	0.35		0.4
55	Average	Negligible	Definite	0.25		0.35		0.4
56	Average	Marginal	Highly U			0.35	0.4	0.25
57	Average	Marginal	Unlikely			0.35	0.65	
58	Average	Marginal	Likely			0.6	0.4	
59	Average	Marginal	Highly L		0.25	0.35	0.4	
60	Average	Marginal	Definite	0.25		0.35	0.4	
61	Average	Moderate	Highly U			0.75		0.25

The generation of the BRB rules presented in Table 5.1 corresponds to three failure parameters, F^{CP}, C^S, and F^L with associated assessment grades to identify the risk level. Generally, the numbers of belief rules are equal to the numbers of all possible combinations. In this study, the number of possible combination with three risk factors and five assessment grades describing the risk factors totals 125 rules.

The rule weighs are not considered in this rule because there is only one rule in each inference path leading to a final outcome. As an example, a belief rule can be developed if the three risk factors F^{CP}, C^S, and F^L with assessment grade importance (AGI) 0.25, 0.4 and 0.35 respectively, are considered. The AGI varies from one study to another, and is dependent on the experts consulted, the risk analyst judgement, and/or the combination of mathematical method applied. In this study a risk analyst judgement approach is used to assign the AGIs based on intuition. Using belief rule 8 as an example:

(0.35) $F^L{}_{\text{Very low}}$: (0.4) $C^S{}_{\text{Marginal}}$: (0.25) $F^{CP}{}_{\text{Likely}}$: the corresponding assessment scale on five (5) is noted i.e. '*5*' for very low, '*4*' for marginal and '*3*' for likely. The safety estimate {poor (*1*), fair (*2*), average (3), good (4) and very good (5)} have the following outcome, {0 poor, 0 fair, 0.25 average – *because* C^S *is one scale 3,* 0.4 good – *because* F^{CP} *falls on scale 4,* and 0.35 very good – *because* F^L *falls on scale 5*} for rule 8.

This method is used to generate all the rules used in this study. The rule inference is a set of conclusions with belief distributions that reflect the effects of all the rules whose truth values are greater than Zero. The results obtained from the truth degrees comes with a belief structure for each failure mode, and the Dempster rule can be used to combine these rules, which can be directly implemented as follows:

1) Tabulated input data received from experts is mapped to its corresponding rule
2) A figure is presented which translates the number of failure modes present in tabulated expert input data to produce a combination of total rules fired and a ratio of rules fired.
3) Tabulate the number of rules fired, with the corresponding rules weight identified as a ratio of failure mode identified.
4) Using the classical Dempster rule of combination, the data from each fired belief can be fused to get the final conclusion generated by aggregating all the rules, which are activated by the actual input of each failure mode.

To estimate failure likelihood in safety analysis, for example, one may use such linguistic terms as highly frequent, frequent, average, low and very low. These linguistic terms are the referential values for an antecedent attribute failure likelihood. In a general rule base, a referential set may be different in type (Yang *et al*., 2006). The importance of fuzzy IF-THEN rules stems from the fact that human expert judgements and engineering knowledge can often be represented in the form of fuzzy rules. Rules based on these types of linguistic variables are more natural and expressive than numerical and criticality calculations. It is clear that such rules can accommodate quantitative data such as F^L and qualitative judgemental data such as the C^S, and combine them consistently in risk level evaluation. More specifically, the kth rule in a rule base in the form of a conjunctive 'if-then' rule can be written as (Yang *et al*., 2006):

IF FL is very low AND CS is negligible THEN RL is low (5.2)

If the failure rate of a hazard is frequent and consequent severity is catastrophic and failure consequence probability is likely, then safety estimate is poor. The linguistic terms frequent, catastrophic, and likely are the referential values of the attribute's failure rate, consequence severity and failure consequence probability, respectively. Poor is the consequent of the rule corresponding to the output attribute safety estimate (Yang *et al*., 2006). A basic rule is composed of a collection of such simple 'if-then' rules. In more complicated rules, the relative importance of an antecedent attribute (attribute weight) is considered (Yang *et al*., 2006). To take into account belief degrees, the attributes in a rule are extended as;

R_k : if A1 then D_k, with a belief degree Bk, and an attribute weights, where (5.3)

Aki is the referential value of the ith antecedent attribute in the kth rule, Tk is the number of antecedent attributes used in the kth rule, and Bk the belief degree to which Dk is believed to be the consequent, given A_{k1},…A_{k2}…in the kth rule.

Rule (5.2) can be further extended to a so-called packet rule using a belief structure, where all possible consequents are associated with belief degrees. A collection of packet rules constitutes a rule base with a belief structure (called a belief rule base) as

R_k: Take, for example, the following belief rule in safety analysis:

R_k : If the failure rate is frequent and the consequence severity is critical and the failure consequence probability is unlikely, then the safety estimate is {(good, 0), (average, 0), (fair, 0.7), (poor, 0.3)}, where {(good, 0), (average, 0), (fair, 0.7), (poor, 0.3)} is a belief distribution representation for safety consequent, stating that it is 70% sure that safety level is fair and 30% sure that the safety level is poor. In this belief rule, the total degree of belief is 0.3+0.7 = 1, so that the assessment is complete. The referential value set for failure rate is given by A_{FR} = {very low, low, reasonably low, average, reasonably frequent, frequent, and highly frequent}.

Remark: antecedent attributes or the number of attributes is not required to be the same from one rule to another, even though they share a common consequent set $D = \{D_n ; n = 1,\ldots,N\}$.

A belief rule based in the form shown in eqn. 5.3 represents functional mapping between antecedents and consequents with uncertainty. It provides a more informative and realistic scheme for uncertain knowledge representation. Note that the degrees of belief B_{ik} could be assigned directly by experts, or, more generally, they may be trained and updated using dedicated learning algorithms if prior or up-to-date information regarding the inputs and outputs of a rule-based system is available. Once such a belief rule base is established, the knowledge contained in the belief rule base can be used to perform inference for a given input (Yang *et al*., 2006).

The relative importance of an attribute to its consequent (attribute weight) plays an important role in rule base inference. For example, using RL 123 in Table 5.1, highly frequent, catastrophic and likely, may lead to consequent [0.75 P, F, 0.25A, G, VG]. The values ‘0.75’ and ‘0.25’ represent the assigned weight of attribute. It is important to assign a weight to each attribute in order to show the relative importance of each attribute to the consequent. Obtaining the consequent weight attribute, the referential values of each safety parameter are used. In this study, the referential values are assigned by the risk analyst as 0.25, 0.4, and 0.65 for F^L, C^S and F^{CP} respectively (Yang *et al*., 2006).

5.5.4 Input transformation

Before an inference process can start, the relationship between an input (fact) and each referential value in the antecedents of a rule needs to be determined so that an activation weight for each rule can be generated (Yang *et al*., 2006). The basic idea is to examine all the referential values of each attribute in order to determine a matching degree to which an input belongs to a referential value. This is equivalent to transforming an input into a distribution on referential values using belief degrees. Once the matching between an input and the referential values of all antecedents in a rule are determined, they are processed to generate the weight rule, which is used to measure the degree to which the packet antecedent of the rule is activated by the input. To facilitate data collection, it is desirable to acquire assessment information in a manner appropriate to a particular attribute. By using the distribution assessment approach, a referential value of an attribute may in general be regarded as an evaluation grade, and the input for each i*th* attribute transformed to a distribution on the referential values of the attributes using the belief degrees.

5.5.5 Rule inference using the evidential reasoning approach

Based on the above belief rule expression, the ER approach can be used to combine rules and generate a final conclusion. Having represented each rule established in Table A, the ER approach can be directly applied as follows. First, transform the degrees of belief β_{jk} for all j = 1,….,N, K= 1,..,L into basic probability masses using the following ER algorithm (Yang and Xu, 2002). Suppose the two rules firing are denoted β^{j}_{Sij} is expressed (Nwaoho *et al.*, 2012).

5.5.6 Defuzzification of output

The use of ER is a resultant overall output is ranked in safety expression, poor, fair, average, good and very good. Its membership function is presented in Table 5.2.

Table 5.2: Membership function for crisp probability value

	1	2	3	4	5	6	7
P	0	0	0	0	0	0.75	1
F	0	0	0	0	0.75	1	0.25
AV	0	0	0	0.75	1	0.25	0
G	0.25	1	0.75	0	0	0	0
VG	1	0.75	0	0	0	0	0

Let P_1= P, P_2 = F, P_3 = AV, P_4 = G, P_5 = VG, then $P_1 = P_5^1/P_1^1$, $P_2 = P_4^1/P_1^1$, $P_3 = P_3^1/P_1^1$, $P_4 = P_2^1/P_1^1$, $P_5 = P_1$. $P_1^1 = [0.75\,(0.75+1)]6 + [1(0.75+1)]7 = 6.571$, $P_2^1 = [0.75\,(0.75+1+0.25)]5 + [1(0.75+1+0.25)]6 + [0.25(0.75+1+0.25)]7 = 5.75$

$P_3^1 = [0.75\,(0.75+1+0.25)]4 + [1(0.75+1+0.25)]5 + [0.25(0.75+1+0.25)]6 = 4.75$

$P_4^1 = [0.25\,(0.25+1+0.75)]1 + [1(0.25+1+0.75)]2 + [0.75(0.25+1+0.75)]3 = 2.25$

$P_5^1 = [1\,(1+0.75)]1 + [0.75(1+0.75)]2 = 1.428$

$P_1 = 1.428/6.571 = 0.217$, $P_2 = 2.25/6.571 = 0.342$, $P_3 = 4.75/6.571 = 0.729$, $P_4 = 5.75/6.571 = 0.875$

$$Q = 0.217T^1 + 0.342T^2 + 0.729T^3 + 0.875T^4 + 1.482T^5 \tag{5.4}$$

where T is the corresponding safety expression of the risk factor assessed

5.5.7 Intelligent decision system software

The aforementioned ER algorithm base in Nwaoho *et al.* (2012) is integrated into a software package called IDS (Yang & Dong, 2002), an intelligent decision system via the ER approach. The IDS software is used in this study to aggregate three or more experts' preference input data based on the ER algorithm. The capability of the IDS software is as referenced (Yang & Xu, 2002, Wang & Elhag, 2008 & Mokhtari *et al*. 2012). Yang and Xu (2002) used the IDS software to rank the overall performance of Kawazaki, BMW, Yamaha and Honda motorcycles. For the purpose of comparison they ranked them as per their average scores derived from the IDS. Likewise, Wang and Elhang (2008) used the IDS for three bridges condition assessment. In their assessment the maximum average score meant the best and safest one. Mokhtari et al. (2012) recently evaluated three Iranian ports of Bushehr, Shahid Rajaie and Chabahar under a fuzzy environment. The overall scores of the three nominated ports were calculated using IDS. As a result, this function of the IDS can prove the results obtained in this study.

5.5.8 Convert crisp possibility score (CPS) into probability value (PV)

The crisp value (Q) (in eqn. 5.4) of every safety description can be converted to its corresponding probability value (PV). In traditional fault tree analysis, input is required in the form of exact probability values; however, in fuzzy evidential reasoning the output is crisp possibility score (CPS) because the occurrence probability of each basic event is presented by fuzzy numbers (Wang *et al*., 2013). There is inconsistency between the real probability data and the possibility score. This issue can be solved by transforming the CPS into the form of probability of occurrence. The following conversion function (Onisawa, 1998, 1990) is proposed:

$$\begin{cases} PV = \frac{1}{10^m}, & CPS = 0 \\ 0, & CPS = 0, \end{cases} \tag{5.5}$$

$$\text{where } m = \left(\frac{1-cps}{cps}\right)^{\frac{1}{3}} \text{ x } 2.301 \tag{5.6}$$

5.5.9 Fussell-Vesely importance of basic events

At the time of a decision-making process, it is useful to have the events sorted according to some criteria. This ranking is enabled by importance analysis. In this study, the importance analysis is carried out based on the investigation of the importance of the middle events, base events and the minimum cut sets in the proposed tree (Wang *et al*., 2013). The Fussell-Vesely importance (FV-I) is employed to evaluate the contribution of the middle event to the occurrence probability of the stability failure in floating dry docks. It provides a numerical significance of all the base events in the stability failure fault tree and allows them to be prioritised. The FV-I of the base event is calculated by the following equation (Vinod *et al*., 2003):

$$I_{x_i}^{FV} = \frac{\mathrm{P_{TE}} - \left(\mathrm{P}_{TE}^{x_i=0}\right)}{\mathrm{P_{TE}}} \tag{5.7}$$

Where $I_{x_i}^{FV}$ is the FV-I index of the *i*th BE; $\mathrm{P}_{TE}^{x_i=0}$is the occurrence probability of the stability failure by setting the probability of the *i*th BE to 0. Decision makers use this importance index to improve the safety features of the analysed floating dry dock.

5.5.10 Cut sets importance

Cut sets importance (CS-I) is used to evaluate the contribution of each minimum cut set (MCS) to the top event (TE) occurrence probability of stability failure in a floating dry dock. This importance measure provides a method for ranking the impact of each MCS and identifying the most likely path that leads to the TE (Wang *et al*., 2013). In order to measure the CS importance, the output fuzzy possibility of each MCS of the stability failure in the floating dry dock fault tree needs to be converted into the probability value using the methods described in Sections 5.5.2-5.5.3. Then the MCS importance is estimated by calculating the ratio of the MCS probability to the stability failure probability. The calculation is performed as follows (Wang *et al*., 2013):

$$I_{\mathrm{j}}^{\mathrm{CS}} = \frac{\mathrm{P^j_{MCS}}}{\mathrm{P_{TE}}} \tag{5.8}$$

where $I_{\mathrm{j}}^{\mathrm{CS}}$ is the CS-I index of the *j*th MCS; P^j_{MCS} is the occurrence probability of the *j*th MCS.

5.5.11 Fault tree ++ software

This is an advanced software package that provides an efficient method for identification of critical components in the stability failure of floating dry docks, and provides ranking of different system components according to their importance using FV-I equations seen in Section 5.5.5. It also provides the results for MCS using equation 5.8. This software package is therefore essential for design alternatives and re-assessment to provide efficient design modifications for decision making in stability failure analysis of floating dry docks

5.6 Structural Failure of Pontoon Due To Excessive Transverse Bending

Structural failures of floating dry dock pontoons due to excessive transverse bending stresses were thought to be relatively rare occurrences. Accidents have been reported due to steel plate panels that have their axis parallel to the longitudinal axis of the dock and perpendicular to the line of transverse compressive stress in the plate when docking a ship (Heger, 2002).

5.6.1 18, 000 ton floating dock

This case involves an 18,000 metric ton capacity floating dock and 180 metres pontoon length. A vessel of 15,000 metric tons (well within the overall capacity of the dock) was being brought out of the water when the pontoon deck suddenly buckled along the length of the dock. The crew stopped pumping, re-ballasted the dock and undocked the vessel. When the empty dock was pumped back up, it could be seen that the pontoon deck and transverse bulkheads had sustained massive damage due to buckling plating. The causes of this accident upon investigation were due to: (a) Pontoon deck's strength; and (b) Method of ballasting.

5.6.1.1 Pontoon's Deck's Strength

The relative difference in stiffener orientation between longitudinal framed and transversely framed deck panels when resisting compression induced by transverse bending of the pontoon is shown in Figure 5.5.

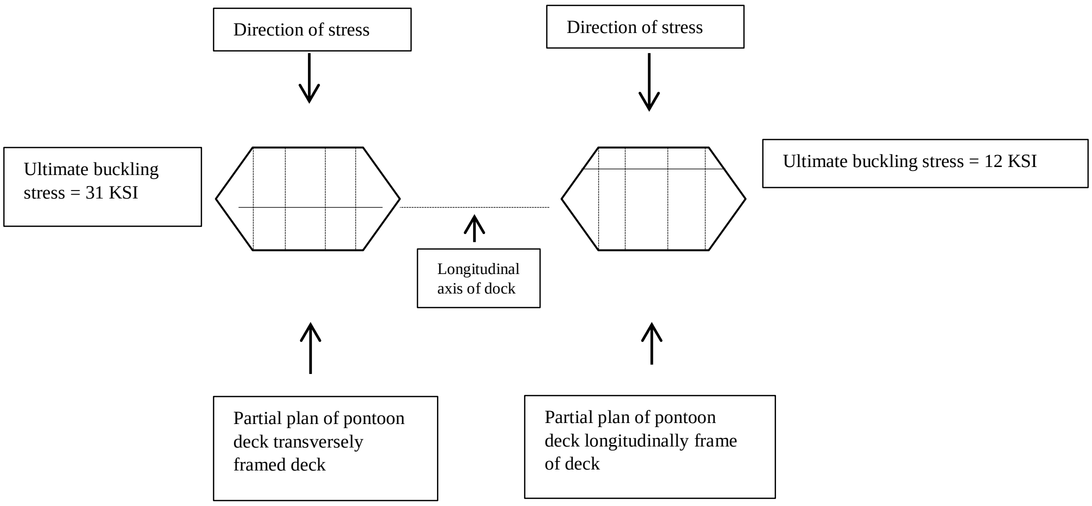


Figure 5.5: Comparison of Panels

The overall strength/capacity of the dock was adequate for lifting vessels within design limits. However, the pontoon deck was stiffened longitudinally. This resulted in deck panels that could buckle if the design limits were exceeded. This means the factor of safety before failure is less for a longitudinally framed pontoon than for a transversely framed pontoon. The dock's rated load capacity of 100 metric tons per metre was based on the structural and buoyancy capacity of the dry dock. According to Navsea (2012), '*a panel framed longitudinally does not have as great a capacity to resist transverse buckling as a transversely framed panel of similar dimensions. A 600mm x 2100 mm panel with plate thickness of 12mm has an ultimate buckling stress (stress in plate at time of failure) of 214,000 KPa if orientated transversely and 82,700 KPa if longitudinally'*.

5.6.1.2 Method of de-ballasting

During the docking, water was at first de-ballasted under the loaded blocks. Since the *block loads* exceeded the *buoyant capacity*, the water in the tanks under the vessel approached their minimum levels and the vessel had to emerge from the water (see Figure 5.6).

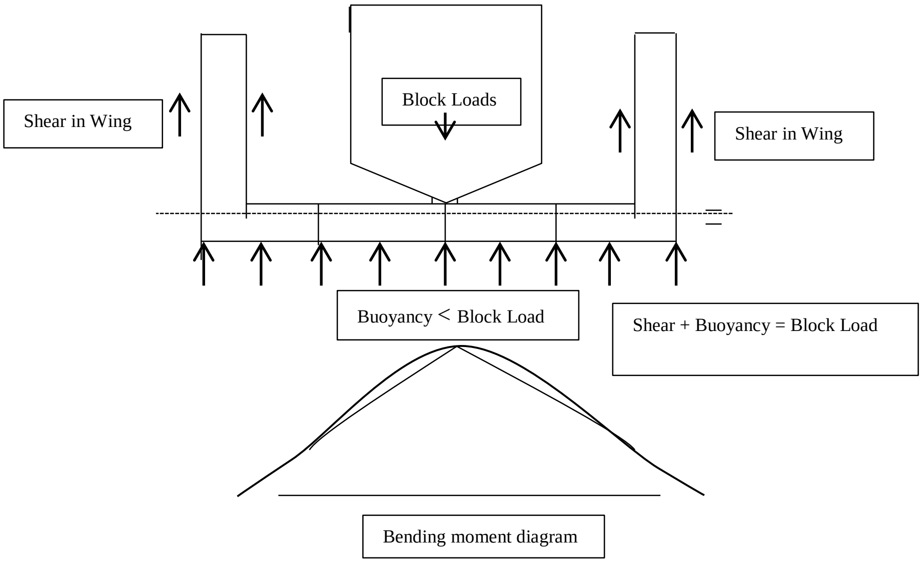


Figure 5.6: Bending moment diagram buoyancy less than load

Unfortunately, the crew was not monitoring longitudinal deflections and there was no method of monitoring transverse stresses. When a loaded tank is de-ballasted, the buoyancy created by removing water is offset by the weight of the vessel being lifted. The buoyancy is spread across the width of the pontoon but the vessel load is concentrated at the centre (on the keel). This creates a tendency of the pontoon to bend up around the keel block. This puts the bottom plate in tension and the pontoon deck plate in compression. Typically, the pontoon is designed to resist the full buoyancy of the tank offset by an equal but opposite vessel load on the keel blocks. If the block load over a tank exceeds the buoyant capacity of the tank, the excess load must be compensated by buoyancy from other areas of the dock. In this case, the additional buoyancy came from the unloaded tanks at each end of the dock (see Figures 5.7 and 5.8).

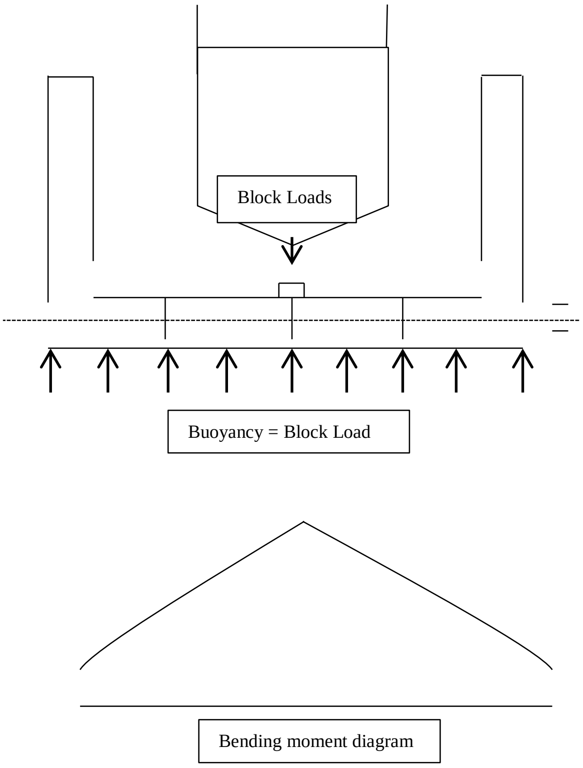


Figure 5.7: Bending moment diagram buoyancy equals load

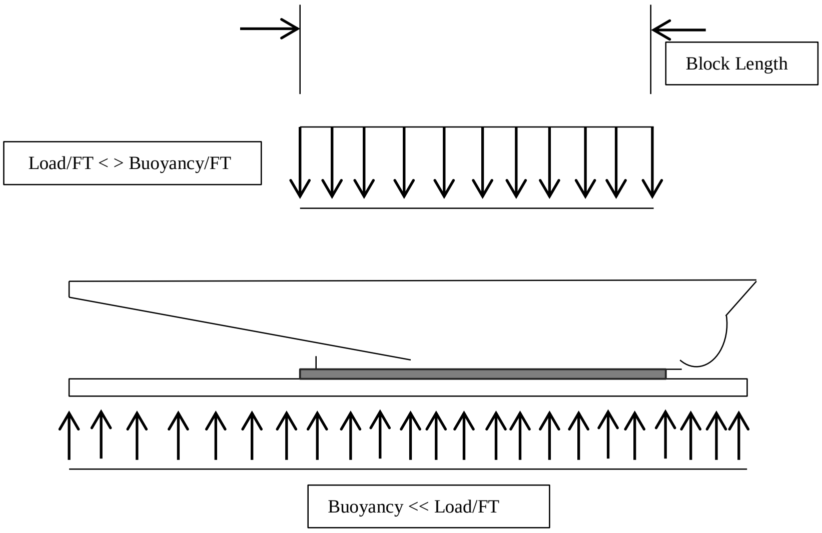


Figure 5.8: Distribution of buoyancy

De-ballasting of the unloaded end tanks was increased to try to get the pontoon out of the water. Pumping in this manner caused the dock to deflect longitudinally and increased the transverse bending moment on the pontoon. When the unloaded tank is de-ballasted, there is no ship weight to offset the increased buoyancy. The pontoon in this area wants to rise out of the water but is held down by vertical walls of the wings. The excess buoyancy is transferred longitudinally down the wing walls as shear load to the area where the ship loads exceeds the local buoyancy. This shear load in the wing walls provides additional force required to hold up the ship. This additional uplift force is located at the wing wall vertical shells and can greatly increase the transverse bending moment on the pontoon. This increase in the moment causes an increase in the bending stresses in the top and bottom plates of the pontoon (see Figure 5.10).

5.6.2 14,200 Ton floating dock

Case 2 involved a 14, 200 metric ton (14,000 long ton) capacity floating dry dock which was docking a CG-47 Class Naval Vessel. Before docking, block loading calculations were performed which showed the vessel's load per metre would exceed the dock's rated capacity if the standard keel block arrangement was used. To reduce the load per metre, the shipyard added additional keel blocks along the fantail. This had the benefit of lengthening the effective keel line and reducing the eccentricity between vessel LCG and block centreline. The result of the longer block line was a reduction in the load per metre to an acceptable value. A pumping plan was prepared based on this loading.

Experience with prior dockings had shown dimensional information on the fantails shape was unreliable for building blocks to the exact height. It was decided to set the initial height of the fantail blocks 75 mm too low. The ship would be landed on the 'standard' keel line, lifted 2 feet and stopped. At that point the fantail blocks would be packed tight by divers and then the vessel lifted the rest of the way. The vessel was landed and the dry dock dewatered according to the pumping plan. After the dock reached operating freeboard it was noticed that the pontoon deck plate had buckled along the entire length of the dock. The dock required extensive rebuilding. An investigation after the accident showed the accident occurred for the following reasons: (a) assumption on calculation; and (b) fantail blocks were not wedged up tight against the hull as originally believed.

5.6.2.1 Assumption on calculation

The keel block loading was calculated assuming that combined 'standard' keel blocks and the fantail blocks were a typical keel line in which a trapezoidal load configuration was developed. The pumping plan was developed based on this loading. In actuality, the vessel was landed on the ‘standard’ keel first and raised 2 feet. This had an effect of preloading the ‘standard’ keel line with higher loads near the aft knuckle before any load was imparted on the fantail blocks.

5.6.2.2 Fantail blocks error

The fantail blocks were not wedged up tight against the hull as originally believed. Divers installed shims in the 75 mm gap between the fantail blocks and hull but they left an approximately 6 mm gap between the shims and the hull. Because of the gap between fantail blocks and hull, the fantail blocks took no load until the vessel was pumped high enough to squeeze the standard blocks and deflect the dry dock until the gap closed up.

5.6.2.3 Pumping plan assumption

The load on the fantail blocks was much less than the pumping plan assumed and the load on the skeg area of the standard blocks was greater than the pumping plan assumed. This high load on the skeg area exceeded the design limit for the dock. This resulted in a situation very similar to the Case 1 accident. The excess buoyancy under the fantail blocks was transmitted through shear in the wing walls to the overloaded skeg area. This increased the transverse bending moment causing the deck to buckle in that area. Other areas failed ‘domino style’ once one area gave way.

5.6.3 Consequence analysis

The accident discussed in this section occurred while the dock was being deballasted in a manner that unknowingly magnified the compressive stress in the pontoon deck plates to a point which exceeded their buckling strength. The accident was caused by this phenomenon. *As the vessel was being pumped up*, the water in the loaded tanks was approaching minimum levels. The crew began to pump more out of the unloaded end tanks to attempt to get the pontoon deck out of the water.

The additional buoyancy force from the end tanks was transferred down to the wings the overloaded tanks. This increased the transverse bending force on the pontoon to the point when the pontoon deck plate panels buckled (probably first in the area of the ship’s knuckle). Once one area failed, the remaining panels would fail, ‘domino’ style.

5.7 Case Study: Pontoon Deck Failure Analysis

The stress in the pontoon deck exceeds the critical buckling stress of the deck panels; a collapse of a generic floating dry dock is presented in Figure 5.9.

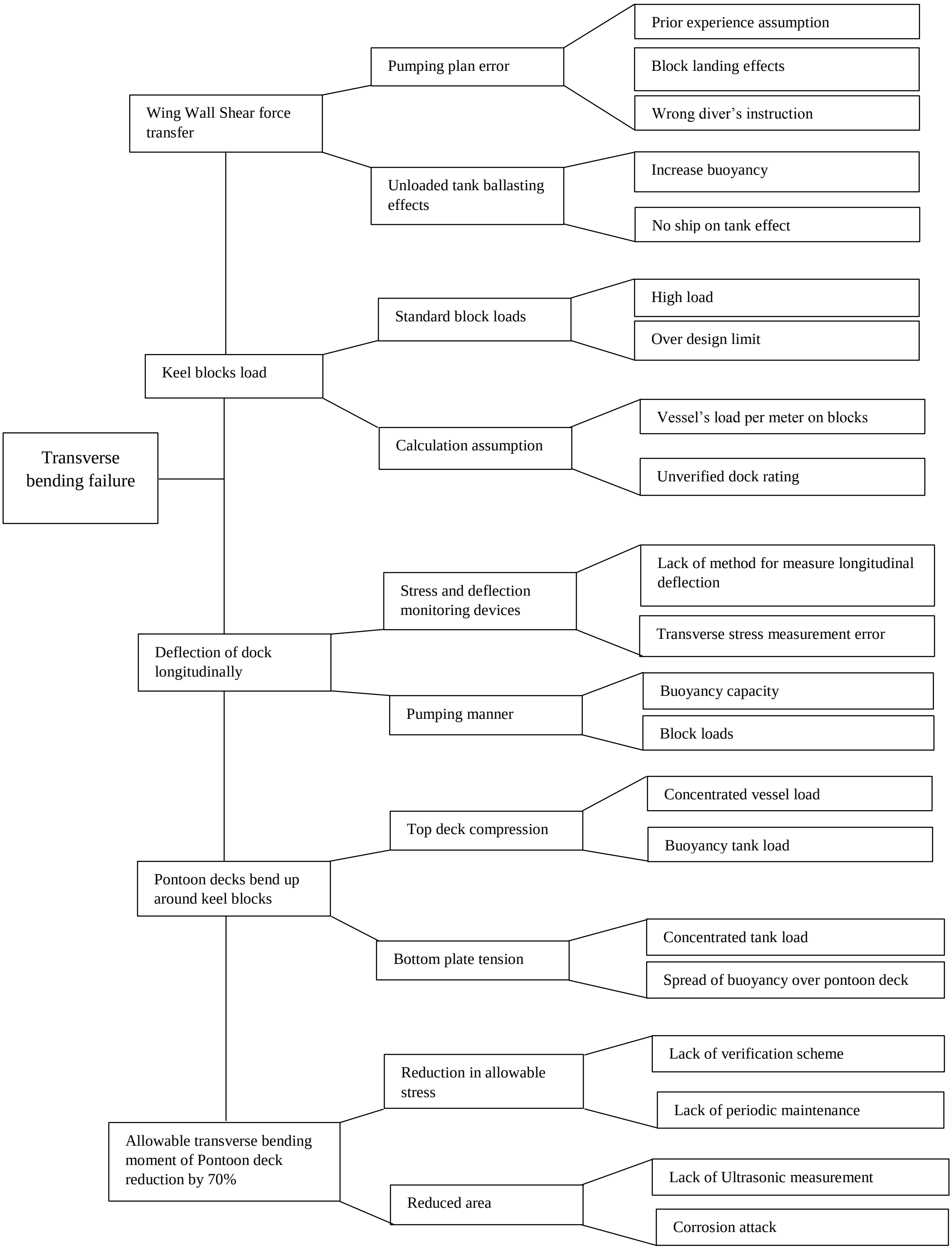


Figure 5.9: Pontoon deck failure model

5.7.1 Case study description

One of the important characteristics that will affect the whole system performance is the pontoon deck transverse bending resistance. Its pontoon deck is designed to operate with transverse stiffened panels. Research from accident investigation shows that longitudinally framed pontoon decks have less critical buckling strength of deck compared with transverse panel of the same dimension. The proposed methodology is designed for determination of the appropriate decision measures to operate a generic floating dock from a risk analysis perspective. In this study, criteria and alternatives are determined by questionnaire technique applied to shipyard specialists possible users working in the maritime sector and specialist working in shipyards. Criteria and sub-criteria were determined via questionnaire and deep discussions with specialists in the maritime sector (especially with the ones working in the floating dry dock area) and also by making use of previous studies and investigative reports. Criteria and sub-criteria (immediate events) of a generic pontoon deck failure are illustrated in Figure 5.11. Here the criterion '*Allowable transverse bending moment of pontoon deck by 70%*' has its sub-criteria '*reduction in allowable stress*' and '*reduced area of the pontoon deck'*. The causes of reduced area of the pontoon deck are '*corrosion attack'* and '*lack of ultrasonic measurement'* to determine loss in metal thickness in the pontoon deck. The causes of '*reduction in allowable bulking stress*es' are '*lack of verification scheme of metal thickness'* and '*lack of periodic inspections of the dock structure*'. Another criterion is '*Pontoon deck bend up around the keel'*, which has two sub-criteria, which are the reaction between '*top deck compression'* and '*bottom plate tension'*. The full interaction between sub-criteria is self-explanatory, as illustrated in Table 6.3.

The evaluation of the structural failure of the pontoon is to estimate a possibility degree to what extent the objective of docking a vessel in a floating dry dock is attained. At the lowest level, the value of the possibility degrees reflects the capacity 'no failure of the pontoon involving transverse bending failures'. The proposed belief structure FIS is used for risk assessment of pontoon deck structural failure whilst loading a vessel. One of the challenges in quantifying the risk in this realm is dealing with incommensurable and uncertain information, which needs rational aggregation schemes (Franciscque *et al*., 2009). Assuming that some incommensurable attributes are available that can indicate the risk at the lowest level, then the different levels of each attribute can be defined by experts. The experts are provided with a sample description of a generic failure model and potential accident model. As an example a specific evaluation is considered to illustrate the proposed method. Let it be required that the evaluation of the possibility degree of no failure of the pontoon involving bending transverse failure within the operation of a floating dry dock be assessed by three (3) parameters: (1) failure consequence probability (F^{CP}); (2) consequence severity (C^{S}); and (3) failure likelihood (F^{L}). For simplicity but without loss of generality, it is supposed that the evaluation linguistic grades involved in the case study are {very low, low, medium, high and very high}. Each indicator and the process are assessed into a belief distribution of these five values. For example, if the assessment of an output indicator A is: {(very low, β_1, low, β_2, medium, β_3, high, β_4, and very high, β_5)}, this implies the possibility of existing and the confidence level, β_i (i= 1,..,5) represents the degree of confidence in a particular belief.

The linguistic variables are defined to represent the level of each pontoon structural failure parameter converted to its corresponding fault tree. For the value of F^{L}, an expert may choose from a set of linguistic variables "very low (VL)", "low (L)", "medium (M)", "high (H)", very high (VH)". The value for attribute F^{CP} is defined by five linguistic variables "highly unlikely (HU)", "unlikely (U)", "likely (L)", "highly likely (HL)", and "definite (D)"; C^{S} is defined as "negligible (N)", "marginal (MA)", "moderate (M)", "critical (CR)" and "catastrophic (CT)". The fuzzy propositions are defined for these attributes based on literature review, experts' experience in docking a vessel in floating dry docks, and author's judgement. The FIS output, which is defined as the risk associated with DN27 pontoon structural failure, is characterised by five linguistic fuzzy grades: "very poor (VP)", "poor (P)", "average (A)", "good (G)", and "very good (VG)" with belief degree {(very low, β_1, low, β_2, medium, β_3, high, β_4, and very high, β_5)}.

The uncertainty and incomplete knowledge about the pontoon deck failure is modelled using the proposed FER system. For different conditions in the operation model, nonspecific and uncertain assignments to the fuzzy output risks levels are possible. Other parameters representing the rule uncertainty such as initial rule and attribute weights are also considered (Aminravan *et al.,* 2012). Experts are given the opportunity to provide nonspecific and uncertain assignments for the set of possible conditions. The experts used in this case study have different experiences in floating dry docking industry. Five were consulted with weights 0.1, 0.2, 0.3, 0.3, 0.5 which represents 08 years, 11 years, 15 years, 17 years, and 26 years respectively of different multi-national experts consulted for this study. The weights of the three attributes (indicators) were extracted through ER elicited from experts. The weights of the attributes remain unchanged in the designed FIS engine as failure consequence probability (F^{CP}) = 0.25, consequence severity (C^{S}) = 0.4 and failure likelihood (F^{L}) = 0.35.

The full account of all the rules of all knowledge bases and how the representation of uncertainty is presented as related to all the rules presented in the FRB Table 5.1. Suppose that F^{CP}_U corresponds to a set of indicators. Accordingly, U_F^{cp}, U_C^P and U_F^L correspond to the strength of the weights respectively. There are a total of 25 indicators. If each indicator is described by five grades, then there should be a total of 5 x 25 = 125 rules as constructed in Table 5.1 called the belief rule base (BRB) developed for this case study.

Table 5.3: The immediate event

Influence criteria	**Influencing Criteria**
Wing Wall Shear force	Pumping plan Unloaded tank ballasting effect
Keel blocks load	Standard block load Calculation assumption
Deflection of dock longitudinally	Stress and deflection monitoring devices error Inappropriate pumping method
Pontoon deck bend up around keel block	Top deck compression Bottom plate tension
Pumping manner	Top deck compression Bottom plate tension
Allowable transverse bending moment of pontoon deck reduction by 70 %	Reduction in allowable stress Reduce surface acting area

Table 5.4: Event symbols

	Top event		**Base event**
TE	Pontoon deck failure due to bending stress		
		B1	Corrosion attack
U	Immediate Event	**B2**	Lack of Ultrasonic measurement
		B3	Lack of periodic maintenance
U1	Allowable transverse bending moment	**B4**	Lack of verification scheme
U2	Pontoon deck bending up	**B5**	Spread of buoyancy over pontoon deck
U3	Pontoon deck deflection longitudinally	**B6**	Concentrated tank load
U4	Keel blocks	**B7**	Buoyancy tank load
U5	Wing walls shear force transfer	**B8**	Concentrated vessel load
		B9	Block loads
V	**Intermediate Event**	**B10**	Buoyancy capacity
		B11	Lack of method for measuring transverse stress
V1	Reduced area of pontoon deck	**B12**	Lack of method for measuring longitudinal deflection
V2	Reduction in allowable bulking stress	**B13**	Unverified dock rating
V3	Bottom plate tension	**B14**	Vessel’s load per meter on blocks
V4	Top plate compression	**B15**	Over design limit
V5	Pumping manner	**B16**	High load
V6	Lack of deflection monitoring devices	**B17**	No ship on tank effect
V7	Calculation assumptions	**B18**	Increased buoyancy
V8	Standard block loads	**B19**	Wrong instruction to diver
V9	Unloaded tank deballasting effect	**B20**	Block landing effects
V10	Pumping error	**B21**	Prior experience assumption

The information that is related to most uncertainty factors of failure in pontoon deck is not numerical. Fuzzy set theory provides an approximate model for the evaluation of risk faced by a typical floating dock pontoon failure through a linguistic approach. The procedure for fuzzy risk analysis is based on the framework outlined in Section 5.5, which consists of seven (7) steps: Hazard identification and fault tree construction, belief rule base inference, input transformation, rule inference using the evidential reasoning approach, defuzzification of output, convert crisp possibility score to probability value, importance calculation of immediate events and minimum cut sets. The first step is a compilation of a list of the most significant uncertainty factors and their descriptions, as in Table 5.3. This is the identification of risk associated with typical pontoon deck failure. However, little empirical research has focused on identifying the potential accident scenarios. The dimension of risk is listed in Table 5.4, formulated as a result of risk fault tree classification diagram in Figure 5.10.

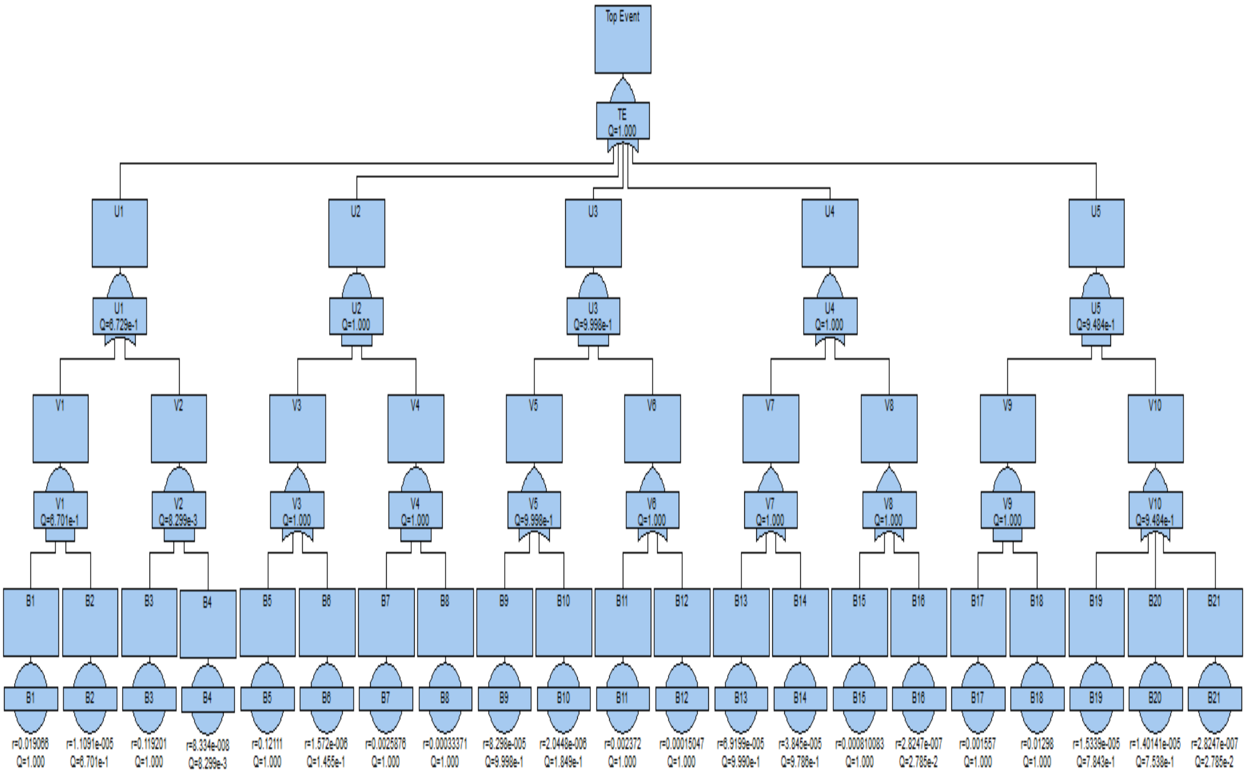


Figure 5.10: Fault tree diagram of pontoon deck failure

5.7.2 Expert linguistic input data

Due to lack of the precise probability data of Base events (BEs) of failures on pontoon deck in floating dry dock industry, the approach synthesizing the fuzzy set theory and experts' linguistic judgements is proposed to quantify the occurrence possibilities of the BEs. In this study five experts, including a reliability analyst are invited to perform the assessments of each BE. In order to capture experts' linguistic notions of the probabilities for each events, the linguistic scale presented in Section 5.7.1 is proposed. An example of input data for base event (B19), B12 and B1 is presented in this study for illustrative purposes. RIMER was proposed by Yang (2002) based on the evidence theory. RIMER consist of two parts, first building the BRB and then integrating the activated rules from the BRB using the ER algorithm, as briefly introduced in Section 5.5. When a BRB is constructed, it is required to cover all possible combinations of each attribute for each basic event (or attribute). Based on RIMER framework presented in Section 5.5, the steps considered are:

1. Step 1: Determine the three parameters concerning the structure of the BRB, including the number of attributes (base events) and alternatives for each attribute (middle events) and number of immediate events.
2. Step 2: Invite experts to link attributes to those having strong connections. The experts are required to select the appropriate linguistic scale of the base event probability of failure.
3. Invite experts to give rules for the input data.
4. Identify and integrate the activated rules using RIMER is the kernel part of this study.

5.7.3 Belief rule inference using evidential reasoning (ER)

To illustrate how the RIMER system works in this framework, the definitions of the belief rules using linguistic terms with the consequents having the dedicated belief degrees considering only three indicators are given in Table 5.1. Using the rule-base and the RIMER inferences, the consequent estimate is generated. In the following, three scenarios are explored on some possible combinations of the values to obtain the output. In this case, base events (B) – B19 (lack of periodic maintenance), B12 (buoyancy capacity), and B1 (priori assumption error) – are used. Scenario 1: the input for "lack of periodic maintenance (B19)" is given by five experts (E1.., E5, with different experience, hence different weights in the floating dry-dock industry) with the three indicators' linguistic description (F^{CP},C^{S} ,F^{L}) as presented in Table 5.5 to Table 5.10. Details of the input data for other base events not presented here is seen in Appendix 6.

Scenario 1: the input for "lack of periodic maintenance (B12)" is given by five experts (E1.., E5, with different experience, hence different weights in the floating dry-dock industry) with the three indicators' linguistic description (F^{CP},C^{S} ,F^{L}) as presented in Table 5.5.

Step 1: *Transform the input*. Here the input is given in linguistic terms with the belief degrees based on subjective judgement. Each belief is the individual matching degree of the input to the linguistic values. The input for B19 is presented in Table 5.5 and Figure 5.11.

Step 2: *Calculate the rule activation weights.* The activation weights W_K for all the 18 rules R_K (K =1…..9) are generated.

Table 5.5: Expert input for B19

E/B	**B 19**
E1	F^{L}_{HF} C^{S}_{CR} F^{CP}_{HL}
E2	F^{L}_{AV} C^{S}_{MO} F^{CP}_{HU}
E3	F^{L}_{L} C^{S}_{MO} F^{CP}_{HU}
E4	F^{L}_{L} C^{S}_{MO} F^{CP}_{U}
E5	F^{L}_{L} C^{S}_{CR} F^{CP}_{HU}
S O	S_{19}

HF	CR	HL
AV	MO	HU
L	MO	HU
L	MO	U
L	CR	HU

=

3/5 HF	1/5 CR	1/5 HL
1/5AV	3/5 MO	1/5 U
1/5L		3/5 HU

=

3 x 2x 3 = 18 rules

Figure 5.11: B19 Rules combination

Table 5.6: Rule weight for B19

NO	**Rule weight**	**F^{L}**	**C^{S}**	**F^{CP}**	**Rule**
1	(3/5) (1/5)(1/5)	HF	CR	HL	119
2	(3/5)(1/5) (1/5)	HF	CR	U	117
3	(3/5)(1/5)(3/5)	HF	CR	HU	116
4	(3/5) (3/5 (1/5)	HF	MO	HL	114
5	(3/5)(3/5)(1/5)	HF	MO	U	112
6	(3/5)(3/5)(3/5)	HF	MO	HU	111
7	(1/5)(1/5 (1/5)	AV	CR	HL	69
8	(1/5)(1/5)(1/5)	AV	CR	U	68
9	(1/5)(1/5)(3/5)	AV	CR	HU	67
10	(1/5)(3/5)(1/5)	AV	MO	HL	64
11	(1/5)(3/5)(1/5)	AV	MO	U	62
12	(1/5)(1/5)(1/5)	AV	MO	HU	61
13	(1/5)(1/5)(1/5)	L	CR	HL	44
14	(1/5)(1/5)(1/5)	L	CR	U	42
15	(1/5)(1/5)(3/5)	L	CR	HU	41
16	(1/5)(3/5)(1/5)	L	MO	HL	39
17	(1/5)(3/5)(1/5)	L	MO	U	37
18	(1/5)(1/5)(1/5)	L	MO	HU	36

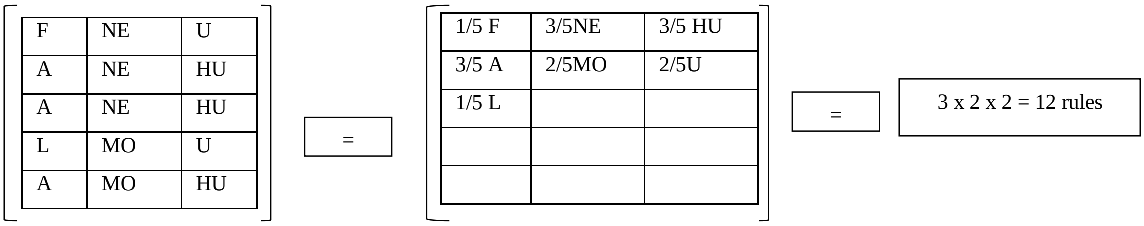
Expert aggregation of base events to obtain output

Step 3: *Combining activated rules.* The ER approach is employed to combine the activated rules. The activated rules can be combined to yield the following outcome: S19 = [0.2713VP, 0.1878P, 0.3351A, 0.0848G, 0.121VG], which means that we are 27.13% sure that B19 can happen with very poor confidence, 18.78% poor confidence, 33.51% average confidence, 8.48% good confidence, and 21.1% very good confidence.

Scenario 2: the input for "buoyancy capacity (B12)" is given by five experts (E1.., E5, with different experience, hence different weights in the floating dry-dock industry) with the three indicators' linguistic description (F^{CP},C^{S} ,F^{L}) as presented in Table 5.7 and Figure 5.12.

Table 5.7: Expert input for B12

E/B	**B 12**
E1	F^{L}_{F} C^{S}_{NE} F^{CP}_{U}
E2	F^{L}_{A} C^{S}_{NE} F^{CP}_{HU}
E3	F^{L}_{A} C^{S}_{NE} F^{CP}_{HU}
E4	F^{L}_{L} C^{S}_{MO} F^{CP}_{U}
E5	F^{L}_{A} C^{S}_{MO} F^{CP}_{HU}
S O	S_{12}



F	NE	U
A	NE	HU
A	NE	HU
L	MO	U
A	MO	HU

=

1/5 F	3/5NE	3/5 HU
3/5 A	2/5MO	2/5U
1/5 L		

=

3 x 2 x 2 = 12 rules

Figure 5.12: B12 Rules combination

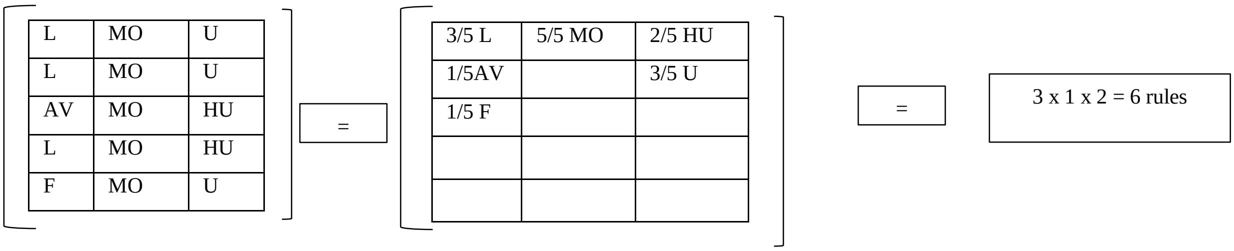
Table 5.8: Rule weight for B12

NO	Rule weight	F^{L}	C^{S}	F^{CP}	Rule	P	F	A	G	VG
1	(1/5) (3/5)(3/5)	F	NE	HU	76		0.35			0.65
2	(1/5)(3/5) (2/5)	F	NE	U	77		0.35		0.25	0.4
3	(1/5) (2/5)(3/5)	F	MO	HU	86		0.35	0.4		0.25
4	(1/5) (2/5)(2/5)	F	MO	U	87		0.35	0.4	0.25	
5	(3/5) (3/5)(3/5)	A	NE	HU	51			0.35		0.65
6	(3/5) (3/5)(2/5)	A	NE	U	52			0.35	0.25	0.4
7	(3/5) (2/5)(3/5)	A	MO	HU	61			0.75		0.25
8	(3/5) (2/5)(2/5)	A	MO	U	62			0.75	0.25	
9	(1/5) (3/5)(3/5)	L	NE	HL	26				0.35	0.65
10	(1/5) (3/5)(2/5)	L	NE	U	27				0.6	0.4
11	(1/5) (2/5)(3/5)	L	MO	HU	36			0.4	0.35	0.25
12	(1/5) (2/5)(2/5)	L	MO	U	37			0.4	0.6	

Scenario 3: the input for "priori assumption error (B1)" is given by five experts (E1.., E5, with different experience, hence different weights in the floating dry-dock industry) with the three indicators' linguistic description (F^{CP},C^{S} ,F^{L}) as presented in Table 5.9 and Figure 5.13.

Table 5.9: Expert input for B1

E/B	**B 1**
E1	$\mathbf{F^{L}}_{L}$ $\mathbf{C^{S}}_{MO}$ $\mathbf{F^{CP}}_{U}$
E2	$\mathbf{F^{L}}_{L}$ $\mathbf{C^{S}}_{MO}$ $\mathbf{F^{CP}}_{U}$
E3	$\mathbf{F^{L}}_{AV}$ $\mathbf{C^{S}}_{MO}$ $\mathbf{F^{CP}}_{HU}$
E4	$\mathbf{F^{L}}_{L}$ $\mathbf{C^{S}}_{MO}$ $\mathbf{F^{CP}}_{HU}$
E5	$\mathbf{F^{L}}_{F}$ $\mathbf{C^{S}}_{MO}$ $\mathbf{F^{CP}}_{U}$
S O	$\boldsymbol{S}_{1}$



L	MO	U
L	MO	U
AV	MO	HU
L	MO	HU
F	MO	U

=

3/5 L	5/5 MO	2/5 HU
1/5AV		3/5 U
1/5 F		

=

3 x 1 x 2 = 6 rules

Figure 5.13: B1 Rules combination

Table 5.10: Rule weight for B1

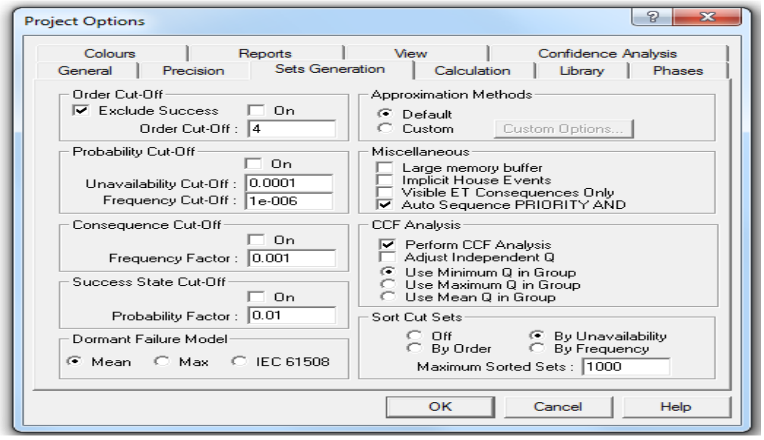
NO	Degree	F^{L}	C^{S}	F^{CP}	Rule	P	F	A	G	VG
1	(3/5) (5/5)(2/5)	L	MO	HU	36			0.4	0.35	0.25
2	(3/5)(5/5)(3/5)	L	MO	U	37			0.4	0.6	
3	(1/5) (5/5)(2/5)	AV	MO	HU	61			0.75		0.25
4	(1/5) (5/5)(3/5)	AV	MO	U	62			0.75	0.25	
5	(1/5) (5/5)(2/5)	F	MO	HU	86		0.35	0.4		0.25
6	(1/5) (5/5)(3/5)	F	MO	U	87		0.35	0.4	0.25	

5.7.4 Combining activation rules

The IDS software is used to combine the activation rules and presented in Table 5.11. Using eqn. 5.11, the output of combination rules is called crisp probability value (CPV) and presented in Table 5.11. Then lastly the probability value (PV) is calculated using eqn.5.12 and eqn. 5.13 is calculated and presented in Table 5.11.

5.7.5 Fault tree quantitative analysis

In order to ensure compatibility between CPS and the exact probability data obtained from sufficient statistical inference CPS must be converted into the form of probability data. This can be achieved by using eqn. 5.12 and 5.13. The corresponding probability of occurrence of base events B1 to B21 is presented in Table 5.11. This value can be input into the fault tree analysis software package discussed in Section 5.5.8 with t = 100,000 hours and with project options presented in Figure 5.14.



Order Cut-Off
☑ Exclude Success ☐ On
Order Cut-Off : 4

Probability Cut-Off
☐ On
Unavailability Cut-Off : 0.0001
Frequency Cut-Off : 1e-006

Consequence Cut-Off
☐ On
Frequency Factor : 0.001

Success State Cut-Off
☐ On
Probability Factor : 0.01

Dormant Failure Model
● Mean ○ Max ○ IEC 61508

Approximation Methods
● Default
○ Custom

Miscellaneous
☐ Large memory buffer
☐ Implicit House Events
☐ Visible ET Consequences Only
☑ Auto Sequence PRIORITY AND

CCF Analysis
☑ Perform CCF Analysis
☐ Adjust Independent Q
● Use Minimum Q in Group
○ Use Maximum Q in Group
○ Use Mean Q in Group

Sort Cut Sets
○ Off ● By Unavailability
○ By Order ○ By Frequency
Maximum Sorted Sets : 1000

Figure 5.14: Project options

Table 5.11: Probability value of base event

B	SAFETY OUTPUT (SO)	CPV	PV
B1	[0VP, 0.51F, 0.4915A, 0.37G, 0.8099VG]	0.70546	0.10966
B2	[0VP, 0.2785F, 0.198A, 0G, 0.5262VG]	0.09106	1.1091 x 10^{-5}
B3	[0.172VP, 0.399F, 0.2108A, 0.99G, 0.118VG]	0.93923	0.1192009
B4	[0VP, 0.0811F, 0.1755A, 0.353G, 0.3902VG]	0.0332	8.334 x 10^{-8}
B5	[0.161VP, 0.393F, 0.233A, 0.885G, 0.1241VG]	0.63376	0.12111
B6	[0VP, 0F, 0.1295A, 0.4015G, 0.4691VG]	0.05867	1.572 x 10^{-6}
B7	[0VP, 0F, 0A, 0.226G, 0.774VG]	0.413	2.5876 x 10^{-3}
B8	[0.1433VP, 0.3129F, 0.5438A, 0G, 0VG]	0.3012	3.371 x 10^{-4}
B9	[0VP, 0.439F, 0A, 0.561G, 0VG]	0.152	8.298 x 10^{-5}
B10	[0VP, 0.1134F, 0.4067A, 0.124G, 0.3554VG]	0.062	2.0448 x 10^{-6}
B11	[0VP, 0F, 0.317A, 0.8114G, 0.1287VG]	0.4025	2.372 x x 10^{-3}
B12	[0VP, 0.593F, 0.383A, 0.147G, 0.4099VG]	0.179	1.5047 x 10^{-4}
B13	[0.34VP, 0.3175F, 0.22687A, 0.4218G, 0VG]	0.1445	6.9199 x 10^{-5}
B14	[0VP, 0.133F, 0.542A, 0.2075G, 0.1163VG]	0.124	3.845 x 10^{-5}
B15	[0VP, 0F, 0.657A, 0.4047G, 0.5296VG]	0.2919	8.1003 x 10^{-4}
B16	[0VP, 0F, 0.25A, 0.4G, 0.35VG]	0.04157	2.8247 x 10^{-7}
B17	[0VP, 0F, 0A, 0.25G, 0.75VG]	0.355	1.557 x 10^{-3}
B18	[0VP, 0.211F, 0.9491A, 0.29G, 0VG]	0.6446	0.01298
B19	[0.271VP, 0.188F, 0.3351A, 0.0848G, 0.12VG]	0.0984	1.5339 x 10^{-5}
B20	[0VP, 0.214F, 0.459A, 0.326G, 0VG]	0.0963	1.4014 x 10^{-5}
B21	[0VP, 0.419F, 0.58A, 0G, 0VG]	0.2022	2.3121 x 10^{-4}

5.7.6 Results

Results of occurrence probability of top event show that at time t = 100, 000 hours, is 0.47% obtained from when project options in Figure 5.14 are used, which matches experts' judgement. An important aim of many reliability and risk analyse is to identify the most important base events or immediate events and minimum cut sets from reliability or risk viewpoint so that they can be given priority for improvements. The most crucial middle events in the pontoon failure fault tree for causing the occurrence of top event can be justified through FV-importance (FV-I) measures. Using Eq. (5.16), the FV-I indexes of all immediate event are calculated and ranked as shown in Figure 5.15 and Figure 5.16. The result helps to conclude that particular attention must be given to the events U4, U2, U3, U5 and U1 in descending order.

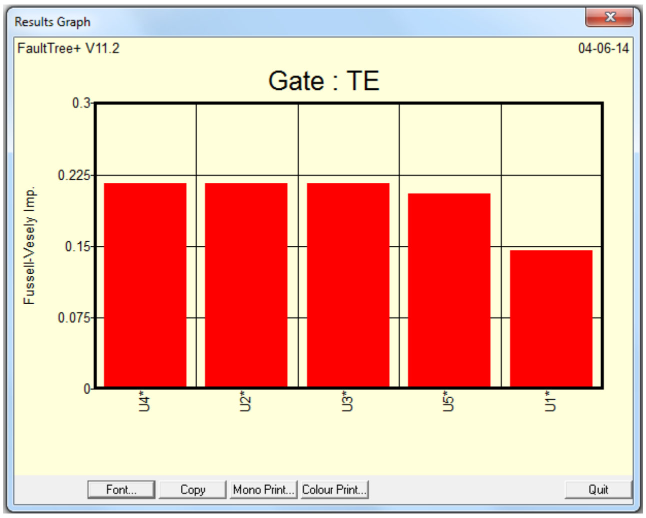
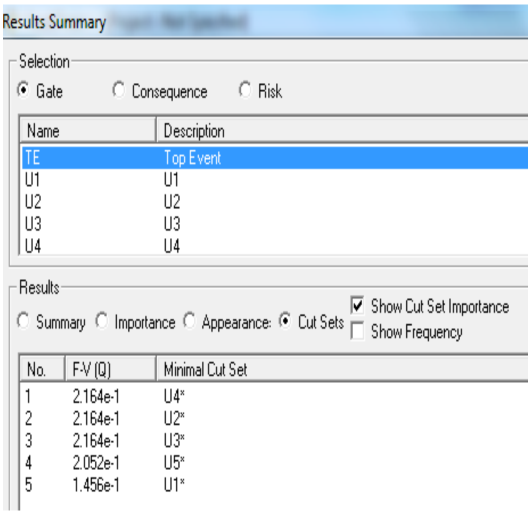


Figure 5.15: TE Graphical result


Results Summary

Selection

● Gate ○ Consequence ○ Risk

Name	Description
TE	Top Event
U1	U1
U2	U2
U3	U3
U4	U4

Results

○ Summary ○ Importance ○ Appearance: ● Cut Sets ☑ Show Cut Set Importance ☐ Show Frequency

No.	F-V (Q)	Minimal Cut Set
1	2.164e-1	U4*
2	2.164e-1	U2*
3	2.164e-1	U3*
4	2.052e-1	U5*
5	1.456e-1	U1*

Figure 5.16: TE Result summary

According to the FV-I and FV-I ranking result, the immediate events which have to be given the utmost attention are U4 (keel blocks loads) and U2 (Pontoon deck bending up around keel). The second immediate event to be receive attention is U3 (deflection of dock longitudinally), and fourth is U5 (Wing wall shear force). The least immediate events to receive attention is U1 (allowable transverse bending moment of pontoon deck reduction by 70%). The calculations have been carried out by fuzzy rule based approach and traditional approach. Table 5.10 presents the final important results. The result shows that;

1) Fuzzy rule base fault tree provides detailed information about the contribution of linguistic rating scale to the occurrence probability of base events.
2) There is a slight difference in the most critical middle events and slight differences in ranking of the base events.

5.7.7 Sensitivity analysis

Parameter sensitivity analysis is completed to show how sensitive the results of a belief update (propagation of evidence) are in variations in the values of a parameter in the model. The parameters of a model are the entries of probability of failures. Improving the failure rates of basic events 1, 3, 12, 13 and 19 by 55 % means that, RCO1 is well implemented and results from fault tree analysis shows the occurrence probability of top event reduced from 0.47% to 0.35, leading to a percentage reduction of 45.8%. Again, improving the failure rates of basic events 13, 20 and 21 by 30% means that, RCO 2 is well implemented and results from the fault tree analysis shows the occurrence probability of top event is reduced from 0.47% to 0.256% leading to a percentage reduction of 46.4%. Thirdly, improving the failure rates of basic events 2, 11, 17, 18 and 19 by 15% means that RCO 3 is well implemented and results from the fault tree analysis shows the occurrence probability of top event is reduced from 0.47% to 0.39% leading to a percentage reduction of 46.1%. The results from the sensitivity analysis shows that, an improvement of base events leads to reduction of occurrence of top event.

5.7.8 Discussion

The main reason for this difference is that fuzzy rule base FTA approach distributes all base events data uncertainty in the rule developed. In reality it is unreasonable to evaluate the occurrence of each base event by using a single-point estimate without considering inherent uncertainty and imprecision a state has. Overall the noteworthy attributes of the fuzzy rule base FTA approach, including the resilience towards lack of precision in base event data and more detailed probability information provided, confirmed that the fuzzy rule base FTA approach enables better probability assessment of the accident analysis and more reliable identification of the most critical middle events, and hence provides effective help for risk management and decision making.

According to the results of this study, the following conclusions are drawn: (1) The fault tree of floating pontoon failure is constructed, and the qualitative analysis of the tree shows that it totally includes 21 base events and 5 minimal cut-sets possibly leading to the accident; (2) The proposed approach which incorporates the fuzzy rule base theory and the conventional FTA technique is demonstrated as a viable and effective method for estimation of the top event occurrence probability when encountered with base event uncertainty; (3) The approach can be used to perform the important analysis of the pontoon failure fault tree which can provide valuable information for the decision maker to improve the safety performance of the floating docking operation.

FTA is a useful and effective method for identifying the root causes of certain accidents. In this study, FTA was used to show how root causes, which are also the basic events in the FT, interact to cause the complete loss of a floating dry dock. The results show the two most common root causes of these accidents are '*keel blocks load*' and '*pontoon decks bend up around keel*'. Therefore, sufficient attention and resources should be allocated to maintain the keel block calculation loading diagrams and also on the pontoon deck for bending around the keel.

5.7.9 Conclusion

This chapter outlines and explains a philosophy of subjective risk based risk analysis and decision making for risk control and management in floating dry docking operations using fuzzy logic and ER approaches. For each base event, the safety output is obtained first by using FRB-ER approach. Then the FT is used to calculate the occurrence probability of top event. Finally the most important immediate events are identified for decision making. The belief rule base system introduced in terms of flexibility, applicability and predictive performance was well balanced. Specifically, the major advantage of the BRB is that it offers and facilitates a very simple and efficient rule based generation approach with high performance from the given sample data from consulted experts in the floating dry docking industry. It is worth noting that that the distinct feature of this proposed BRB model leads to decision attributes definitions, rule base representation and generation, inference can be designed and implemented in an integrated fault tree system. A case study in a real world pontoon failure has shown the high efficiency and consistently better performance approach.

As traditional rule base including fuzzy rule base as well as belief rule base in RIMER are all special cases of the BRB, it's believed that such more general, flexible, and efficient and effective rule based representation, inference, and generation system is more acceptable in more complex systems. Rule base updating is also an interesting issue as well to be investigated to fit with dynamic situations, it is easy to see the proposed BRB actually already provided a much easier way to update the rule when new sample data is added, that is simply to add a new rule generated from this new data. It is possible to add a new test data result into the generated rule base iteratively in order to obtain a better overall performance.

Chapter 6 – Risk Control Options and Cost Benefit Analysis for Docking Operation

Summary

In this chapter, a failure/accident analysis model is proposed to develop the cost-effective safety measures for preventing accidents in dry docking and undocking operations. The model comprises two parts. In the first part is a quantitative failure analysis model built by Bayesian Network (BN) which can be utilised to present the corresponding prevention measures. In the second part, the proposed prevention measures are ranked in a cost-effective manner through a Bayesian Network (BN) approach. A case study is analysed as an illustration. The case study shows that the proposed model can be used to seek out failure/accident causes and rank the derived safety measures from a cost-effectiveness perspective. The proposed model can provide accident investigators with a tool to generate cost-efficient safety intervention strategies.

6.1 Introduction

When an accident occurs, it is important to understand the root cause in order to take effective preventive measures. A failure model provides the cause effect analysis. Failure analysis always implies a failure model is a set of assumptions of what the underlying mechanism is (Hollnagel, 2002). A failure model is an abstract conceptual representation of the occurrence and development of an accident; it describes the way of viewing and thinking about how and why an accident occurs (Huang *et al*., 2004). Accident model is also a very important process for providing input into the development of proactive and cost-effective safety measures (Psarros *et al*., 2010).

Naturally, a qualitative failure model has some weaknesses such as managing information systems for effective safety measures in: availability, performance, security, and modifiability, as well as in predicting values in different future scenarios in today's complex ship docking and undocking operation, which remains a great challenge (Franke *et al.*, 2009). First, a great number of factors influence a system's cost-effective safety measures. Second, the factors are intertwined in a complex manner. The researcher who sets out to model these interdependencies thus inevitably faces a discomforting number of modelling choices, all of which to some extent influence the ability of the final assessment framework to provide accurate decision support for managing decisions (Franke *et al.*, 2009). Furthermore, all modelling choices represent a cost in terms of collecting the information needed for actually using the model. This cost, whether expressed in money, effort, or time, must be kept under control, lest the entire effort of modelling the cost-benefit effectiveness be misguided (Franke *et al*., 2009).

As opposed to other publications addressing similar issues, such as Fenton and Pfleger (1997), Zuse (1997) and Kan (2003), this chapter adopts Bayesian formalism for expressing these uncertainties. The application of Bayesian networks (BNs) in a graphical environment for decision support using cost-effectiveness enables us to create the most efficient model, given the available information on uncertainties and the cost of data collection. With a hierarchy of nodes and states defined, a BN, which represents the relationship among failure variables, can be constructed.

The relationship depicted in any hierarchy structure is mapped onto the BN via its graphical representation with edges connecting nodes at a particular level to those located one level below. Even if the data available before modelling is scarce, the proposed model forces the modeller to make implicit assumptions explicitly, hence decisions become transparent. Furthermore, cost efficiency is taken into consideration in the early phases (IMO, 1997; Norway, 2000).

The purpose of cost benefit analysis (CBA) is to compare the costs and benefits associated with the implementation of safety measures. There are many papers carrying out safety assessment using a formal safety assessment (FSA) method, in line with well-established cost-effective criteria (IMO, 1997; Norway, 2000). This study applies BN techniques to analyse and verify the relationships among cost and benefit factors in dry docking and undocking operations, using expected cost factors, expected benefit factors, risk reduction factors, reference value factors, and uncertainty factors (IMO, 1997; Norway, 2000).

This chapter presents findings of analysis of stability and pontoon deck failure in floating dry dock docks, and the dry dock gate failure of graving docks. The examinations presented are: (1) the cost effectiveness of a failure model of a large dry dock gate in Birkenhead graving dock, UK, where the results of possible risk control options using fault tree-Bayesian network (FT-BN) are revisited; (2) the cost-effectiveness of an accident model of a typical floating dry dock pontoon failure due to transverse bending, whereby the outcome of using the fuzzy rule base with belief degree and evidential reasoning presents possible risk control options to help prevent future accidents of buckling failure of the deck (IMO, 1997; Norway, 2000).

The result of this failure/accident analysis model is safety risk measures categorisation. Lessons learned from accidents are important for identifying weaknesses in the present system and avoiding them in future (European Communities, 2001). For existing failure models, the quantitative analysis for failure modes and cost-effectiveness analysis for safety measures are not sufficient. As a response, an extended failure model analysis is constructed to seek failure causes and propose cost-effective safety measures in this chapter. The benefits of applying BN cost-effective measures are obtained where the findings provide great potential to improve the strategic planning of docking and undocking operations, hence adopting more suitable development activities related to risk.

This chapter is organised as follows: the problem is defined in Section 6.2. Section 6.3 provides the safety measures review. Section 6.4 contains the cost-effectiveness analysis factors which present how a BN can show relationships among cost, benefit, risk reduction, reference value and uncertainty factors. Section 6.5 presents a framework of BN-based cost-effectiveness relationship analysis. Section 6.6 provides the results and Section 6.7 is the conclusion and further study. Figure 6.1 presents the flowchart of the development of this study.

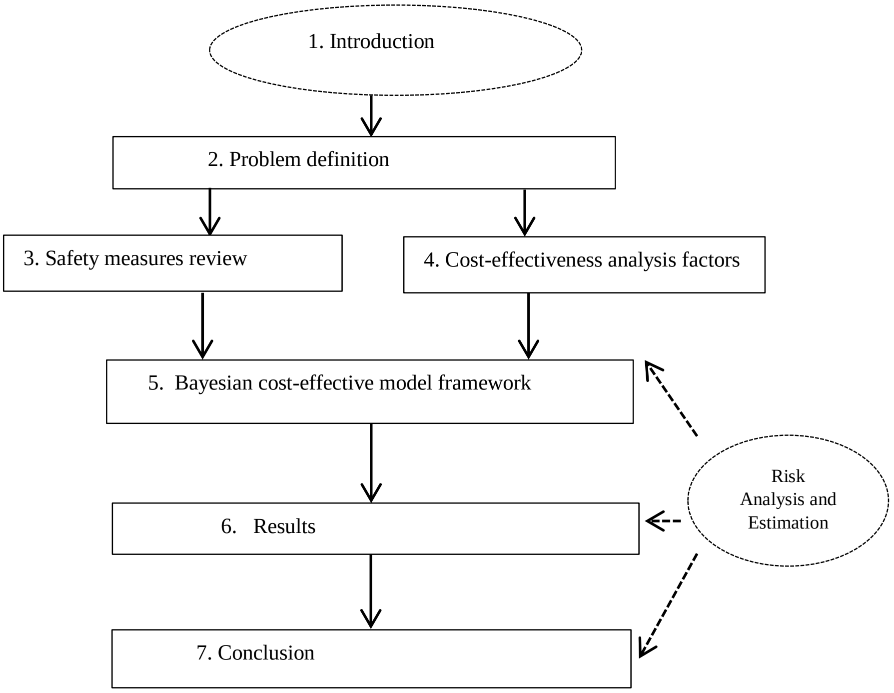


Figure 6.1: Flow chart of the development of study

6.2 Problem Definition

6.2.1 Background problem

The risk control options and cost benefit analysis, of a high level Formal Safety Assessment (FSA) pertaining to floating and graving dry docks according to the FSA guidelines issued by IMO (IMO, 2002). In this stage different risk control options (RCOs) are identified to control the major risks identified in the previous chapters. The RCOs are then assessed through cost benefit analysis using the standard IMO procedures and criteria for cost effectiveness. The assessment consists of three parts: (a) identification of relevant risk control options; (b) estimation of risk reducing effect of identified RCOs; (b) evaluation of cost benefit of RCOs. The results of previous tasks in Chapter 4, and 5 (risk analysis) are used in this of chapter risk control options and cost benefit analysis, covering the final steps of the FSA process. The list of prioritised hazards has been used as input for building risk models and for the identification of appropriate risk control options.

Risk control option is Step 3 of FSA, it proposes effective and practical RCOs compromising of the following stages: (1) focusing on risk areas needing control; (2) identifying potential RCOs; (3) evaluating the effectiveness of the RCOs in reducing risk by re-evaluating Step 2 (risk analysis); (4) grouping RCOs into practical regulatory options. The objective of this Chapter is to address points 1 - 4. The output from this step comprises: (a) a range of RCOs which are to be assessed for their effectiveness in reducing risk, and; (b) a list of interested entities affected by the identified RCOs.

Cost benefit assessment as described in MSC (2003) is to identify and compare the achieved risk reduction and benefits with the costs associated with the implementation of each RCO identified and defined in Step 3. A cost efficiency assessment following the IMO procedure may consist of the following stages: (1) consider the risks assessed in Step 2 (risk analysis) both in terms of frequency, consequence and failure consequence probability, in order to define the base case in terms of risk levels of the situation under consideration; (2) arrange the RCOs in a way to facilitate understanding of the costs and benefits resulting from the adoption of an RCO; (3) estimate the pertinent costs and benefits for all RCOs by reassessing the risk assuming the option under consideration is in place and comparing the risk level to the established base case; (4) estimate and compare the cost effectiveness of each option, in terms of the cost per unit risk reduction by dividing the net cost by the risk reduction achieved as a result of implementing the option; and (5) rank the RCOs from a cost-efficiency perspective in order to facilitate the decision-making recommendations in Step 5. There are several indices used by IMO that express cost effectiveness in relation to safety of life and the environment in the maritime industry are : Gross Cost of Averting a Fatality (GCAF) (eqn.6.1), and Net Cost of Averting a Fatality (NCAF) (eqn.6.2).

$$GCAF = \Delta C/\Delta Rs \tag{6.1}$$

$$NCAF = \Delta C\text{-}\Delta B/\,\Delta Rs \tag{6.2}$$

Where, ΔC is the cost per floating/graving dock of the risk control option during the lifetime of the system, ΔB is the economic benefit per floating/graving dry dock per ship resulting from the implementation of the risk control option during the lifetime of the system (includes environmental and property benefits), ΔR is risk reduction per floating/graving dock, in terms of the number of fatalities averted (ΔRs). Concerning the analysis of cost effectiveness, its criticism can be elaborated upon the following points. Firstly, because NCAF/GCAF imposes the maximum cost of averting a fatality, one feels that the avoidance of a fatality, if such is possible, should be done at all costs rather than having this cost fixed (Puisa and Vassalos, 2013).

In addition to this ethical dilemma, the continuous adjustment process of NCAF and GCAF values makes their application troublesome. Hence, an ideal situation would be to avoid imposing any maximum values at all or amend the approach by an alternative. Secondly, there is a clear overlap between NCAF and GCAF criteria. Specially referring to the original interpretation of the criteria in IMO (2003) page 56: (a) GCAF or NCAF- in principle, either of the two criteria can be used. However, it is recommended to firstly consider GCAF instead of NCAF. The reason is that NCAF also takes into account economic benefits from RCOs under consideration. This may be misused in some cases for pushing certain RCOs rather than other RCOs. If the cost-effectiveness of an RCO is in the range of the criterion, then NCAF may be also considered (Puisa and Vassalos, 2013).

6.2.2 Cost-effectiveness analysis problem

Cost-effectiveness analysis is often used as the basis for evaluation of alternative safety measures. In such an analysis, indices of the form ‘expected cost per expected number of lives saved’ are calculated. This method does not explicitly set a value to the benefit, e.g. value of a statistical life, as is required in a cost-benefit analysis. The cost-effectiveness analysis is a well-established discipline (Reed *et al*., 2010). There is, however, a gap between the theoretical cost-effectiveness analysis and the practical implementation of the tool as providing decision-making support. Ideally, the decision-maker should have a number of methods at hand. Some of these should be detailed and sophisticated and be used when a few safety measures are compared and the consequences of unfavourable decisions are severe. On the other hand, a simplified method to sort out some cost-effective measures for many alternatives in less complicated studies or pre-studies before more sophisticated comparisons is required (Reed *et al.*, 2010).

Traditional cost-effectiveness indices such as expected cost per expected number of lives saved provide useful insight, but, as pointed out by many analysts and researchers, cost-effectiveness indices based on expected values are not sufficient for evaluating cost effectively. Uncertainty must be considered beyond the cost-effectiveness indices. The main problem is that the expected values are conditional on specific background knowledge, and expected values could produce poor predictions (Reed *et al.,* 2010). Surprises may occur, and by only addressing expected values such surprises may be overlooked (Aven, 2007, 2008). A similar idea underpinning these approaches is seen in risk governance framework (Renn 2008) and the risk framework used by the UK Cabinet Office (Cabinet Office 2002).

6.2.3 *A priori* assessment problem

Many safety measure properties – availability, performance, security, and modifiability, to name a few – share the elusive feature that while they are easy to define *a posteriori*, i.e. after system implementation, such definitions give precious little guidance on how to ensure them *a priori*, i.e. before safety measure implementation. For example, measuring the cost of change of a system *a posteriori* is mere book-keeping (Franke *et al.,* 2009), but assessing it beforehand is a formidable task. Such assessment must be carried out by measuring variables available prior to the modification (Franke *et al.,* 2009).

A typical running cost with six key problems will be addressed in this chapter (Franke *et al.,* 2009): (1) the choice of *a priori* measurement quantity is the problem of finding a measure (complexity) that correlates accurately with the sought *a posteriori* quantity (cost of change); (2) definitional uncertainty must be handled since most concepts of safety measure can be interpreted in many different ways; (3) measurement devices, which range from software tools to expert estimates, are necessary and crucial instruments, but introduce further uncertainties; (4) selection of appropriate scales affects precision and imposes constraints on which statistical operations are permissible to be performed on the data; (5) discretisation of measurement variables simplifies measurements and maps them onto the desired scales, but only at the cost of lost accuracy; (6) the overall accuracy of the model must be weighed against the cost of performing the measurement. Out of several models, the most cost-efficient one always ought to be selected. Therefore, this chapter scrutinises a number of general problems related to measurements of cost-effective-related decision-making activities. It has been argued that these problems are not in general given sufficient thought when making decisions about how to model software systems in failure/accident modelling in docking and undocking a vessel. The risk safety measures used in this chapter provide ample proof of the concept regarding the method proposed. However, due to somewhat laborious nature, care should be taken when deciding how and when to model.

6.3 Safety Measures Review in Docking and Undocking Operations

6.3.1 Safety measures key information

The starting point for the suggested approach is the risk assessment process, as described in standards relevant for risk management – see for example ISO 31000 (2008) and ASNZS4360 (2004). The key information for evaluating safety measures is: (1) information about safety requirements in regulations; (2) alternative safety measures and their effects and cost; (3) risk reduction effect; (4) information about uncertainty; (5) decision-makers’ reference value; and (6) other factors like political issues, media focus, stakeholders’ preferences, etc. Attention is paid to aspects 2-5 in the list: the effectiveness, cost, uncertainty, reference value and risk reduction aspects. Aspect number 1 is not subject to the decision-making process in this study, and, although number 6 certainly affects the decision-making process, it is not covered by the cost-effectiveness model presented.

6.3.2 Risk safety measures for gate and pontoon deck failure

The main purpose of formal safety assessment is to rank accident causes, evaluate and control the risks for docking and undocking success using an effective risk analysis tool. After calculating the probability of accident, the appropriate risk control option is then implemented using a cost effective analysis. The overview of this framework is presented in Figure 6.2.The measurement of a docking operation is difficult because it may be changed by the docking phase and decision makers involved. However, these docking criteria are generally measured by time overrun, cost overrun, and technical performance (Baccarini and Archer, 2001; Williams, 1993).

The two failure models studied in the previous chapter of this research are revisited. The first (Study A) is the failure mode of a dry dock gate in Birkenhead, UK having 6 risk control options (RCO), 8 risk safety measures (RSM) and 24 risk control measures (RCMs). One accident model (Study B) is revisited as presented in chapter 5. This is the total loss of DN27 floating dry dock accident involving transverse bending failure of the pontoon consisting of 6 RCOs, 6 RSMs and 21 RCMs. RCOs are grouped into maintenance (Ma), awareness (A), inspection (I), monitor (Mo), prevention (P), re-design (D), guidelines (G) and operations (O).

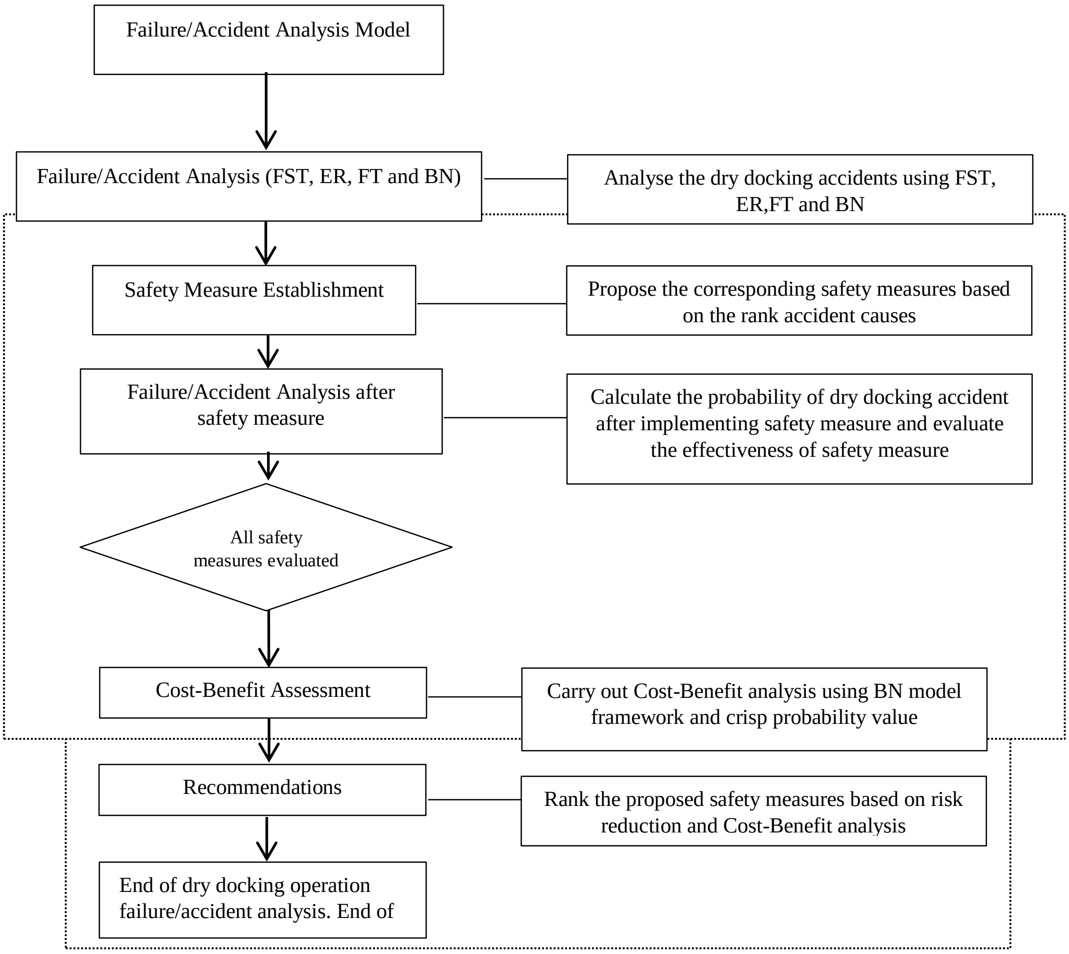


Figure 6.2: Formal safety assessment showing cost-benefit assessment

The output from the step of cost-benefit assessment is: (1) costs and benefits for each RCO identified from an overview perspective; (2) costs and benefits for those interested entities which are the most influenced by the problem in question and; (3) cost effectiveness expressed in terms of suitable indices. The purpose of this study only point to 1 and 3 just described. The risk safety measures for gate failure and pontoon deck failure are used as an input for cost benefit assessment. The benefits are the avoidance of accidents and these can be measured by evaluating the avoidance of harm to people, damage to property and environment, and other costs. Potential risk control options are: Operations (O) - (proper equipment), Awareness (A) - (improved training, drills to respond to common incidents, special procedures for higher risk evolutions, response plans, emergency plans), Preventive Maintenance (Ma) - (detailed procedures), Monitor (Mo) - (enhanced surveys), Inspection (I) - (improved enhanced surveys), Redesign (Rd) - (alarms, communication equipment, remote sensors, re-check lists for routine evolution) (Lois *et al.*, 2004). These are the six categories according to which the risk control options (RCOs) are evaluated. Table 6.1 presents the RCO for the failure mode of a dry dock gate in Birkenhead, UK.

Table 6.1 Risk safety measures for study A

RCOA	**RSM**	**RCM**
		1) Maintenance on rolling rails (Mo)
	1) Maintenance of towing system	2) Maintenance on rollers (Mo)
1. Maintenance		3) Maintenance on system failure (Mo)
	2) Improve awareness on preventing any buoyancy in upper chamber	4) Maintenance on air chamber (O)
		5) Check stability issues (O)
	3) Constantly controlling an even draught	6) Maintenance on flap wires (Mo)
2. Awareness		7) Maintenance on ballast tanks (Ma)
		8) Maintenance on wires (Ma)
	4) Improve structural inspection on structural elements	9) Maintenance of floors (Ma)
3. Inspection		10) Maintenance of walls (Ma)
		11) Maintenance on handrail (Ma)
	5) Monitor loads from water pressure-rolling of recess	12) Maintenance on ladder (Ma)
4. Monitor		13) Prepare against increased sea state (O)
		14) Prepare against high tides (A)
	6) Maintenance on gate water tightness	15) Prepare against hurricane (A)
		16) Increase inspection on the rubber L-shape (I)
5. Prevention		17) Improve strength on sea state effect (A)
	7) Preventing failure of control system	18) Improve strength against hurricane (P)
		19) Check water level (O)
6. Operations		20) Check control system (Mo)
		21) Improve undetactability (P)
	8) Tank Operations issues	22) Inspection on trimming tanks (I)
		23) Improve maintenance on scuttle tanks (Ma)
		24) Improve scrum tank inspection (I)

The expected output of this assessment is to identify cost and benefit for gate failure and pontoon deck failure from an overview perspective. The purpose of identifying risk control options is to propose an effective way of minimising high risks identified from the information produced in the risk assessment.

The identification of RCOs can have the following attributes: (1) those relating to the fundamental type of risk reduction (i.e. preventative or mitigating); (2) those relating to the type of action required and therefore to the cost of the action (i.e. the engineering procedural); (3) those relating to the confidence that can be placed in the measure (i.e. active or passive and single or redundant). The practical RCOs' action can be determined by repeating risk analyses and comparing the results to the original case (Lois *et al.,* 2004). Table 6.2 presents the total loss of DN27 floating dry dock accident involving transverse bending failure of the pontoon consisting of 6 RCOs, 6 RSMs and 21 RCMs. RCOs are grouped into maintenance (Ma), awareness (A), inspection (I), monitor (Mo), prevention (P), re-design (D), guidelines (G) and operations (O).

Table 6.2: Risk safety measures for study B

RCOC	**RSM**	**RCM**
1. Awareness		1) Avoid *a priori* experience assumptions (A)
	1) Improve knowledge on wing wall shear force	2) Check load landing effects (Mo)
		3) Improve divers' skills (A)
		4) Check increased buoyancy inspection (I)
	2) Inspect keel blocks load	5) Check no ship on tank effect (O)
2. Inspection		6) Check high load (Mo)
		7) Check design limit (Re)
	3) Monitor and inspect deflection of dock longitudinally	8) Proper calculations on loads on blocks (G)
		9) Double-check dock rating (G)
3. Monitor		10) Longitudinal deflection measuring follow-up (I)
		11) Transverse stress measuring improvement (Mo)
	4) Inspect pontoon decks for bend-up around keel	12) Check buoyancy capacity (A)
		13) Check block loads (A)
4. Operations		13) Inspection on buoyancy tank load (I)
		15) Check concentrated tank load (Mo)
		16) Check buoyancy over pontoon deck (O)
5. Guidelines	5) Guidelines' improvement on allowable transverse bending	17) Improve verification scheme (Mo)
		18) Improve periodic maintenance (M)
		19) Maintenance on gate water tightness (M)
6. Redesign		20) Improve ultrasonic measurement (I)
		21) Inspection on corrosion attack (I)

6.3.3 Risk control and risk re-assessment result

After the main failure or accident causes are discerned for studies A, and B, in Section 4.3.1, and Section 5.3.2 respectively, the corresponding RCOs are presented. In order to evaluate the effectiveness of the proposed safety measures, the reduction of accident probability after implementing every safety measure is calculated using the posterior inference of BN and fault tree analysis for the corresponding failure/accident model. Risk items which affect docking operations performance are measured by a sensitivity analysis in BN (study A) and fault tree (studies B). Important risk items with respect to identified RCOs that should be controlled are identified. After the risk items to be controlled are identified, the extents to which the probabilities of undocking operational performance risk are subjected with the relative change in various degrees of RCO implementation (Lee *et al*., 2009). To achieve a balance, the benefit of a RCO must be considered and compared to the cost of its implementation. The cost benefit BN model compares estimated levels of risk against the pre-established criteria and considers the balance between potential benefits. This enables decisions to be made about the extent and nature of treatments required and about priorities (ASNZS4360, 2004).

6.4 Cost-Effectiveness Analysis Factors

In the evaluation of safety measures a cost-effectiveness analysis may be adopted. A cost-effectiveness analysis compares the costs and the effects of a decision alternative, where the cost is measured in monetary terms and the effects are measured in natural units, such as lives saved (Boardman *et al*., 2006, Baron, 2000 and Petitti, 2000). Other important factors considered in the cost-effectiveness frameworks are: the reference values (Reed *et al*., 2010), the risk reduction effects (Wang *et al*., 2012) and uncertainty (Reed *et al*., 2010).

Upon proposing various safety measures, the next step is to carry out cost-benefit analysis (CBA) on each safety measure. CBA aims to rank different safety measures by identifying the benefits from accident prevention and the cost associated with safety measures. The evaluation of costs, benefits and other factors may be conducted using various techniques (IMO, 2007). However, due to unavailability of reliable data, these factors are very difficult to assess in an exact manner (IMO, 2007).

Safety experts as well as decision-makers often like to use linguistic variables to estimate costs, benefits and other associated factors affecting CBA incurred in safety improvements. Under such considerations, it may be more appropriate to estimate using ranking nodes in a BN, where the BN allows for experts to express their subjective judgements (Wang *et al.*, 2013). When applying the proposed cost-effective BN framework, the following activities should be carried out (Reed *et al.*, 2010) : (1) identify initiating events based on a facilitated brainstorming process supported by a checklist and comprehensive literature review in undocking and docking a vessel in graving/floating dry dock; (2) describe the potential consequences and associated probabilities for each initiating event; (3) categorise the potential consequences and associated probabilities by use of a qualitative or a semi-quantitative approach; (4) identify potential safety measures for initiating events.

A similar method has been used several times in risk analyses in this research. The initial part of this research is the risk assessment process carried out in a workshop where experts on the failure/accident model in floating/graving dock system participated, and the information gathered in the workshop was subsequently refined by the risk analyst for cost-effectiveness analysis. The factors affecting the cost effectiveness model are presented in Figure 6.3.

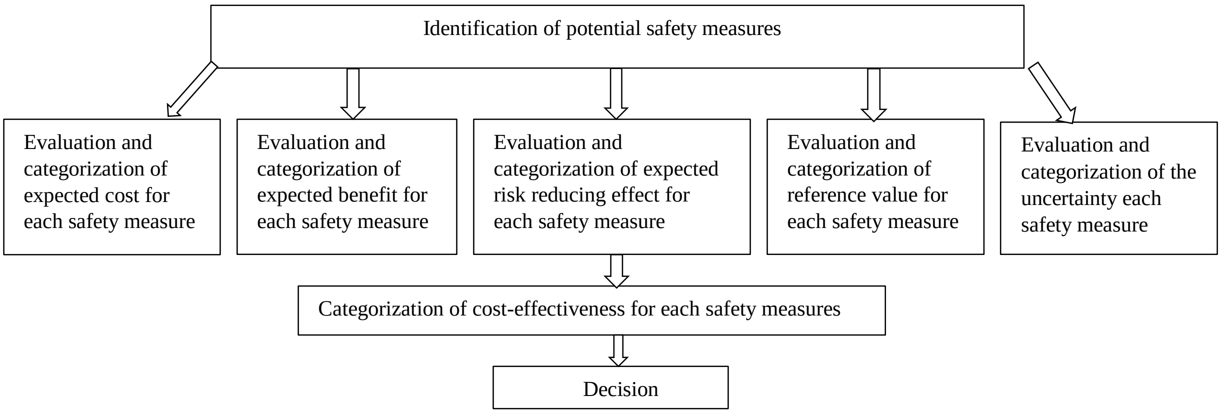


Figure 6.3: Factors affecting cost-effectiveness

6.4.1 Expected cost

As for the expected cost, it is common to use expected values for the cost dimension. Predictions of cost for implementing and operating safety measures can be calculated as several levels of detail. Examples of cost prediction categorisation (in £): very low < 10.000: low ≥ 10.000 and < 100.000: medium ≥ 100.000 and < 500.000: high ≥ 500.000 <1.000.000: and very high: > 1.000.000 (Reed *et al.*, 2009). All cost categories are covered in the assessment including, capital, appraisal, failure, operational, maintenance, training, administrative, formal safety assessment cost, cost of result accuracy, etc. (Lois *et al.*, 2004). For example, prevention cost is the cost of preventing failures, whilst failure cost is cost incurred as a result of scrap, rework, and failure. Appraisal cost is cost of measurement.

6.4.2 Evaluation of expected benefits

To find the expected benefit, the implementation can be done by paying attention to the expected risk reducing effect. For each risk reducing measure, the expected risk reducing effect should be given a qualitative assessment and description, and then be categorised according to the assigned expected risk reducing effect. Emphasis should be on the description of physical matters. Some answers may need the support of quantitative studies. The categorisation process should be based on some criteria to ensure consistency. What categories need to be applied depends on the level of detail of the analysis. In this study, the five categories used for expected benefit are: very low = no benefit from reduced risk, low = small benefit from reduced risk, medium = medium benefit from reduced risk, high = high benefit from reduced risk, and very high = very high benefit from reduced risk (Lois *et al*., 2004). In the categorisation process, both the initial risk picture determined in the risk assessment and the expected risk reducing effect given the initiating event have to be considered (Reed *et al.*, 2009).

6.4.3 Evaluation of expected risk reducing effect

A coarse evaluation of the risk reducing effect for each safety measure needs to be considered. It is also called the risk reduction after implementation of safety measure. It should be noted that in this factor the risk reducing effect (RRE*i*) is not measured as the product of probability and consequence, but is calculated in terms of reduction in the expected number of fatalities once a specific safety measure is implemented. This implies that, at least for the moment, only consequences incurring fatalities are considered. The risk reducing effect is calculated by:

$$\Delta \, \mathrm{RRE}i = \Delta \mathrm{P}_f \, . \, \mathrm{C}_f \tag{6.3}$$

Where, Δ RRE*i* is risk reduction effect [fatalities year^{-1}], ΔP_f is reduction of accident probability after adopting safety measure [year $^{-1}$], and C_f is the accident consequence [fatalities]. The linguistic scale can be used to estimate the accident consequence (Wang *et al.*, 2013).

6.4.4 Reference value for each safety measure

The results of a cost-effectiveness analysis may be expressed in two main ways: either as a cost-effectiveness ratio or as an effectiveness-cost ratio. The review and discussion of the cost-effectiveness analysis that follows focuses on the cost-effectiveness ratio, which is by far the more commonly used ratio. The reference value (R*i*) clarifies how much money the decision-maker (DM) is willing to pay to obtain one unit of effectiveness. Implementation of the safety measure is preferred to status quo if the decision-maker is willing to pay more to obtain one unit of effectiveness than the cost-effectiveness index expresses, which means that safety measure 1 is preferred to status quo if R is considered (Reed *et al.*, 2009).

6.4.5 Uncertainty effects for each safety measure

Valuable insight is provided through cost-effectiveness indices, but there is a need for a broader consideration of uncertainties, as discussed in Abrahamsen *et al*. (2004) and Aven (2008). The main argument is that the expected values are conditional background knowledge, and may produce poor predictions. The background knowledge includes historical system performances, system performance characteristics and knowledge about the systems in question. Assumptions are an important part of this knowledge. A result is that a true objective expectation value does not exist due to these uncertainties (U*i*) (Reed *et al.*, 2009). *Uncertainty may be regarded as the values predictability of the real outcomes*. High uncertainty may indicate that the *expected risk reduction effect* can give a poor prediction of the real risk reducing effect. The uncertainty categorisation should be based on some criteria to ensure consistency (Reed *et al.*, 2009).

Three categories are used for the uncertainty dimension: *Low uncertainty*, all the following conditions are met - The phenomena involved are well understood, the models used are known to give predictions with accuracy- The assumptions made are seen as very reasonable- Much relevant and reliable data and/or experience are available - There is broad agreement among experts. For the uncertainty dimension: *High uncertainty*, one or more of the following conditions are met- The phenomena involved are not well understood - The assumptions made represent strong simplifications-Data and/or experiences are unreliable - There is lack of agreement/consensus among experts. For the uncertainty dimension: *Medium uncertainty*, (i.e. conditions between high and low uncertainty e.g. - The phenomena involved are well understood, but the models used are too simple- Some reliable data and/or experience are available. The degree of uncertainty must be seen in relation to the effect/influence the uncertainty has on the predicted values. For example, a high degree of uncertainty combined with high effect/influence on the predicted values will lead to a conclusion that the uncertainty factor is high.

6.4.6 Ranking of safety measures for decision making

After the cost-effective analysis factors of each safety measure are assessed, the outputs should be combined to provide the overall assessment for the safety measures. The expected cost, expected benefit, risk reducing effect, preference values, and uncertainty of the *i*th safety measure can be evaluated using the crisp probability value (CPV) to rank the output safety measures in preference degree using the seven (7) safety states (See section 5.5.6).

6.4.7 Advantage of Bayesian network-based cost-effectiveness

Bayesian network techniques are a kind of powerful knowledge representation and reasoning tool under conditions of cost-related uncertainty with various domain expert background. In a practical application, the nodes of a BN represent uncertainty factors, and the arcs are the causal or influential links between these factors. The association with each node is a set of conditional probability distribution (CPD) that models the uncertainty relationships between each node and its parent nodes. Many applications have also proven that Bayesian network is an extremely powerful technique for reasoning the relationship among a number of variables under uncertainty (Lu *et al.*, 2009).

Compared with other inference analysis approaches for cost effectiveness analysis, BN techniques have four main advanced features in applications. Firstly, all the parameters in the BN have an understandable semantic interpretation (Mylly-maki, 2002). This feature helps users construct a BN directly by using their domain knowledge. Secondly, BN techniques have the ability to learn a relationship among its related variables. This not only allows users to observe the relationships among its variables easily, but also can handle some missing data issues (Heckerman, 1997).

Thirdly, BN techniques can conduct inference inversely; i.e. BN can conduct bi-direction inference. The fourth advanced feature is that BN techniques can combine *a priori* information with current knowledge to conduct inference as it has both causal and probabilistic semantics in cost-effectiveness analysis. These features will guarantee that using Bayesian networks is a good way to verify those initially identified uncertainty relationships between cost, benefit, risk reduction effect, reference value, and uncertainty factors in the formal safety assessment in docking and undocking a vessel in graving and floating dry docks.

6.5 Cost-Effective Bayesian Network Framework

In general, there are three main steps when applying Bayesian network techniques for cost effectiveness analysis and setting effective relationships for a practical problem: (1) creating a graphical BN structure for the problem, (2) calculating related conditional probabilities to establish a BN, and (3) using the established BN to conduct inference for finding possible relations among these factor nodes of the BN. The following sub-sections will describe the three steps in detail.

6.5.1 Creating a graphical structure for cost-effectiveness factor relationships

A graphical BN structure of cost-effectiveness factors' relationships can be created by linking nodes in the structure using lines. These lines in the graphical BN structure express the significant effect relationships between cost-effectiveness factors' nodes. These nodes and relationships shown in Figure 6.4 are considered as a result obtained from domain safety experts (E) and domain decision-makers' (DM) knowledge. In order to test these established relationships, structural learning is needed to improve the BN by using collected real data from docking and undocking operations. The factors discussed in section 6.4 are therefore used to complete the structured learning of the BN. The BN has 31 nodes and 30 links, and will be used for Bayesian rule-based inference for cost-effectiveness analysis. One BN is constructed by structural and parameter learning, using AgenaRisk (2013) desktop decision support software.

The Bayesian cost-effectiveness framework consists of the *node expect cost (Ci)* with five experts' (E1, E2, E3, E4 and E5) input, the node *expected benefit (Bi)* five experts' (E1_1, E2_1, E3_1, E4_1, and E5_1) input, the node *risk reduction effect (RREi)* with inputs A%, B%, C%, D%, and F% which signify a 15%, 25%, 50%, 60%, and 85% risk safety measure reduction respectively, the node *reference value (RVi)* with five decision-makers' (DM1, DM2, DM3, DM4, and DM5) inputs, and the *node uncertainty (Ui)* with five experts' (E1_2, E2_2, E3_2, E4_2 and E5_2) inputs. This model is used to obtain the output *net expected benefit* for each risk safety measure, for ranking purposes.

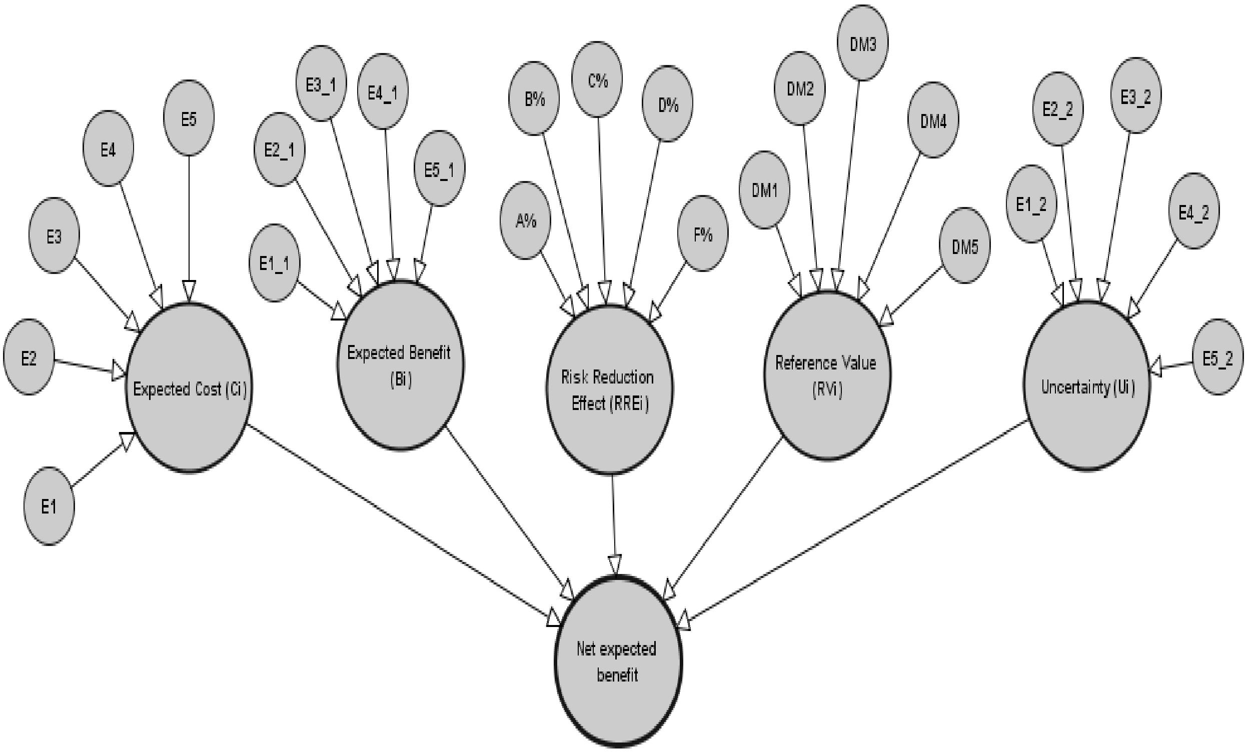


Figure 6.4: Cost-effective BN framework

6.5.2 Calculating the conditional probability distributions

Now let X= ($X_{0,\ldots\ldots,}X_m$) be a node set, and X_i (i=0,1….m) be a discrete node (variable) in a Bayesian network B (m = 31) as shown in Figure 7.4. The CPD for the node X_i is defined as $\beta^{B}_{x_i|PA} = P(X_i=x_i \mid Pa_i = pa_i)$ (Heckerman, 1996), where Pa_i is the parent set of the node X_i, pa_i, is a configuration (a set of values) for the parent set Pa_i of X_i and x_i is a value that X_i takes. Based on data collected in surveys, the CPDs of all nodes shown in Figure 7.4 can be calculated. Before using the BN to conduct inference, learning and establishing the parameters $\beta^{B}_{x_i|pa_i}$ from the data collected should be completed.

In general, the easiest way to estimate the parameters $\beta^{B}_{x_i|pa_i}$ is to use frequency. However, as the size of the data used in this study is not very large, using a frequency method may be not very effective (Lu *et al.*, 2000). BN is a probabilistic graphical model that represents a set of random variables and their conditional independencies via a directed acyclic graph (DAG) (Detcher and Mateescu, 2004). Conditional probability table (CPT) elicitation is a complicated issue due to a large number of judgements required to quantify the relationships of the BN (Rajabally *et al.*, 2004).

Wang *et al.* (2012) also proposed the use of Analytic Hierarchy Process (AHP) and the decomposition method to estimate the CPT for BN nodes. Suppose that a node X (with k states $x_1, x_2,\ldots\ldots x_k$) has n parents ($T^{(1)}, T^{(2)},\ldots. T^{(n)}$). The determination of the conditional distribution $P(X = x_i \mid T^{(1)}, T^{(2)},\ldots. T^{(n)})$ for all possible state combinations of the parents is a complicated process, especially when n is large or when each parent has a large number of states. Using the decomposition method means the conditional probability with each of the n parents can be calculated separately and then combined, while keeping a close look at the normalisation constant ‘α’ to ensure $\sum P(X = x_i \mid T^{(1)}, T^{(2)},\ldots. T^{(n)}) = 1$. This study, however, proposes the use of ranking nodes with experts’ judgements expressed with WeightedMin truncated distribution.

Fenton *et al.* (2007) suggested that ranked nodes represent discrete variables whose states are expressed on an ordinal scale that can be mapped onto a bounded numerical scale that is monotonically ordered with an underlying unit interval, [0,1]. As far as the user is concerned the underlying numeric scale is invisible – the displayed scale is still the labelled one rather than the numeric one, but the latter is used for the purposes of computation (a priori probabilities) and generating CPT.

The crucial thing about the ranked nodes is that they can make the BN construction and editing task much simpler than otherwise possible. By defining nodes as ranked nodes, it is possible to define the CPTs that satisfy the criteria described. As already indicated in section 4.7.3 (ranking nodes in BN), when a node is specified as a ranked node then, no matter how many states a node has, there is an assumption that there is an underlying numerical scale that goes from 0 to 1 in equal intervals. The 5 and 3 mapping scale and underlying numeric ranking is presented in Table 6.3 and Table 6.4. Users of BN never have to construct the mappings. All they need to know is that, irrespective of the linguistic descriptions of the states, the underlying model is working with a numerical scale.

Because it is a numerical scale, the numerical statistical distribution can be defined, and one especially useful distribution is truncated normal (TNormal) and weighted min function (WMIN) (see section 4.7.5) which can be used to generate CPTs, rather than the Normal distribution commonly assumed in linear regression for ranked causal nodes, the doubly truncated Normal distribution (denoted *TNormal* hereafter) as defined, for example in Cozman and Krotkov (1997), where all nodes are truncated in the [0,1] region. Unlike the regular Normal distribution (which must be in the range –infinity to +infinity) the TNormal has finite end points, denoted by TNormal (μ,ϖ^2, 0,1) where μ is the mean and ϖ^2 is the variance.

The priori ranking for E1-E5 is a 5 mapping ranked scaled and a variance $\varpi^2 = 0.2$ and the weights of the experts are E1= 0.1, E2 = 0.2, E3 = 0.4, E4= 0.4 and E5 = 0.5. The nodes E1_1 = 0.1, E1_2 = 0.2, E1_3 = 0.4, E1_4 = 0.4 E1_5 = 0.5 have a variance $\varpi^2 = 0.01$. The nodes A%, B%, C%, D% and F% have the same weights. The five parent nodes DM, have the following weights DM1= 0.2, DM2= 0.2, DM3= 0.3, DM4= 0.4, DM5=0.5 and variance $\varpi^2 = 0.002$. The parent nodes E1_1 are ranked on 3 points mapped with weights E1_1= 0.1, E2_1 = 0.2, E3_1 = 0.3, E4_1 = 0.3, E5_4 = 0.5.

Table 6.3: Five (5) scale mapping

Very low	[0,0.2), the range 0 to 0.2
Low	[0.2,0.4), the range 0.2 to 0.4
Medium	[0.4,0.6), the range 0.4 to 0.6
High	[0.6,0.8), the range 0.6 to 0.8
Very high	[0.8,1), the range to 1

Table 6.4: Three (3) scale mapping

Low	[0,0.333)
Medium	[0.333,0.666)
High	[0.6666,1)

After the prior distributions are determined, the Bayesian network also requires calculation of the posterior distributions of child nodes $\beta^{B}_{xi|pai}$. To conduct this calculation, this study assumes that the state of each node can be one of the five values: very low, low, medium, high, and very high, or it can be one of the three values: low, medium and high. Next, a weighted min function, WMIN, is used in the following general form:

$$WMIN = \min_{i = 1.....n} \left(\frac{w_i X_i + \sum_{i \neq j}^{n} X_j}{w_i + (n-1)} \right) \tag{6.4}$$

Where $w_i \geq 0$ and *n* is the number of parents nodes, with a suitable variance ϖ_Y^2 that quantifies our uncertainty about the result thus giving: p(Y/X) = TNormal [WMIN(X), ϖ^2,0,1]. Thus, WMIN function can be viewed as a generalised version of the normal MIN function. In fact, if all the weights w_i are large then WMIN is close to MIN. At the other extreme, if all the weights w_i =1, then WMIN is simply the average of the X_is. In this case the experts (E) and the decision-maker (DM) need only supply the parameter to both generate the CDP. According to Fenton *et al*. (2009) these sets of functions have been sufficient to generate almost the entire ranked node NPTs elicited in practice.

The CDPs of the cost effective Bayesian framework are: P (expected cost_ E1 0.1, E2 0.2, E3 0.4, E4 0.4 and E5 0.5) and has a variance ϖ_Y^2 0.01 that quantifies our uncertainty in a 'five ranked nodes': P (expected benefit_ E1_1 = 0.1, E1_2 = 0.2, E1_3 = 0.4, E1_4 = 0.5) with a variance ϖ_Y^2 0.01 that quantifies our uncertainty ranked in a five scale: P (risk reduction effect_ A%, B%, C%, D% and F% have the same weights) with a variance ϖ_Y^2 0.03 that quantifies our uncertainty ranked in a three scale; P (reference value_ DM1= 0.2, DM2= 0.2, DM3= 0.3, DM4= 0.4, DM5=0.5) with variance ϖ_Y^2 0.09 that quantifies our uncertainty ranked in a three scale; P (uncertatinty_E1_1= 0.1, E2_1 = 0.2, E3_1 = 0.3, E4_1 = 0.3, E5_4 = 0.5) with variance ϖ_Y^2 0.09 that quantifies our uncertainty ranked in a three scale. The CPD P (net expected benefit_expected cost = 0.1, expected benefit = 0.2, risk reduction effect = 0.3, reference value = 0.2, and uncertainty = 0.1) with variance ϖ_Y^2 0.08 quantifies our uncertainty ranked in a seven scale.

6.5.3 Inference

Having created a cost-effective factor relation BN with both its structure and all conditional probabilities defined for its nodes, it can be used to conduct inference among the relationships identified. The inference process can be handled by fixing the states of observed variables, and then propagating the beliefs around the network until all the beliefs (in the form of conditional probabilities) are consistent. Finally, the desired probability distributions can be shown in the network (Lu *et al.*, 2009). There are a number of algorithms used to conduct inference in BNs, which have different trade-offs between speed, complexity, generality, and accuracy.

The junction-tree algorithm produced by Lauriziten and Spiegelhlater (1988) is one of the most popular algorithms which uses an auxiliary data structure called a junction tree, and computes deep analysis of the connections between graph theory and probability theory, have a limitation such as joint distribution for each maximum clique in a decomposable graph where the initialisation and the process of message passing may miss some important information (Lauriziten & Spiegelhlater, 1988). Good tool support is therefore needed; both for the purpose of building realistic CPTs that adequately capture expert judgement and ranked nodes.

The normalised data can be dealt with by various computerised packages. The AgenaRisk software satisfies the requirements of enabling domain and decision-makers without any statistical knowledge to quickly generate distribution, and provides instant visual feedback to check that the CPTs are working as expected. In the process of inference, this allows experts and decision-makers to continually backtrack between previously estimated values and current values of both variance and expert weights in cases that were felt to be similar. Once the CPT is completed the experts could examine the sensitivity of results by running the model with a click of the mouse. The expectation of the resulting marginal distribution for net expected benefits would be monotonic and smooth given the influence factors of expected cost, expected benefit, risk reduction effects, reference value and uncertainty.

6.5.4 Net expected benefit crisp probability value

The resultant node, *net expected benefit* output is ranked in a 7 scale: lowest, very low, low, medium, high, very high, highest as presented in Table 6.5. This table shows its corresponding membership which can be used to obtain the crisp probability value (CPV) used in categorising the risk safety measures using equation 6.5.

Table 6.5: Membership function for crisp probability value

	1	2	3	4	5	6	7
VP	0	0	0	0	0	0.75	1
P	0	0	0	0	0.75	1	0.25
RP	0	0	0	0.75	1	0.25	0
AV	0	0	0.5	1	0.5	0	0
RG	0	0.25	1	0.75	0	0	0
G	0.25	1	0.75	0	0	0	0
E	1	0.75	0	0	0	0	0

$P_1 = P_7^1/P_1^1$, $P_2 = P_6^1/P_1^1$, $P_3 = P_5^1/P_1^1$, $P_4 = P_4^1/P_1^1$, $P_5 = P_3^1/P_1^1$, $P_6 = P_2^1/P_1^1$, $P_7 = P_1$

$P_1^1 = [0.75\ (0.75+1)]6 + [1(0.75+1)]7 = 6.571$, $P_2^1 = [0.75\ (0.75+1+0.25)]5 + [1(0.75+1+0.25)]6 + [0.25(0.75+1+0.25)]7 = 5.75$, $P_3^1 = [0.75\ (0.75+1+0.25)]4 + [1(0.75+1+0.25)]5 + [0.25(0.75+1+0.25)]6 = 4.75$, $P_4^1 = [0.5(0.5+0.5+1)]3 + [1(0.5+0.5+1]4 + [0.5(0.5+0.5+1]5 = 4$, $P_5^1 = [0.25\ (0.25+1+0.75)]2 + [1(0.25+1+0.75)]3 + [0.75(0.25+1+0.75)]4 = 3.25$, $P_6^1 = [0.25\ (0.25+1+0.75)]1 + [1(0.25+1+0.75)]2 + [0.75(0.25+1+0.75)]3 = 2.25$, $P_7^1 = [1\ (1+0.75)]1 + [0.75(1+0.75)]2 = 1.428$

$$Q = 0.217T^1 + 0.248T^2 + 0.301T^3 + 0.357T^4 + 0.439T^5 + 0.634T^6 + 1T^7 \tag{6.5}$$

6.6 Results

Table 6.6: Truth table for risk control options for studies A and B obtained from experts

	RCOA 1	**RCOA 2**	**RCOA 3**	**RCOA 4**	**RCOA 5**	**RCOA 6**
E1	M	M	VH	M	H	H
E2	VL	M	VH	H	H	VH
E3	VH	H	H	H	M	H
E4	M	M	L	L	VH	H
E5	M	L	M	M	H	M
E1_1	VL	M	M	M	M	VH
E2_1	M	L	L	M	H	H
E3_1	H	L	L	H	H	H
E4_1	M	VH	VH	VH	H	M
E5_1	H	H	H	M	H	H
A%	L	M	M	L	L	L
B%	L	H	H	L	L	M
C%	L	L	L	L	M	M
D%	L	H	H	H	H	H
F%	M	H	M	H	L	H
DM1	M	M	M	M	H	M
DM2	L	H	H	M	H	H
DM3	L	L	L	L	H	H
DM4	H	H	H	L	H	H
DM5	L	H	H	H	H	M
E1_2	L	M	M	M	M	L
E2_2	M	M	M	L	M	L
E3_2	M	L	L	L	H	L
E4_2	L	M	M	L	L	L
E5_2	M	M	M	M	M	L

	RCOB 1	**RCOB 2**	**RCOB 3**	**RCOB 4**	**RCOB 5**	**RCOB 6**
E1	L	VH	M	L	H	M
E2	M	VH	H	M	H	VH
E3	L	H	H	VH	H	VH
E4	M	H	H	H	H	H
E5	M	H	M	L	H	VH
E1_1	VH	H	M	H	VH	M
E2_1	VH	H	VH	H	VH	M
E3_1	VH	H	VH	H	H	M
E4_1	VH	VH	VH	H	M	H
E5_1	VH	VH	H	H	M	H
A%	L	L	L	L	M	M
B%	M	L	L	M	L	L
C%	L	L	L	L	L	L
D%	L	L	M	M	L	L
F%	M	L	M	L	L	L
DM1	L	M	M	H	M	H
DM2	M	H	M	H	H	H
DM3	H	H	H	H	H	M
DM4	H	H	H	H	H	H
DM5	H	H	H	H	H	H
E1_2	M	L	L	M	L	M
E2_2	M	L	M	M	L	M
E3_2	M	L	L	L	L	L
E4_2	M	L	L	L	L	L
E5_2	L	L	H	L	M	L

RCOs subjective assessment obtained from experts opinions and decision maker reference value under uncertainty. Five experts and five decision makers are consulted to obtain truth table. The results from risk reduction effect using fault tree analysis (A%, B%, C%, D%, and F%) are also presented.

6.6.1 Running model

Using AgenaRisk desktop 2013, the truth table obtained from participating experts and corresponding decision maker for each RCOs are depicted in Table 6.7 and Table 6.8.

Table 6.7: Result for study A

	Lowest %	V low %	Low %	Medium %	High %	V High %	Highest %	CPV%	Result No
RCOA1	3.017	11.449	24.474	29.922	20.967	8.332	1.839	1.822	R1
RCOA2	2.816	11.027	24.133	30.034	21.385	8.653	1.953	1.676	R2
RCOA3	0	5.21	16.03	28.143	28.325	16.197	5.144	0.495	R3
RCOA4	0	3.377	12.472	26.039	30.622	19.957	7.022	0.373	R4
RCOA5	0	3.377	12.472	26.039	30.622	19.957	7.022	0.377	R5
RCOA6	0	4.106	13.908	26.942	29.752	18.409	6.196	0.415	R6

Table 6.8: Results for study B

	Lowest %	V low %	Low %	Medium %	High %	V High %	Highest %	CPV%	Result No
RCOB1	0	5.122	16.486	29.041	28.403	15.466	4.63	0.536	R7
RCOB2	0	3.877	13.929	27.773	30.417	17.903	5.506	0.447	R8
RCOB3	0	3.528	12.918	26.463	30.425	19.417	6.716	0.389	R9
RCOB4	1.074	5.853	17.533	29.351	27.605	14.458	4.126	0.816	R10
RCOB5	1.016	5.564	17.004	29.238	28.115	14.856	4.208	0.792	R11
RCOB6	0	4.753	15.615	28.743	29.254	16.126	4.697	0.509	R12

A graphical representation of result No. 2 is presented in Figure 6.5. The results for Study A are presented in Appendix 7. Results No. R7-R12 for Study B are represented in Appendix 7.

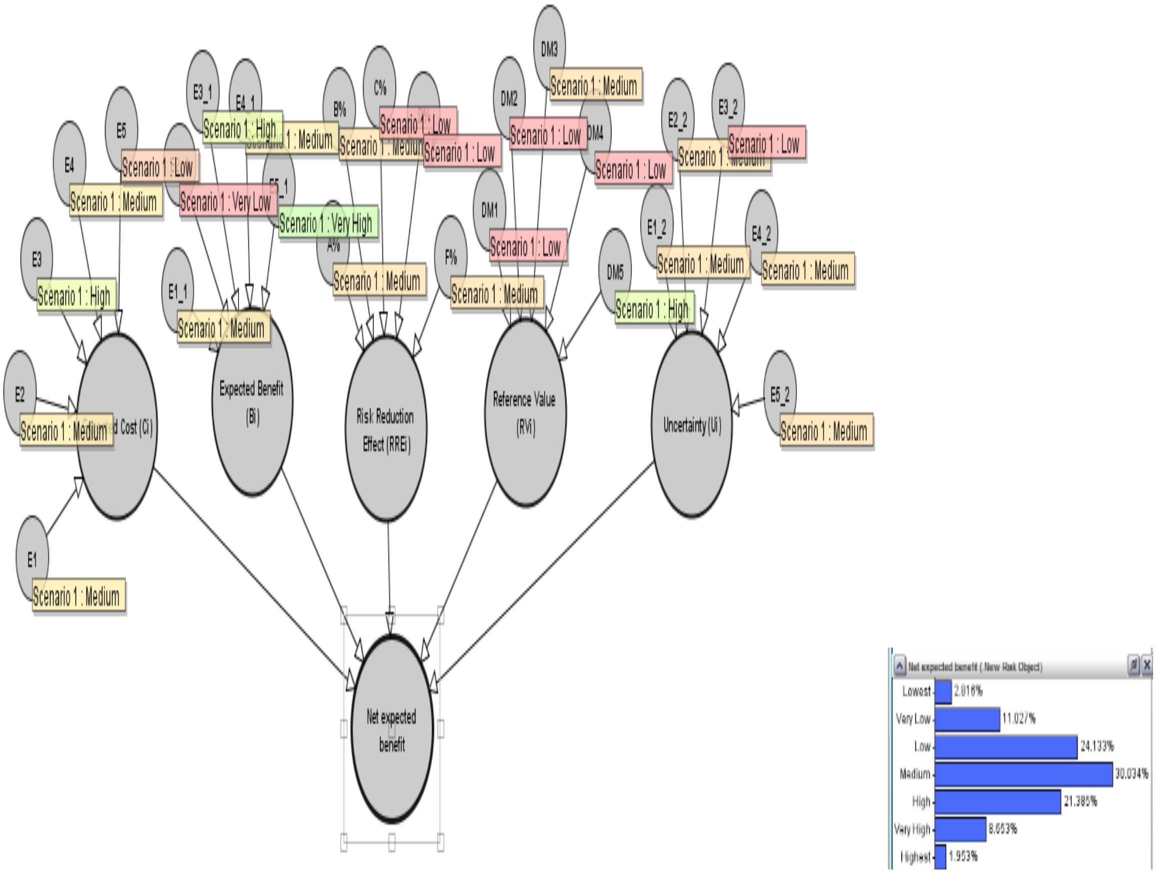


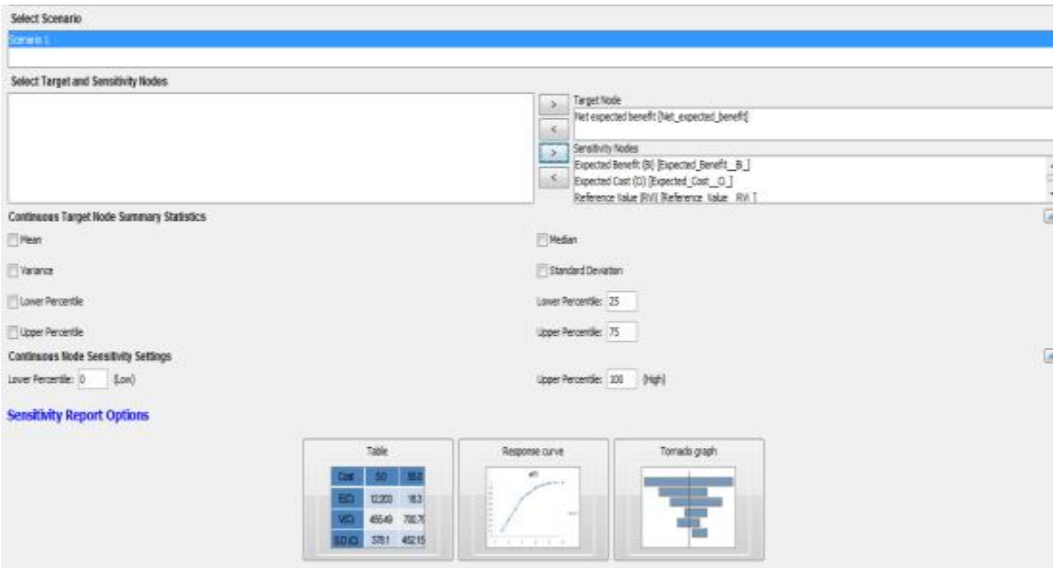
Figure 6.5: Net expected benefit of implementing RCOA2, Result No. 2

6.6.2 Categorisation of cost-effectiveness of each safety measure

The cost-effectiveness of the safety measure can be effectively categorised in the following order for decision making, *RCOA*: RCOA1, RCOA2, RCOA3, RCOA6, RCOB5, & RCOA4 and, RCOB: RCOB4, RCOB5, RCOB1, RCOB6, RCOB2 & RCOB3.

6.6.3 Parameter sensitivity analysis

Parameter sensitivity analysis is completed to show how sensitive the results of a belief update (propagation of evidence) are in variations in the values of a parameter in the model. The parameters of a model are the entries of the conditional probability distributions. Using the sensitivity analysis wizard in AgenaRisk Desktop as presented in Figure 6.6 showing the node, net expected benefit is set as target node.



Select Scenario
Scenario 1

Select Target and Sensitivity Nodes
Target Node: Net expected benefit [Net_expected_benefit]
Sensitivity Nodes:
Expected Benefit (B) [Expected_Benefit__B_]
Expected Cost (O) [Expected_Cost__O_]
Reference Value (RV) [Reference_Value__RV_]

Continuous Target Node Summary Statistics
☐ Mean
☐ Median
☐ Variance
☐ Standard Deviation
☐ Lower Percentile
Lower Percentile: 25
☐ Upper Percentile
Upper Percentile: 75

Continuous Node Sensitivity Settings
Lower Percentile: 0 (Low)
Upper Percentile: 100 (High)

Figure 6.6: Target node and sensitive node selection

6.6.4 Result analysis

Over all the inference results obtained through running the TNormal distribution with ranked nodes, twelve (12) main significant results (Net expected benefit result 1-12) are particularly used to categorise the cost-effectiveness of each safety measure. The next results' analyses (Results 9 and 1) are particularly discussed. These results are under the evidences that the 'target node' is with either 'high' or 'low' value. For the other situations such as under the evidence that the node is 'low', similar results have been obtained.

Result 9. Assuming that the net expected benefit for RCOB3 is highest, we obtained the probabilities of the other factor nodes under the evidence. The result is shown in Figure 6.7 for further explanation. We can find that when the value of RCOB3 NEB is 'highest' the probability of expected cost (C_i) is the highest impacted. This indicates that if the company's net expected benefit is high, it is highly due to its level of influence on expected cost (C_i). It is also shown that the probability of a risk reduction effect (RRE_i) is the second most important criterion to consider when implementing safety measure RCOB3. These results mean that a company's high investment in both expected cost (Ci) and risk reduction effect (RREi) will bring the highest significant enhancement of the implementation of safety measure RCOB3. This is true as shown in Figure 6.7 for low implementation of safety measure RCOB3.

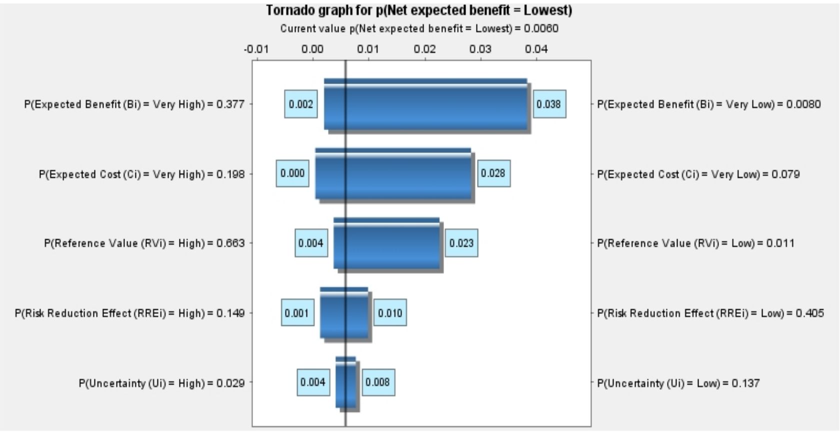


Figure 6.7: Sensitivity analysis using RCOB3

Result 20. When RCOA1 net expected benefit is highest, we can obtain the probabilities of the other nodes under evidence (Figure 6.8). Figure 6.8 shows the effect of expected cost as highest with probabilities '0.051' low and '0.26' high. This suggests that high investment on expected cost affects the net benefit the most as required. The second most important factor is improving on expected benefit. Uncertainty and the reference values affect the net expected benefit the least.

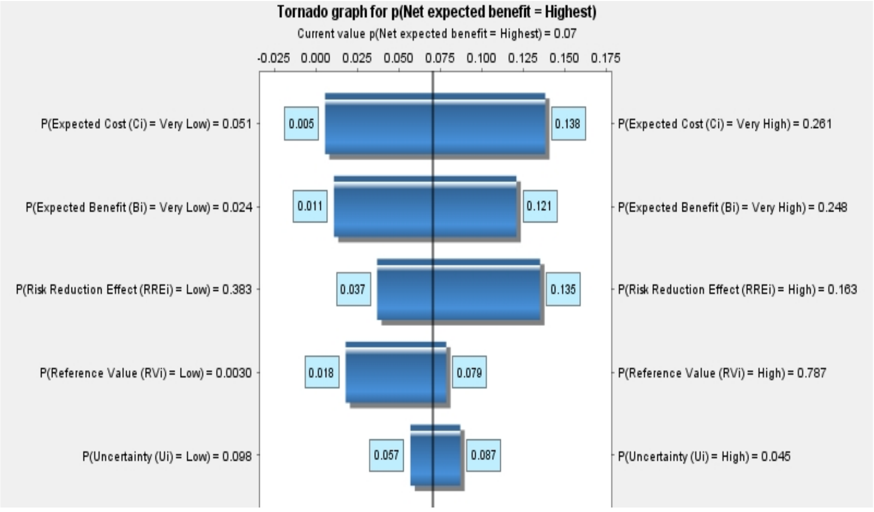


Figure 6.8: Sensitivity analysis using RCO4A

6.7 Conclusion

One of the most important challenges in building effective BN models to solve real-world cost-effective analysis problems is that of constructing the CTPs. Because of the need to involve busy domain experts and decision-makers (who do not necessarily understand probability theory in detail), it is required to construct the CTPs using the minimal amount of expert elicitation, recognising that it is rarely cost-effective or feasible to elicit complete sets of probabilities values. In the past, other modelling approaches for real applications have been too costly and demanding feasibility. This approach marks an improvement over current practice and has proven to be acceptable to practitioners in other fields.

On a second level, partners and decision-makers need models to produce predictions and supportive decision insights that can demonstrate better results than from methods that require detailed statistical understanding. Also, since this approach has been used in a number of application areas such as for operational risk assessment (Fenton *et al*., 2007, these results show that the elicitation burden is much reduced by using ranked nodes by simply eliciting a small number of parameters from experts and decision-makers.

On a third level, by applying Bayesian network techniques this study explored and verified a set of relations between cost factors, benefit factors, reference factors, risk reduction effect factors, and uncertainty factors in the application of decision making in docking and undocking ship operation. A cost-benefit factor relation model proposed in this study was considered as domain knowledge and the data collected through a literature survey was evidence to conduct the *inference-based verification*. Through calculating the node probabilities table (NPT) of these factors, it was found that certain cost factors are more important than others to achieve certain aspects of benefits in relation to reference, risk reduction effect and uncertainty factors:

(1) Compared with other risk safety measures in Study A, increased investments in implementing RCOA1 would significantly contribute to three benefit aspects of reducing stability failure in floating dry dock during docking and undocking a vessel, hence improving a company’s image and competitive advantage.

(2) Compared with other cost items in Study B, the increased investment in implementing risk safety measure RCOB1 would significantly help reduce the failures of a dry dock gate in docking and undocking a vessel in a graving dry dock,

(3) Compared with other cost items in C, the increased investment of implementing risk safety measure RCOB4 would greatly reduce the probability of total loss of a floating dry dock due to pontoon deck failure, hence building cooperation with other companies.

(4) Comparing the relations of safety factors more is required to be done in improving awareness importance of benefit factors. Depending on the RCO under study, the ranking of impact factor provides the least important factor to be taken into consideration when making decisions. For example, using RCOB1, decision-makers should pay more attention to improving benefits and pay less attention to reference value factor and uncertainty factor, while using RCOB3 recommendation for decision making should be to improve the risk reduction effect and to pay less attention to the reference value and uncertainty factors.

Based on these findings, if a dry docking company plans to improve the perceived company image through one of the following operations, it would be appropriate for the company to have considerable investments when implementing these risk safety measures as categorised in this study. Therefore, these will provide a great practical recommendation for managers in dry docking operations when they develop risk assessment strategies to reduce identified failures, thereby enhancing system functionality and increasing the benefits of docking a vessel for repair in both floating and graving dry docks.

Chapter 7 – Integration of PhD Chapters

Summary

This chapter briefly summarises the risk assessment and decision-making approaches presented in the previous chapters that would be of benefit in the safety of a ship-docking operation and management system. In summary, it is concluded that the developed models can be integrated to formulate a platform to facilitate risk assessment and decision making.

7.1 Dry Docking Formal Safety Assessment Management

The FSA management process in dry dock is an enhancement of the traditional safety management process in that the three fundamental components – surveillance, periodic dry dock safety reviews, and maintenance procedures – are central to the procedure. Together they permit informed decision making concerning the manner in which the risks are being controlled. The purpose of this section is to provide an overview of the various aspects of the dry dock formal safety assessment management framework in line with the outcome of this PhD research. A comprehensive framework is illustrated in Figure 7.1.

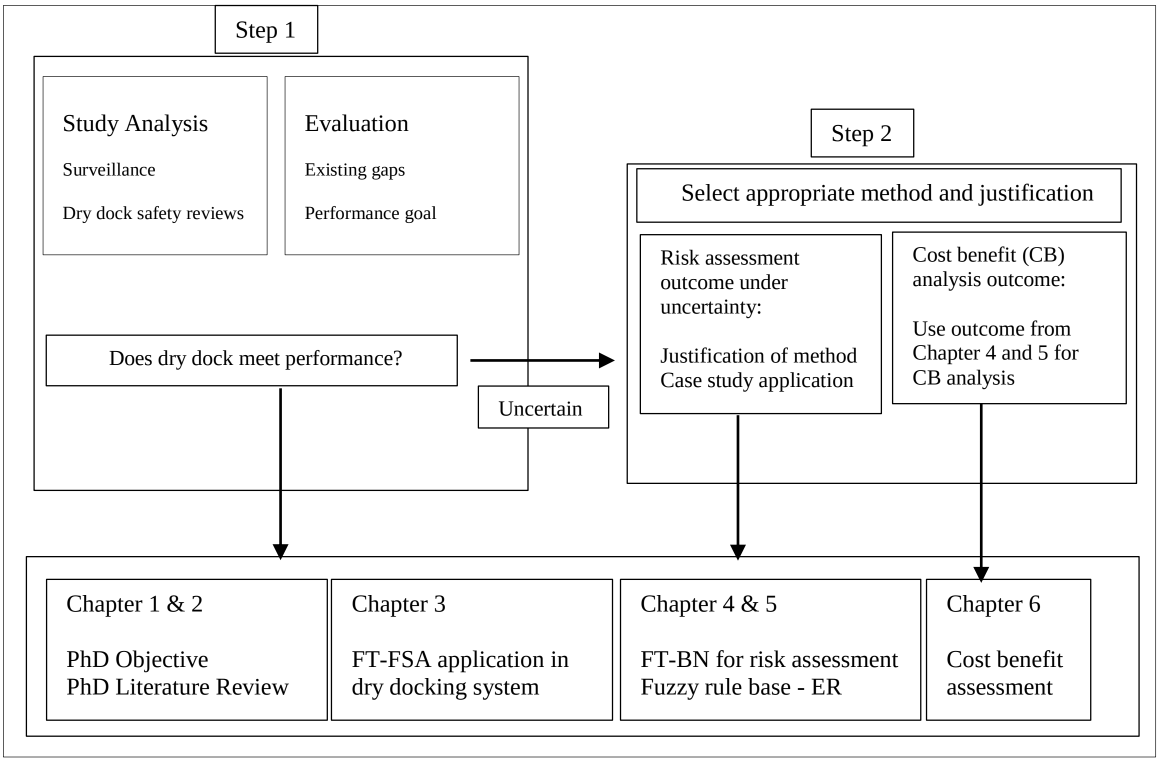


Figure 7.1 Dry dock formal safety assessment process

The enhancement of this PhD research is achieved through an integrated process that affords to explicitly recognise and analyse risk in dry docking system (Chapter 3) with formal treatment of uncertainties (Chapters 4 and 5) that are ever-present in safety practice. A defined risk evaluation process (Chapter 6) leading to recommendations for decision making is also presented. The safety decision making requires five supporting processes:

1. The generation and analysis of information about individual dry dock systems (Chapter 2, Section 2.3-2.5)
2. The establishment of criteria with which the information on the individual dry dock systems can be assessed (Chapter 3, Section 3.3-3.5)
3. Risk analysis under uncertainty (Chapters 4 and 5, Sections 4.4 and 5.5-5.8 respectively)
4. A control process to ensure adequate control of risks (Chapter 6, Section 6.3)
5. A decision-making process which leads to the most appropriate course of action (Chapter 6, Section 6.6.4)
6. A periodic audit to continually monitor the scope and suitability of the risk controls (Chapter 6, Section 6.6.4 and Section 6.7)

7.2 Risk Assessment and Cost Benefit Analysis

Risk assessment is central in this PhD research and its essential features are illustrated in Figure 7.2. The results of the risk analysis and risk evaluation process are intergraded for cost benefit analysis (Chapter 6). The final step of FSA is ‘decision making’, which aims at giving recommendations and making decisions for safety improvements.

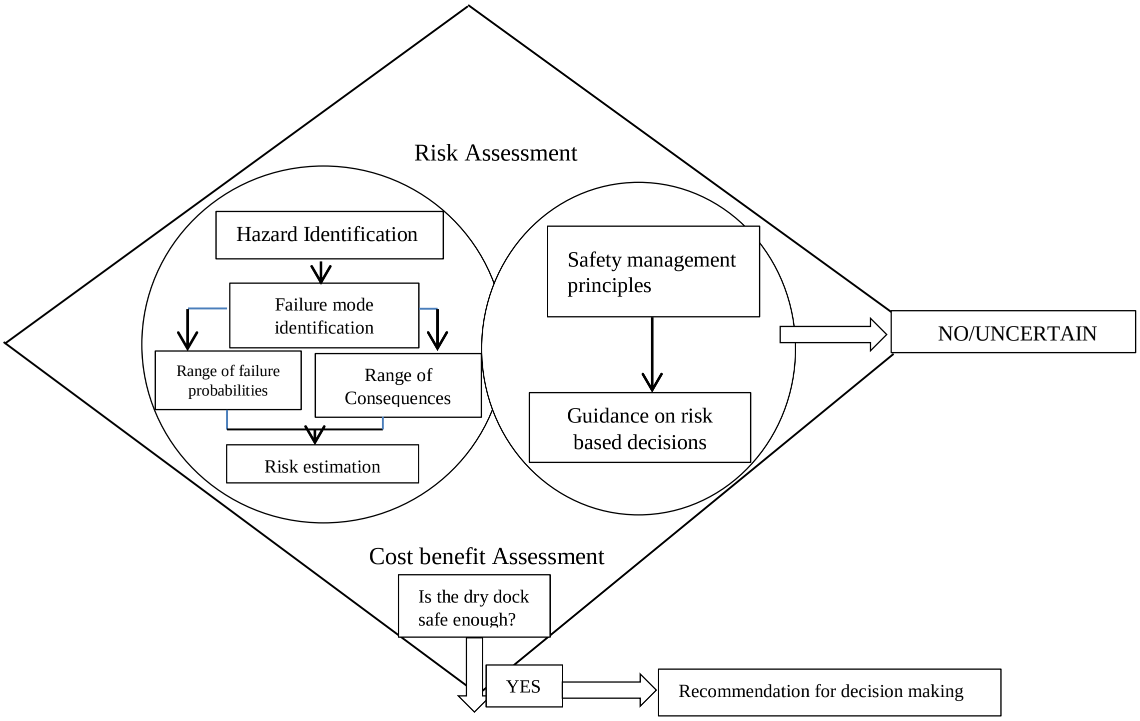


Figure 7.2: Risk assessment and cost benefit analysis framework

Dry docking evolution can lead to serious accidents. Therefore, dry docking-related safety has to be improved; this can be carried out by using scientific risk assessment methodologies. The findings from the literature review have exposed that there are no conceptual risk assessment methodologies available for dry docking problems and the risk assessment of ship docking is closely associated with high levels of uncertainty. Thus, Chapters 3, 4, and 5 have demonstrated the risk analysis approach based on the safety principles of FSA under a high level of uncertainty, and Chapter 6 has presented a cost benefit approach for recommendation as a conclusion of this work. The developed methodologies are generic in nature and can be applied to any situation. In summary, these methodologies can be concluded as follows:

7.2.1 Fault tree-Formal safety assessment in dry docking operation

In dry docks, occupational accidents are frequent. An occupational accident is defined as an unexpected and unintended incidence while occupied in an economic activity, which results in one or more workers getting injured or loss of life (Baris, 2012). Every 15 seconds, a worker dies as a result of occupational accidents or work related diseases. One hundred and sixty workers have an occupational accident statistically every 15 seconds. Over 2.3 million deaths per year and more than 336 million accidents occur at work annually (ILO, 2011). In shipyards, these occupational accidents are classified by several statistical agencies under the construction or repairing topics. Shipbuilding and repair is a complex business, with huge tasks performed in parallel. The steel handling and processing production process requires great space, which must be inspected, sorted and stored. On these steel products, further activities are required, which include blasting, priming, shaping, forming to designed shape, welding to make assemblies, panel, fabrication, block assembly, pre-outfitting, air conditioning, electrical cable fitting, surface preparation and coating (ILO, 2011). This has been the challenge in respect to shipbuilding and repair system safety, which stands out as being complex and uncertain.

The adoption of the fault tree-formal safety assessment (FT-FSA) concept is used to solve existing gaps. Existing gaps within the framework are the unavailability of experts to carry out a proactive risk-based approach to deal with accidents and eliminate their occurrence from its origin. FSA consists of five steps. FT is a formal method used in steps 1 and 2 in this study. Hollnagel (2004) categorises these accident models in the following three types: (a) sequential accident model, which describes an accident as a result of a sequence of events that occurred in a specific order; (b) epidemiological accident model, which describes an accident in an analogy with the spreading of diseases; (c) systemic accident model, which describes the performance of a system as a whole, rather than on the level of cause-effect mechanisms or epidemiological factors.

Fault tree analysis (FTA) is a very popular and diffused technique for modelling and evaluation of large, safety and critical systems. Henley *et al*. (1995) carried out a diffused analysis on dependability modelling using FSA. It is a deductive analysis, starting with potential or actual failures and deducting their causes (Chris *et al*., 2012). Root causes of failures frequently have to be inferred from multiple indirect observations. Fault trees are intended for reliability and fault analysis rather than diagnostic observation (Wojtek and Milford, 2006).

FTA has wide applications in system safety engineering such as security design, risk assessment, and the management of safety-critical projects (Zhuang *et al*., 2011). FTA is used for preliminary safety analysis, especially the qualitative analysis of identifying the root causes for the development of RCOs. FTA is an effective methodology in the safety analysis of a system; it also has some deficiencies, especially when being used in complex engineering systems such as dry docking. These disadvantages include (Hu *et al*., 1995): (a) events in FT are assumed to have only two states, namely working or failure, but in actual engineering some events are polymorphic; (b) events in FT are assumed to be independent, but actually some of them may have interdependent relations. FTA is more applicable to a system analysis problem in which fault mechanism and logic relationship are clearly defined. For complex and uncertain systems, a probabilistic network approach should be a better choice (Jong and Leu, 2013).

7.2.2 Fault tree-Bayesian networking approach for dry docking operations

As mentioned in section 7.2.1, FT-FSA is a common diagnostic tool used to assess the reliability of a ship-docking system. However, FTA has some limitations in modelling, such as lack of lateral links and limited definition of event states and logic gates. To overcome the limitations of FT-FSA, Bayesian network (BN) has been proposed and widely applied for uncertainty analysis. However, the establishment of BN for practical applications could be quite difficult and tedious, especially with complicated ones.

This Chapter combines the advantages of FTA and BN to propose a more effective BN development process by transforming a multi-state FT into a BN framework. The process was then used to build a ship-docking system. Model validation and sensitivity analysis are performed to further assess the application of this approach.

Particularly, in building a large BN, the model must be mathematically sound, and at the same time easy for the decision-maker to understand. Furthermore, such models require a set of parameters to be fully specified, and either statistical data or expert judgement must be used to estimate them. Finally, the model must be represented such that the interested quantities can be calculated efficiently (Barlow, 1988). To overcome the challenges of representation, the FT-BN method is used and, to overcome the challenges of better quantification, a method of ranking subjective nodes from experts' elicitation using WeightedMin truncated normal distribution (TNormal) is adopted in BN to easily calculate and represent the priori probabilities and conditional probability table (CPT) of corresponding nodes.

The combination of these two approaches has been reported in aerospace and manufacturing industries (Zhuang *et al*., 2011). BN is an approach to deal with intrinsic drawbacks in FTA. This method is based on uncertainty treatment theory. It is usually grouped under uncertain categories like fuzzy logic, Markov models, artificial neural networks, Monte Carlo simulation, grey theory, and Dempster-Shafer theory (Yang *et al*., 2005). BN has great ability to model randomness and capture nonlinear causal relationships. This potential has increased its popularity in recent years. Yang *et al*. (2008) state that it is '*a powerful risk analysis tool*' because it can be used in a range of real applications concerned with predicting properties of safety-critical systems. In this chapter, it was realised that, although the mechanism of transforming from FT to BN has been well examined, the use of BN, nevertheless, relies on the input of experts' experiences for the linkages and CPTs. Data provided by different experts will directly affect the accuracy and the assessment quality of BN. Special attention is therefore required to be carried out in the next stage of this research through cost benefit analysis. If complete and sound maintenance data are available, an objective BN can be established.

7.2.3 Fuzzy rule base with belief degree for risk analysis in dry docking operation

The methods of rule-based evidential reasoning are based on the synthesis of the tools of Fuzzy Set Theory (FST) and the Dempster-Shafer Theory (DST). The integration of FST and DST within symbolic, rule-based models was primarily in maritime safety analysis. These models combine these theories in a synergic way, preserving their strengths while avoiding the disadvantages they present when used as a mono-strategy approach.

The main advantage in a belief rule system is that each possible consequence of a rule is associated with a belief degree. Such a rule base is capable of capturing more complicated and continuous causal relationships between different factors than traditional IF-THEN rules. Therefore, the traditional IF-THEN rules may be treated as special cases of the more general belief rule systems. In the framework of rule-based inference methodology, using an evidential reasoning approach (RIMER), the decision characterised by the maximal aggregated degree of belief is the best choice (Ferdous *et al.*, 2009). So, the RIMER approach can be used for building decision support systems.

To make the presentation of the approach of this chapter more transparent, an illustration is simple enough, but a real-world problem in a floating dry dock is used. The success of FSA depends on how practical solutions are provided for decision making under uncertainty in dry docking operations. Fuzzy evidential reasoning (FER) capable of dealing with uncertainty can be used either as a standalone method or be combined as part of an FSA methodology (Godaliyadde *et.al*, 2009). The main focus of this chapter is to use fuzzy theory and evidence theory approaches to deal with linguistic/subjective uncertainties of event probabilities, and the latter is also used to handle incomplete/partial ignorance of expert knowledge (Ferdous *et al.*, 2009).

Nevertheless, there are two restrictions in the RIMER approach that reduce its ability to deal with uncertainties that decision-makers often meet in practice. The first restriction is that, in the framework of RIMER approach, a degree of belief can be assigned only to a particular hypothesis, not to a group of them, whereas the assignment of the belief mass to a group of events is a key principle of the DST (Dymova and Savastjanov, 2014). The second restriction is concerned with the observation that in many real-world decision problems we deal with different sources of evidence and a combination of them is needed. The RIMER approach does not provide a technique for the combination of evidence from different sources (Liu *et al.*, 2013). To overcome these limitations, it is required to carry out a cost benefit analysis to select the best control safety measures from the outcomes of using RIMER and FT-BN.

7.2.4 Risk control options and cost benefit analysis in a dry docking operation

It is hoped to find acceptable ways of estimating and also reducing the cost of operating a ship-docking system. This might enable the decision-maker to choose the most cost-effective method that will improve ship-docking safety, environmental protection, profitability and cope with the strong competition within the ship-docking industry.

This chapter provides a robust method for evaluating the cost-effectiveness (CE) of risk control options, which are identified in Chapters 4 and 5. The deficiencies of current CE methods are highlighted, undermining the lucidity and consistency in application. The proposed approach outlines a subjective mathematical formulation that neatly integrates all aspects of CE measures along with its application based on the ranked nodes with a Truncated Normal distribution Bayesian network. This method is used in FSA for docking and undocking systems, demonstrating the ease of the application and clarity of results' interpretation. FSA forms the basis for decision making towards mitigation of risk. The latter is performed through determination of risk control options (RCOs), ranking them according to impact on risk and cost, and provision of recommendations as to which RCOs are most sensible. Again, the communication between analysts and other stakeholders about safety measures is usually based on cost-effectiveness indices. These indices are based on expected values. In the literature it is argued that such indices are not appropriate for evaluation and communication of cost-effectiveness as a broader reflection of uncertainty (Reed *et al.*, 2010).

In Chapter 6 a quantitative approach for evaluation of safety measures of a ship-docking system is based on cost-effectiveness. The initial part of the risk assessment process is carried out in Chapters 4 and 5 using expert elicitation. The risk-control safety measures are categorised by cost-effectiveness to provide support for decision making. In the proposed method, evaluation of the cost-effectiveness is based on calculating expected values, as in a traditional cost-effectiveness analysis, as well as uncertainties. The uncertainties are systematically addressed by adjusting the cost-effectiveness categories in accordance with the perceived degree of uncertainty. Since the proposed procedure is not particular labour intensive, it can be used to compare a high number of safety measures.

7.4 Recommendations for Decision Making

The final step in a formal safety assessment is decision making, which gives recommendations for safety improvement. The selection of risk-control options for the decision making is based on the cost-effectiveness and the principles of ALARP (As Low As Reasonably Practicable). Intolerable risk is controlled regardless of costs. Reasonable means the costs are grossly disproportionate to the benefits. On the first level, this approach marks an improvement over current practice in ship docking and has proven to be acceptable to practitioners in other fields.

On a second level, partners and decision-makers need models to produce predictions and supportive decision insights that can demonstrate better results than from methods that require detailed statistical understanding. Also, since this approach has been used in a number of application areas such as for operational risk assessment (Fenton *et al.*, 2007), these results show that the elicitation burden is much reduced by using ranked nodes by simply eliciting a small number of parameters from experts and decision-makers.

On a third level, by applying Bayesian network techniques, this study has explored and verified a set of relations between cost factors, benefit factors, reference factors, risk reduction effect factors, and uncertainty factors in the application of decision making in docking and undocking ship operations. A cost-benefit factor relation model proposed in this study was considered as domain knowledge and the data collected through a literature survey was evidence to conduct the *inference-based verification*. Through calculating the CPT of these factors, it was found that certain cost factors are more important than others to achieve certain aspects of benefits in relation to reference, risk reduction effect and uncertainty factors (Section 6.5 -6.6):

(5) Compared with other risk safety measures in A, increased investments in implementing RCOA1 would significantly contribute to three benefit aspects of reducing stability failure in a floating dry dock during docking and undocking a vessel, hence improving a company’s image and competitive advantage.
(6) Compared with other cost items in B, the increased investment in implementing risk safety measure RCOB1 would significantly help reduce the failures of a dry dock gate in docking and undocking a vessel in a graving dry dock,
(7) Comparing the relations of safety factors, more is required to be done in improving awareness of the importance of benefit factors. Depending on the RCO under study, the ranking of impact factors provides the least important factor to be taken into consideration when making decisions. For example, using RCOB1, decision-makers should pay more attention to improving benefits and pay less attention to reference value factor and uncertainty factor, while using RCOB3 recommendation for decision making should be to improve the risk reduction effect and to pay less attention to the reference value and uncertainty factors.

Based on these findings, if a dry docking company plans to improve the perceived company image through one of the following operations, it would be appropriate for the company to have considerable investments when implementing these risk safety measures as categorised in this study.

Note: Study A is result from Chapter 4 of thesis, and Study B is result from Chapter 5.

Chapter 8 – Conclusion and Implications

Summary

Highlighting the research contribution, final conclusions and recommendations of application of the Formal Safety Assessment (FSA) for dry docking evolution modelling is performed by summarising the research outcomes of the thesis. Implications for further research are described based on key findings and limitations of this PhD research.

8.1 Research Background

Formal safety assessment (FSA) is a systematic, formal and integrated assessment approach being used by maritime companies. The main aim of this methodology is to improve the level of maritime safety connected with either life and health security or the environment and property protection. It is most useful in making decisions using risk analysis, the estimation of costs and profits and also creating decision trees (Mikulik and Zajdel, 2009).

FSA gives the opportunity to gain as much security as possible through the selection of the risk control variant, which yields huge risk reduction and good financial benefits, since FSA not only judges whether and how each means applied is helpful in gaining a higher safety level or lower pollution level, but it also estimates cost of operation (Wang, 2001). Furthermore, this methodology keeps good cognition of precautions through detailed identification of who or what is the real cause of the risk, who will take advantage of risk control and reduction, and who will bear costs (Wang, 2001).

Since formal safety assessment has been introduced into the ship-safety field, it has proved to be a method widely applicable, detailed in statistical analysis and effective in assessment, featured by formal operation procedures, serial standards analysis techniques and decision making based on cost-benefit assessment (Mikulik and Zajdel, 2009). During the last few years, it has also been adapted to some other fields in which risk estimation plays a significant role, such as pilotage, environment protection and public transport (Mikulik and Zajdel, 2009). This PhD research shows how to use FSA methodology as a helpful tool when docking a vessel for ship repair in a graving-floating docking system. All five steps of FSA with their main aspects described in detail are addressed; however, the risk assessment is a critical step and the core process in the establishment of the risk model (Mikulik and Zajdel, 2009). Following the identification of the research needs, this PhD study has developed one data model and three analytical models capable of performing risk assessment and decision-making process.

8.2 Research Contribution

Dry docking operations can lead to serious accidents. Therefore, dry docking-related safety has to be improved; this can be carried out by using scientific risk assessment methodologies. The findings from the literature review have exposed that there are no conceptual risk assessment methodologies available for dry docking safety-related problems and the risk assessment of ship docking is closely associated with a high level of uncertainty. Thus, Chapters 3, 4, and 5 have demonstrated the risk assessment based on safety principles of FSA under a high level of uncertainty, and Chapter 6 is a cost benefit approach for decision making. The developed methodologies are generic in nature and can be applied to any situation. In summary, these methodologies can be concluded as follows:

Also, following the identification of the research needs, this PhD study has developed one data model and two analytical models capable of performing risk assessment and decision-making processes with confidence under the aforesaid circumstances. Such frameworks have been demonstrated by three corresponding test cases with regard to the safety of ship-docking operations. The frameworks have been developed in a generic sense to be applicable to both engineering and managerial problems. They provide the basis for the generation of the various risk analysis methods and decision-making procedures. In summary, the methods and techniques can be concluded as follows:

- Using FT-FSA to deal with the complexity of ship-docking operations and to provide a framework to deal with a data model. The adoption of the FT-FSA concept is used to solve existing gaps identified in this PhD (Section 1.4, Section 1.52 and Section 3.2).
- Applying FT-BN to evaluate the risks of objects, subsystems and overall safety of a typical graving-dock failure. Section 4.2 defines the importance of FT-BN overcoming the limitations of FT-FSA, and Section 4.5 presents the framework, and this chapter is concluded with a test case.
- Employing Fuzzy Evidential Rule Base (FERB) to evaluate the risks of floating docking to model epistemic uncertainties including non-specificity and vagueness (Section 5.4-5.5). The advantages of this framework are demonstrated by using a numeric example (Section 5.6)
- Using truncated normal distribution BN for cost benefit analysis where many risk control measures are involved (Section 6.4-6.6). In brief, Sections 8.2.1 to 8.2.3 highlight some key aspects of these approaches.

8.2.1 FT-FSA approach in dry docking operation

The aim of the chapter is to show that the FT-FSA methodology of safety-relevant scenarios in occupational accidents in shipyards can be analysed. The exemplary application is a 'Fall from Height' scenario, which deals with concurrently interacting human operations and technical system, and was used as a data model for decision making.

8.2.2 FT-BN approach in dry docking operation

The combination of these two approaches has been reported in aerospace and manufacturing industries (Zhuang *et al*., 2011). BN is an approach to deal with intrinsic drawbacks in FTA. This method is based on uncertainty treatment theory. BN has great ability to model randomness and capture nonlinear causal relationships. This potential has increased its popularity in recent years. Yang *et al*. (2008) state that it is '*a powerful risk analysis tool*,' because it can be used in a range of real applications concerned with predicting properties of safety-critical systems.

8.2.3 FERB approach in dry docking operation

The success of FSA depends on how practical solutions are provided for decision making under uncertainty in dry docking operations. Fuzzy evidential reasoning (FER) capable of dealing with uncertainty can be used either as a standalone method or be combined as part of an FSA methodology (Godaliyadde *et.al*, 2009). The main focus of this chapter is to use fuzzy theory and evidence theory approaches to deal with linguistic/subjective uncertainties of event probabilities, and the latter is used to handle incomplete/partial ignorance of expert knowledge (Ferdous *et al*., 2009).

8.2.4 Truncated normal distribution BN cost benefit analysis in dry docking operation

This chapter provides a robust method for evaluating the cost-effectiveness (CE) of risk control options, which are identified in Chapter 4, 5 and 6. The deficiencies of current CE methods are highlighted, undermining the lucidity and consistency in application. The proposed approach outlines a subjective mathematical formulation that neatly integrates all aspects of CE measures along with its application based on the ranked nodes with Truncated Normal distribution Bayesian network. FSA forms the basis for decision making towards mitigation of risk. The latter is done through determination of risk control options (RCOs), ranking them according to impact on risk and cost, and provision of recommendations as to which RCOs are most sensible.

8.3 Practical Applications of PhD Research

It is also believed that these methods can be tailored to practical applications of dealing with safety problems in other industries, especially in situations where a high level of uncertainty exists. The implementation of the described approaches could have highly beneficial effects in real life. More specific description can be provided as follows:

1) A framework of aggregative risk assessment for representing the relationships of component, subsystems and overall ship-docking floating system
2) A framework of FTA for representing the cause-effect relationship of specific risks
3) A framework for decision making when considering cost-effectiveness of controlled risks

FSA is used to evaluate the framework of aggregative risk assessments for a ship-docking system. Two mathematical theories are combined for assessing risks (FT-BN and FERB) in Chapters 4 and 5. Fuzzy set theory is used to represent the characteristics of a hazard such as likelihood of occurrence and consequence severity. ER is used to combine newly obtained data for the updating existing risk estimates at the bottom level of the framework. Risk analysts can use this information to compare risks of base events (BE) and even the overall risk of the system. As demonstrated in Table 5.11 and Figure 5.12, the overall failure of the system is presented according to the FV-I ranking result, where the intermediate events needing the most attention are presented. By considering the risk value or probability value and the weight of each expert, the most critical intermediate system can be identified. Keel block loads calculations are selected as the most critical event concerning the failure of the pontoon deck.

In the absence of exact data, and where there exists common failures, it is necessary to work with subjective probabilities. The combination of the mathematical theories of FT-BN is used. This combines the advantages of FTA and BN to propose a more effective BN development process by transforming a multi-state FT into a BN framework. The process was then used to build a ship-docking system. The results of FT-BN are the likelihood of occurrence for specific risks and importance measures of potential contributing factors. Application of FT-BN in Chapter 4 shows that it is useful to identify critical intermediate events for a specific risk, as shown in Table 4.5 and Table 4.6.

Results of Chapters 4 and 5 help the analyst to select RCOs to mitigate risk for the most critical intermediate events and overall safety of the ship-docking structure. It is not financially possible to select all the proposed RCOs. Therefore, truncated normal distribution using a weighted average BN structure is tailored to select the best RCO from a large number of RCOs. When dealing with RCO ranking/selecting, available decisions are collected not only from experts but from decision-makers as well. When evaluating RCOs for enhancing the safety of a ship-docking system, there are parameters that need to be considered, as presented in Table 6.1 and Table 6.2. On the basis of the test case in Chapter 6 involving elements of pontoon deck failure and gate failure, it is reasonable to judge that the decision-making model developed is capable of handling such problems. The proposed method is particularly useful in circumstances where multiple experts and multiple decision-makers are involved.

Since the test cases in this study provide reasonable results, it is felt that the analytical models developed have the potential to improve the safety of ship-docking operations. Such models can be applied in individual shipyards. More importantly, these frameworks can be integrated to formulate a formal safety platform to facilitate risk assessment and safety management of ship-docking operations without jeopardising the efficiency of operations in a variety of situations where traditional techniques may not be applied with confidence.

8.4 Integration of Results

This PhD research compares the outcome of using risk assessment and cost benefit analysis. For Study A (Chapter 4) the most critical intermediate events identified are in the following order (section 4.8.6 – section 4.8.7): RCOA2, RCOA7, RCOA5, RCOA8, RCOA1, RCO3 and RCOA4.

RCO 2- *Preventing any buoyancy obtained from the upper chamber*, these include improved inspection in Tidal Chamber, focusing on Tidal flaps connected by wires, and tidal valves.

RCO 7- *Preventing failures of control system*, these include maintenance of driving winch, control panels and control tank gauges.

RCO 5- *Loads from water pressure – rolling and holding gate in centre of recess* – roller guide gates using a pair of rollers, into a central guide-wall, holding the gate in the centre of the recess.

RCO 8- *Tank operation issues*, putting in permanent ballast to *bring the gate to an even keel,* two scuttle tanks, used to *sink the gate into position*, how the two ballast tanks are flooded when the gate is closed to increase stability and prevent any movement due to wave action.

RCO 1- *Maintenance on towing system*, these include removal and maintenance of the rollers in air chambers, gate-shifting system inspection (A 2-pile system, and hydraulic trolley).

RCO 3- C*onstantly controlling an even draught* (stability concerns) by using trimming tanks.
RCO 4- *Improve structural element inspection* – walls, floors, decks, walkway, handrails, guiding post.

RCO 6- M*aintain gate water tightness* – a roller L-shaped strip was fixed to the outer edge of the green heart-facing pieces, which must be constantly maintained and checked.

But comparing the result of Chapter 4, with the result of cost effectiveness analysis (section 6.6.2 – section 6.6.3) categorised in the following order *RCOA*: RCOA1, RCOA2, RCOA3, RCOA6, RCOB5, & RCOA4, we noticed that RCOA1 is the most important risk control option as opposed to RCOA2. Therefore care is required when making decisions between the risk analysis method and cost-benefit assessment.

Likewise, the result of Chapter 5 (section 5.7.7) identifies the following critical intermediate events in the following order: RCOB4, RCOB2, RCOB3 and RCOB5, and the result from cost-effectiveness (section 6.6.2) gives a different ranking order RCOB: RCOB4, RCOB5, RCOB1, RCOB6, and RCOB2 & RCOB3.

8.5 Limitations of Research

Floating and graving dry dock failure data are scarce or incomplete; as such, the uncertainty associated with docking and undocking evolution problems may significantly undermine the risk assessment conducted based on traditional risk assessment techniques. In order to deal with these, novel risk assessment techniques have to be developed and applied.

The first challenge under uncertainty comes when risk estimation is conducted for the identified hazards. Hazard identification is normally carried out by employing traditional hazard identification techniques such as preliminary hazard analysis (PHA) and hazard and operability study (HAZOP). Hazard identification and risk estimation can also be conducted by utilising techniques like fault tree analysis (FTA) and event tree analysis (ETA). However, due to high levels of uncertainty related to docking and undocking evolution problems, such techniques may be unsuitable; therefore the solution is achieved by developing a novel approach with the combination of fuzzy rule base, evidential reasoning, and Bayesian networks.

The second challenge is associated with decision making based on risk estimation results under a high level of uncertainty. The problem becomes more complex if interval data have to be taken into account. Interval data increase the complexity of criteria aggregation which further increases the complexity of the problem. It should be noted that when the complexity of a problem increases uncertainty will be further increased. These problems are solved and decision making conducted by carrying out cost benefit analysis.

The third challenge under uncertainty arises when risk control options are chosen for identified areas of high-risk estimation. Also, expert judgement plays a vital role in this subjective assessment. There is also the challenge of validating the generic models developed in each technical chapter. These are all novel models in an area in which no conceptual scientific risk assessment work has been done so far. However, this challenge is partially met by applying these models to real floating and graving dry docks**.**

8.6 Implications for Further Research

On the basis of the key findings and limitations of this PhD research, further research will be needed in a number of areas. The major challenge of conducting this research was the high level of uncertainty which arises from the lack of data for use in risk assessment. The confidence and effectiveness of application of the FSA methodology is highly dependent on the reliability of system failure and accident data. It was found that many organisations dealing with ship-repairing activities have a poor organisational structure. This research shows the importance of recording relevant dry docking accident data for conducting risk assessments to obtain reasonable results. It is anticipated that the application of FSA may trigger the organisations concerned about ship repair to collect the relevant data by improving their organisational structure. The ship docking organisations may improve their organisational structure by implementing the following steps:

- Keep a separate log book for each docking ship problem,
- Keep health records for workers under health surveillance,
- Keep a record of the risk assessment and control actions,

Appropriate training and educational programmes could be developed for the crew, identifying ways in which ship docking problems could be prevented and how such problems should be dealt with should they occur. Such training programmes could become the starting point for the development of a safety culture within the ship docking industry. The outcome of the risk assessment of ship docking operations may be used to identify areas in which development of such training and education programmes is required. This could lead to the reduction of human error on board, which is one of the leading contributory factors for marine accidents (IMO MSC/Circ. 565, 2001). The findings and results produced in this research can also be helpful in conducting human error analysis in ship docking organisations.

There are some limitations of the generic uncertainty treatment methods developed in this research. Further research would be needed to improve these novel methods. Since these methods are generic they can be applied and improved in other industries such as nuclear, oil and gas, and aviation. Furthermore, the development of software tools incorporating the developed models in this research may be potentially useful. The marine industry is heading towards a goal-setting risk-based regime under the safety principles of FSA, which gives decision-makers more flexibility for developing and utilising novel risk assessment methods; one of which is a subjective modelling approach.

The key element for reaching adequate results is gaining suitable data. Often in dry docking operations, domain data are collected as linguistic variables. Then they are processed into numerical data with some errors. But even if data are hard to obtain and vary a lot with time, the FSA method based on fuzzy rule base, evidential reasoning, and Bayesian networks helps to get an acceptable outcome, with great tolerance, and it is insensitive to errors made in changing linguistic into numerical data, which is the biggest problem in such domains of research.

Lack of reliable safety data and lack of confidence in safety assessment have been two major problems in safety analysis in dry docking operations. To solve such problems, further development may be required to develop novel and flexible safety assessment techniques for dealing with uncertainty properly and also to use decision-making techniques on a rational basis. Also software safety analysis is another area where further study is required. In recent years, advances in computer technology have been increasingly used to fulfil control tasks to reduce human error and to provide operators with a better working environment in ship-docking systems. The utilisation of software in control systems has introduced new failure modes and created problems in the development of safety-critical systems. In formal ship-docking safety assessment, every safety-critical system also needs to be investigated to make sure that it is impossible or extremely unlikely that its behaviour will lead to a catastrophic failure of the system and also to provide evidence for both the developers and the assessment authorities that the risk associated with software is acceptable within the overall system risks (Wang, 2007). It is also very important to take into account human error problems in formal safety assessment. Factors such as language, education and training, which affect human error, need to be taken into account. The confidence of formal safety assessment greatly depends on the reliability of failure data. When evaluating risks under circumstances of the scarcity of data, perhaps due to the high level of costs in conducting a full-scale experiment, the use of computer simulation may be potentially useful.

More test case studies also need to be carried out to evaluate and modify formal ship-docking safety assessment and associated techniques and to provide more detailed guidelines for their employment. This would enable validation of them and can also direct the further development of flexible risk modelling and decision-making techniques and facilitate the technology transfer to industries. The dry docking industry is moving towards a risk-based goal-setting regime. This provides safety analysts with more flexibility to employ novel and the latest risk modelling and decision-making techniques. Subjective modelling and approximate reasoning methods may be useful approaches. It may be beneficial if the novel techniques developed in this research could be further applied to facilitate risk modelling and decision making. The cost data are related to the estimation of investment costs, operating costs, inspection and maintenance costs, and the cost for clean-up, pollution, etc. In many cases, data are insufficient to carry out an appropriate estimation of risk. Also, since the methodologies proposed in this research are generic in nature, such frameworks can be further verified for safety analysis outside the dry docking industry. This will provide an added value to the promotion of their use in different industries.

It is clear that it would be possible to reduce ship docking accidents by good design, training and operation in an appropriate formal safety management system. As public concern regarding maritime safety increases, more and more attention has been directed to the wide application of formal safety assessment of ship-docking system as a regulatory tool. It is believed that the adoption of this PhD research in the ship-docking operation will reduce maritime risks to a minimum level. This PhD research also provides a platform on which further research on risk assessment of ship docking evolution, based on the safety principles of FSA, could be undertaken to improve the safety of the ship-docking environment.

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Appendix

Appendix 1- Definitions of typical terms

Accident: An unintended event involving fatality, injury, ship or other property loss or damage, and/or environmental damage (IMO MSC/Circ.829, 1997; IMO MSC/Circ.1023, 2002).

Consequence: The outcome of an accident, there may be different possible consequences, e.g. human fatalities (or injuries), environmental pollution, loss / damage to property (Wang & Trbojevic, 2007).

Failure: Any change in the shape, size or material properties of a structure, machine, or component that renders it unfit to carry out its specified function adequately (Dhillion, 1998).

Formal Safety Assessment: A structured and systematic methodology, aimed at enhancing marine safety, including protection of life, health, the marine environment and property by using a scientific approach (Maistralis, 2007).

Generic Model: A set of functions which are common to all ships or areas or properties under consideration (Eleye-Datubo, 2006).

Hazard: A physical situation with a potential for human injury, damage to property or the environment or some combination of those items (Wang & Trbojevic, 2007).

Uncertainty: A state of doubt regarding quantitative or qualitative information describing, prescribing or predicting deterministically and numerically a system, its behaviour or other characteristics (Zimmermann, 2000).

Appendix 2 - Journal publication arising from this PhD research

Njumo, D.A., (2013). *Fault tree analysis-Formal safety assessment in ship repair industry – A made easy approach.* International Journal of Maritime Engineering. Transaction of Royal Institute of Naval Architecture, Jan-Mar, UK

FAULT TREE ANALYSIS (FTA) - FORMAL SAFETY ASSESSMENT (FSA) IN SHIP REPAIR INDUSTRY A MADE EASY APPROACH

D A. Njumo, Liverpool John Moore's University, UK

Summary

Fault tree-Formal Safety Assessment (FT-FSA) is the premier scientific method that is currently being used for the analysis of maritime safety and for formulation of related regulatory policy. To apply FSA in this paper, all five steps are considered and critical information highlighted in each step as reviewed in the literature. A novel 15 steps approach of FT-FSA is introduced in the systematic accident scenario considered in this study as emergent phenomena from variability and interactions in shipyard (considered as a complex system).The results of this paper will be useful for guidelines and regulatory reforms in ship repair industry as demonstrated by identifying 'fall from height in ship repair occupational hazards' for recommendation in decision making.

Appendix 3 - Shipbuilding/repair-kind of accident by report type (HSE UK)

KIND	FATAL			MAJOR			3 DAY			TOTAL		
	99/00	00/01	01/02	99/00	00/01	01/02	99/00	00/01	01/02	99/00	00/01	01/02
Machinery	0	0	0	6	3	5	18	13	10	24	16	15
Hit by object	0	0	0	23	32	15	114	99	77	137	131	92
Fall structure						1			3			4
Fall equipment						2			5			7
Ejected						1			2			3
Pressure						0			1			1
Hand tool						1			11			12
Hit by vehicle	0	0	0	1	0	3	1	7	2	2	7	5
Forward	-	-	0	-	-	2	-	-	1	-	-	3
Reverse	-	-	0	-	-	1	-	-	1	-	-	2
Overturn	-	-	0	-	-	0	-	-	0	-	-	0
Runaway	-	-	0	-	-	0	-	-	0	-	-	0
Other	-	-	0	-	-	0	-	-	0	-	-	0
Hit Something fixed	0	0	0	6	8	5	52	28	26	58	36	31
Structure	-	-	0	-	-	3	-	-	21	-	-	24
Vehicle	-	-	0	-	-	0	-	-	0	-	-	0
Step on	-	-	0	-	-	0	-	-	1	-	-	1
Other	-	-	0	-	-	2	-	-	4	-	-	6
Handling	0	0	0	7	9	9	166	120	144	173	129	153
Sharp	-	-	0	-	-	4	-	-	28	-	-	32
Body Movement	-	-	0	-	-	0	-	-	42	-	-	42
Person	-	-	0	-	-	0	-	-	0	-	-	0
Person, Equipment	-	-	0	-	-	0	-	-	0	-	-	0
Lifting, Putting down	-	-	0	-	-	0	-	-	26	-	-	26
Pushing, Pulling	-	-	0	-	-	0	-	-	8	-	-	8
Carrying	-	-	0	-	-	0	-	-	7	-	-	7
Other	-	-	0	-	-	5	-	-	33	-	-	38
Slip,trip	0	0	0	26	27	34	140	108	96	166	135	130
Wet	-	-	0	-	-	3	-	-	9	-	-	12
Dry	-	-	0	-	-	1	-	-	5	-	-	6
Obstruction	-	-	0	-	-	10	-	-	30	-	-	40
Uneven	-	-	0	-	-	3	-	-	8	-	-	11
Other	-	-	0	-	-	17	-	-	44	-	-	61
Fall	1	0	0	30	27	22	62	62	22	93	89	44
High	1	0	0	8	10	7	12	10	1	21	20	8
Low	0	0	0	20	14	13	41	45	10	61	59	23
Other	0	0	0	2	3	2	9	7	11	11	10	13
Collapse	0	0	0	0	1	0	0	1	1	0	2	1
Drown, Asphyxiation	0	0	0	0	2	0	1	1	0	1	3	0
Water	-	-	0	-	-	0	-	-	0	-	-	0
Other Liquid	-	-	0	-	-	0	-	-	0	-	-	0
Engulf	-	-	0	-	-	0	-	-	0	-	-	0
Confined	-	-	0	-	-	0	-	-	0	-	-	0
Choke	-	-	0	-	-	0	-	-	0	-	-	0
Other	-	-	0	-	-	0	-	-	0	-	-	0
Exposure	0	0	0	3	1	1	19	16	7	22	17	8
Handling	-	-	0	-	-	1	-	-	0	-	-	1
Failure	-	-	0	-	-	0	-	-	0	-	-	0
Normal	-	-	0	-	-	0	-	-	1	-	-	1

Appendix 4 – Experts' background

Expert	Name	Years of experience	Expert weight
1	**Mbunja Gustave** Head of Department for Marine Cameroon Shipyard and Industrial Engineering Tel : +237 233403056 Mob : +237 675295337	**26**	**5**
2	**Samuel Owusu Appiah** Head of Projects Ghana Shipyard Tel : +233 244336272 Mob : +233241014311	**17**	**3**
3	**Federick Asamoah** Senior Surveyor Tema Maritime Tel : +233242854992 Mob : +2233303210255	**15**	**3**
4	**Clarence Kweku Akuamoa** Senior Surveyor DNV Maritime Industry, North West Africa Tel : +23330303684 Mob : +233303210260	**11**	**2**
5	**ANOLONG Emeranda Ndikum** Head of Department for Quality, Health and Safety Tel : +237 233403488 Mob : +237 679518911	**08**	**1**

N.B: Grade category

Years of experience	Grade
26 and above	5
20 to 25	4
14 to 19	3
9 to 13	2
Less than 9	1

Appendix 5– Rule continuation 62-125 from Table 5.1

62	Average	Moderate	Unlikely			0.75	0.25	
63	Average	Moderate	Likely			1		
64	Average	Moderate	Highly L		0.25	0.75		
65	Average	Moderate	Definite	0.25		0.75		
66	Average	Critical	Highly U		0.4	0.35		0.25
67	Average	Critical	Unlikely		0.4	0.35	0.25	
68	Average	Critical	Likely		0.4	0.6		
69	Average	Critical	Highly L		0.65	0.35		
70	Average	Critical	Definite	0.25	0.4	0.35		
71	Average	Catastrophic	Highly U	0.4		0.35		0.25
72	Average	Catastrophic	Unlikely	0.4		0.35	0.25	
73	Average	Catastrophic	Likely	0.4		0.6		
74	Average	Catastrophic	Highly L	0.4	0.25	0.35		
75	Average	Catastrophic	Definite	0.65		0.35		
76	Frequent	Negligible	Highly U		0.35			0.65
77	Frequent	Negligible	Unlikely		0.35		0.25	0.4
78	Frequent	Negligible	Likely		0.35	0.25		0.4
79	Frequent	Negligible	Highly L		0.6			0.4
80	Frequent	Negligible	Definite	0.25	0.35			0.4
81	Frequent	Marginal	Highly U		0.35		0.4	0.25
82	Frequent	Marginal	Unlikely		0.35		0.65	
83	Frequent	Marginal	Likely		0.35	0.25	0.4	
84	Frequent	Marginal	Highly L		0.6		0.4	
85	Frequent	Marginal	Definite	0.25	0.35		0.4	
86	Frequent	Moderate	Highly U		0.35	0.4		0.25
87	Frequent	Moderate	Unlikely		0.35	0.4	0.25	
88	Frequent	Moderate	Likely		0.35	0.65		
89	Frequent	Moderate	Highly L		0.6	0.4		
90	Frequent	Moderate	Definite	0.25	0.35	0.4		
91	Frequent	Critical	Highly U		0.75			0.25
92	Frequent	Critical	Unlikely		0.75		0.25	
93	Frequent	Critical	Likely		0.75	0.25		
94	Frequent	Critical	Highly L		1			
95	Frequent	Critical	Definite	0.25	0.75			
96	Frequent	Catastrophic	Highly U	0.4	0.35			0.25
97	Frequent	Catastrophic	Unlikely	0.4	0.35		0.25	
98	Frequent	Catastrophic	Likely	0.4	0.35	0.25		
99	Frequent	Catastrophic	Highly L	0.4	0.6			
100	Frequent	Catastrophic	Definite	0.65	0.35			
101	Highly F	Negligible	Highly U	0.35				0.65
102	Highly F	Negligible	Unlikely	0.35			0.25	0.4
103	Highly F	Negligible	Likely	0.35		0.25		0.4
104	Highly F	Negligible	Highly L	0.35	0.25			0.4
105	Highly F	Negligible	Definite	0.6				0.4
106	Highly F	Marginal	Highly U	0.35			0.4	0.25
107	Highly F	Marginal	Unlikely	0.35			0.65	
108	Highly F	Marginal	Likely	0.35		0.25	0.4	
109	Highly F	Marginal	Highly L	0.35	0.25		0.4	
110	Highly F	Marginal	Definite	0.6			0.4	
111	Highly F	Moderate	Highly U	0.35		0.4		0.25
112	Highly F	Moderate	Unlikely	0.35		0.4	0.25	
113	Highly F	Moderate	Likely	0.35		0.65		
114	Highly F	Moderate	Highly L	0.35	0.25	0.4		
115	Highly F	Moderate	Definite	0.6		0.4		
116	Highly F	Critical	Highly U	0.35	0.4			0.25
117	Highly F	Critical	Unlikely	0.35	0.4		0.25	
118	Highly F	Critical	Likely	0.35	0.4	0.25		
119	Highly F	Critical	Highly L	0.35	0.65			
120	Highly F	Critical	Definite	0.6	0.4			
121	Highly F	Catastrophic	Highly U	0.75				0.25
122	Highly F	Catastrophic	Unlikely	0.75			0.25	
123	Highly F	Catastrophic	Likely	0.75		0.25		
124	Highly F	Catastrophic	Highly L	0.75	0.25			
125	Highly F	Catastrophic	Definite	1				

Appendix 6 – Base events combination rules

Base event 19

HF	CR	HL
A	MO	HU
L	MO	HU
L	MO	U
L	CR	U

=

3/5 HF	1/5 CR	1/5 HL
1/5AV	3/5 MO	1/5 U
1/5L		3/5 HU

=

3 x 2x 3 = 18 rules

NO	**Plausibility**	**F^L**	**C^S**	**F^{CP}**	**Rule**
1	**(3/5) (1/5)(1/5)**	**HF**	**CR**	**HL**	**119**
2	**(3/5)(1/5) (1/5)**	**HF**	**CR**	**U**	**117**
3	**(3/5)(1/5)(3/5)**	**HF**	**CR**	**HU**	**116**
4	**(3/5) (3/5 (1/5)**	**HF**	**MO**	**HL**	**114**
5	**(3/5)(3/5)(1/5)**	**HF**	**MO**	**U**	**112**
6	**(3/5)(3/5)(3/5)**	**HF**	**MO**	**HU**	**111**
7	**(1/5)(1/5 (1/5)**	**AV**	**CR**	**HL**	**69**
8	**(1/5)(1/5)(1/5)**	**AV**	**CR**	**U**	**68**
9	**(1/5)(1/5)(3/5)**	**AV**	**CR**	**HU**	**67**
10	**(1/5)(3/5)(1/5)**	**AV**	**MO**	**HL**	**64**
11	**(1/5)(3/5)(1/5)**	**AV**	**MO**	**U**	**62**
12	**(1/5)(1/5)(1/5)**	**AV**	**MO**	**HU**	**61**
13	**(1/5)(1/5)(1/5)**	**L**	**CR**	**HL**	**44**
14	**(1/5)(1/5)(1/5)**	**L**	**CR**	**U**	**42**
15	**(1/5)(1/5)(3/5)**	**L**	**CR**	**HU**	**41**
16	**(1/5)(3/5)(1/5)**	**L**	**MO**	**HL**	**39**
17	**(1/5)(3/5)(1/5)**	**L**	**MO**	**U**	**37**
18	**(1/5)(1/5)(1/5)**	**L**	**MO**	**HU**	**36**

Expert aggregation of base events to obtain output **S**

Output **S aggregation** using ER to obtain middle event reliability input M

S 19 = [0.2713P, 0.1878F, 0.3351A, 0.0848G, 0.1210VG]

Basic event 20

F	MO	L
A	MA	HL
A	MA	HL
A	MA	L
F	MA	L

=

2/5 F	1/5 MO	2/5 HL
3/5A	4/5 MA	3/5 L

=

2 x 2 x 2 = 8 rules

NO	**Degree**	**F^L**	**C^S**	**F^{CP}**	**Rule**
1	**(2/5) (1/5)(2/5)**	**F**	**MO**	**HL**	**89**
2	**(2/5)(1/5) (3/5)**	**F**	**MO**	**L**	**88**
3	**(2/5)(4/5)(2/5)**	**F**	**MA**	**HL**	**84**
4	**(2/5) (4/5 (3/5)**	**A**	**MA**	**L**	**83**
5	**(3/5)(1/5)(2/5)**	**A**	**MO**	**HL**	**64**
6	**(3/5)(1/5)(3/5)**	**A**	**MO**	**L**	**63**
7	**(3/5)(4/5 (2/5)**	**A**	**MA**	**HL**	**59**
8	**(3/5)(4/5 (3/5)**	**A**	**MA**	**L**	**58**

S20 = [OP, 0.2144F, 0.4594A, 0.3262G, 0VG]

Basic Event 21

A	MO	L
A	CR	L
A	CR	L
A	CR	L
A	MO	L

=

5/5 A	3/5 CR	5/5L
	2/5 MO	

=

1 x 2 x 1 = 2 rules

NO	**Degree**	**F^L**	**C^S**	**F^{CP}**	**Rule**
1	**(5/5) (3/5)(5/5)**	**A**	**CR**	**L**	**63**
2	**(5/5)(2/5) (5/5)**	**A**	**MO**	**L**	**68**

S 21= [0P, O.419F, 0.58A, 0G, 0VG]   0R [OP, 0.964F, 0.0906A, 0, 0]

Basic event 18

A	MO	L
A	MO	L
A	MO	L
A	MO	L
L	MO	HL

=

4/5 A	4/5 MO	4/5 L
1/5L		1/5H L

=

2 x 1 x 2 = 4 rules

NO	Degree	F^L	C^S	F^{CP}	Rule	P	F	A	G	VG
1	(4/5) (4/5)(4/5)	A	MO	L	63			1		
2	(4/5)(4/5) (1/5)	A	MO	HL	64		0.25	0.75		
3	(1/5) (4/5)(4/5)	L	MO	L	38			0.65	0.35	
4	(1/5) (4/5)(1/5)	L	MO	HL	39		0.25	0.4	0.35	

S18 = [0P, 0.211F, 0.9491A, 0.297G, 0E]

Basic event 17

L	NE	U
VL	MO	U
VL	MA	U
VL	MA	U
L	MA	HL

=

3/5VL	1/5 NE	4/5 U
2/5 L	3/5MA	1/5HL
	1/5MO	

=

2 x 3 x 2 = 12 rules

NO	Degree	F^L	C^S	F^{CP}	Rule	P	F	A	G	VG
1	(3/5) (1/5)(4/5)	VL	NE	U	2				0.25	0.75
2	(3/5)(1/5) (1/5)	VL	NE	HL	4			0.25		0.75
3	(3/5) (3/5)(4/5)	VL	MA	U	7				0.65	0.35
4	(3/5) (3/5)(1/5)	VL	MA	HL	9		0.25		0.4	0.35
5	(3/5) (1/5)(4/5)	VL	MO	U	12			0.4	0.25	0.35
6	(3/5) (1/5)(1/5)	VL	MO	HL	14		0.25	0.4		0.35
7	(2/5) (1/5)(4/5)	L	NE	U	27				0.6	0.4
8	(2/5) (1/5)(1/5)	L	NE	HL	29		0.25		0.35	0.4
9	(2/5) (3/5)(4/5)	L	MA	U	32				1	
10	(2/5) (3/5)(1/5)	L	MA	HL	34		0.35		0.65	
11	(2/5) (1/5)(4/5)	L	MO	U	37			0.4	0.6	
12	(2/5) (1/5)(1/5)	L	MO	HL	39		0.25	0.4	0.35	

S17 = [0P, 0F, 0A, 0.25G, 0.75E]

Basic event 16

VL	CR	L
VL	CR	L
A	MA	L
VL	MA	L
VL	MA	L

=

4/5VL	3/5 MA	5/5 L
2/5 A	2/5CR	

=

2 x 2 x 1 = 4 rules

NO	Degree	F^L	C^S	F^{CP}	Rule	P	F	A	G	VG
1	(4/5) (3/5)(5/5)	VL	MA	L	8			0.25	0.4	0.35
2	(4/5)(2/5) (5/5)	VL	CR	L	18		0.4	0.25		0.35
3	(2/5) (3/5)(5/5)	A	MA	L	58			0.6	0.4	
4	(2/5) (2/5)(5/5)	A	CR	L	68		0.4	0.6		

S = [0P, 0F, 0.25A, 0.4G, 0.35E]

Basic event 15

A	CR	HL
A	CR	L
A	CR	HL
A	CR	HL
A	CR	L

=

5/5A	5/5 CR	3/5 L
		2/5HL

=

1 x 1 x 2 = 2 rules

NO	Degree	F^L	C^S	F^{CP}	Rule	P	F	A	G	VG
1	(5/5) (5/5)(3/5)	A	CR	L	68			0.4	0.6	
2	(5/5)(5/5) (2/5)	A	CR	HL	69	0.25	0.4	0.35		

S = [0P, 0F, 0.657A, 0.4047G, 0.5296E]

Basic event 14

L	MO	L
VL	CR	L
L	MO	L
VL	CR	L
L	MO	L

=

3/5 L	3/5 MO	5/5 L
2/5 VL	2/5 CR	

=

2 x 2 x 1 = 4 rules

NO	**Degree**	**F^L**	**C^S**	**F^{CP}**	**Rule**	**P**	**F**	**A**	**G**	**VG**
1	(3/5) (3/5)(5/5)	L	MO	L	38			0.65	0.35	0.35
2	(3/5)(2/5) (5/5)	L	CR	L	43		0.4	0.25	0.35	
3	(2/5) (3/5)(5/5)	VL	MO	L	13			0.65		0.35
4	(2/5) (2/5)(5/5)	VL	CR	L	18		0.4	0.25		0.35

S14 = [0P, 0.1337F, 0.5424A, 0.2075G, 0.1163VG]

Basic event 13

F	MA	L
F	MA	L
F	MA	L
F	MA	L
F	MA	HL

=

5/5F	5/5 MA	4/5 L
		1/5HL

=

1 x 1 x 2 = 2 rules

NO	**Degree**	**F^L**	**C^S**	**F^{CP}**	**Rule**	**P**	**F**	**A**	**G**	**VG**
1	(5/5) (5/5)(4/5)	F	MA	L	83		0.35	0.25	0.4	
2	(5/5)(5/5)(1/5)	F	MA	HL	69	0.6			0.4	

S13 = [0.34P, 0.3175F, 0.22687A, 0.42187G, 0E]

Basic event 12

F	NE	U
A	MO	U
A	MA	U
L	MA	U
A	MA	HL

=

1/5 F	3/5NE	3/5 HU
3/5 A	2/5MO	2/5U
1/5 L		

=

3 x 2 x 2 = 12 rules

NO	Degree	F^L	C^S	F^{CP}	Rule	P	F	A	G	VG
1	(1/5) (3/5)(3/5)	F	NE	HU	76		0.35			0.65
2	(1/5)(3/5) (2/5)	F	NE	U	77		0.35		0.25	0.4
3	(1/5) (2/5)(3/5)	F	MO	HU	86		0.35	0.4		0.25
4	(1/5) (2/5)(2/5)	F	MO	U	87		0.35	0.4	0.25	
5	(3/5) (3/5)(3/5)	A	NE	HU	51			0.35		0.65
6	(3/5) (3/5)(2/5)	A	NE	U	52			0.35	0.25	0.4
7	(3/5) (2/5)(3/5)	A	MO	HU	61			0.75		0.25
8	(3/5) (2/5)(2/5)	A	MO	U	62			0.75	0.25	
9	(1/5) (3/5)(3/5)	L	NE	HL	26				0.35	0.65
10	(1/5) (3/5)(2/5)	L	NE	U	27				0.6	0.4
11	(1/5) (2/5)(3/5)	L	MO	HU	36			0.4	0.35	0.25
12	(1/5) (2/5)(2/5)	L	MO	U	37			0.4	0.6	

S12 = [0P, 0.593F, 0.3839A, 0.1470G, 0.4099E]

Basic event 11

L	MA	U
L	NE	U
L	MA	U
VL	MA	U
VL	MA	HL

=

2/5VL	1/5 NE	4/5 U
3/5 L	4/5MA	1/5 L

=

2 x 2 x 2 = 8 rules

NO	Degree	F^L	C^S	F^{CP}	Rule	P	F	A	G	VG
1	(2/5) (1/5)(4/5)	VL	NE	U	2				0.25	0.75
2	(2/5)(1/5) (1/5)	VL	NE	L	3			0.25		0.75
3	(2/5) (4/5)(4/5)	VL	MA	U	7				0.65	0.35
4	(2/5) (4/5)(1/5)	VL	MA	L	8			0.25	0.4	0.35
5	(3/5) (1/5)(4/5)	L	NE	U	27				0.6	0.4
6	(3/5) (1/5)(1/5)	L	NE	L	28			0.25	0.35	0.4
7	(3/5) (4/5)(4/5)	L	MA	U	32				1	
8	(3/5) (4/5)(1/5)	L	MA	L	33			0.25	0.75	

S11 = [0P, 0F, 0.317A, 0.8114G, 0.1287E]

Basic event 10

F	MO	L
A	MO	L
F	MO	L
A	MO	L
A	CR	L

=

3/5A	4/5 NE	5/5 L
2/5 F	1/5MA	

=

2 x 2 x 1 = 4 rules

NO	Degree	F^L	C^S	F^{CP}	Rule	P	F	A	G	VG
1	(3/5) (4/5)(5/5)	A	NE	L	53			0.6		0.4
2	(3/5)(1/5) (5/5)	A	MA	L	58			0.6	0.4	
3	(2/5) (4/5)(5/5)	F	NE	L	78		0.35		0.25	0.4
4	(2/5) (1/5)(5/5)	F	MA	L	83		0.35	0.25	0.4	

S10 = [0P, 0.1134F, 0.4067A, 0.1245G, 0.3554E]

Basic event 9

F	MA	HL
F	MA	HL
F	CR	HL
L	CR	HL
L	CR	HL

=

3/5 L	4/5 MA	5/5 HL
2/5 F	1/5 CR	

=

2 x 2 x 1 = 4 rules

NO	Degree	F^L	C^S	F^{CP}	Rule	P	F	A	G	VG
1	(3/5) (4/5)(5/5)	L	MA	HL	34		0.25		0.75	
2	(3/5)(1/5) (5/5)	L	CR	HL	44		0.65		0.35	
3	(2/5) (4/5)(5/5)	F	MA	HL	84		0.6		0.4	
4	(2/5) (1/5)(5/5)	F	CR	HL	83		1			

S9 = [0P, 0.4394F, 0A, 0.5606G, 0VG]

Basic event 8

A	CT	HL
A	CT	HL
A	MO	HL
A	MO	HL
A	CR	HL

=

5/5A	2/5 MO	5/5 HL
	1/5CR	
	2/5 CT	

=

1 x 3 x 1 = 3 rules

NO	Degree	F^L	C^S	F^{CP}	Rule	P	F	A	G	VG
1	(5/5) (2/5)(5/5)	A	MO	HL	64		0.25	0.75		
2	(5/5)(1/5) (5/5)	A	CR	HL	69		0.65	0.35		
3	(5/5) (2/5)(5/5)	A	CT	HL	74	0.4	0.25	0.35		

S8 = [0.1433, 0.3129F, 0.5438A, 0G, 0E]

Basic event 7

VL	MA	HU
L	NE	HU
VL	MA	HU
L	NE	HU
VL	NE	HU

=

3/5 VL	3/5 NE	5/5 HU
2/5 L	2/5 MA	

=

2 x 2 x 1 = 4 rules

NO	Degree	F^L	C^S	F^{CP}	Rule	P	F	A	G	VG
1	(3/5) (3/5)(5/5)	VL	NE	HU	1					1
2	(3/5)(2/5) (5/5)	VL	MA	HU	6				0.4	0.6
3	(2/5) (3/5)(5/5)	L	NE	HU	26				0.35	0.65
4	(2/5) (2/5)(5/5)	L	MA	HU	31				0.65	0.35

S7 = [0P, 0F, 0A, 0.2260G, 0.774VG]

Basic event 6

L	MO	HL
L	NE	HL
L	MO	UL
HF	NE	UL
HF	NE	HL

=

3/5L	3/5 NE	2/5 UL
2/5HF	2/5MO	3/5 HL

=

2 x 2 x 2 = 8 rules

NO	**Degree**	**F^{L}**	**C^{S}**	**F^{CP}**	**Rule**	**P**	**F**	**A**	**G**	**VG**
1	(3/5)(3/5)(2/5)	L	NE	UL	2				0.25	0.75
2	(3/5)(3/5) (3/5)	L	NE	HL	3			0.25		0.75
3	(3/5) (2/5)(2/5)	L	MO	UL	7				0.65	0.35
4	(3/5) (2/5)(3/5)	L	MO	HL	8			0.25	0.4	0.35
5	(3/5) (3/5)(2/5)	HF	NE	UL	27				0.6	0.4
6	(2/5) (3/5)(3/5)	HF	NE	HL	28			0.25	0.35	0.4
7	(2/5) (2/5)(2/5)	HF	MO	UL	32				1	
8	(2/5) (2/5)(3/5)	HF	MO	HL	33			0.25	0.75	

S6 = [0P, 0F, 0.1295A, 0.4015G, 0.4691E]

Basic event 5

A	CR	HL
A	CT	L
L	CT	HL
VL	CR	HL
VL	CT	L

=

2/5 VL	2/5 CR	2/5 L
1/5 L	3/5CT	3/5 HL
2/5 A		

=

3 x 2 x 2 = 12 rules

NO	**Degree**	**F^{L}**	**C^{S}**	**F^{CP}**	**Rule**	**P**	**F**	**A**	**G**	**VG**
1	(3/5) (3/5)(2/5)	VL	CR	L	18		0.4	0.25		0.35
2	(3/5)(3/5) (3/5)	VL	CR	HL	19		0.65			0.35
3	(3/5) (2/5)(2/5)	VL	CT	L	23	0.4		0.25		0.35
4	(3/5) (2/5)(3/5)	VL	CT	HL	24	0.4	0.25			0.35
5	(3/5) (3/5)(2/5)	L	CR	L	43		0.4	0.25	0.35	
6	(2/5) (3/5)(3/5)	L	CR	HL	44		0.65		0.35	
7	(2/5) (2/5)(2/5)	L	CT	L	48	0.4		0.25	0.35	
8	(2/5) (2/5)(3/5)	L	CT	HL	49	0.4	0.25		0.35	
9	(3/5) (3/5)(2/5)	A	CR	L	68		0.4	0.6		
10	(3/5) (3/5)(2/5)	A	CR	HL	69		0.65	0.35		
11	(3/5) (3/5)(2/5)	A	CT	L	73	0.4		0.6		
12	(3/5) (3/5)(2/5)	A	CT	HL	74	0.4	0.25	0.35		

S5 = [0.161P,0.3937F,0.2328A,0.885G,0.1241E]

Basic event 4

L	MA	U
F	NE	U
L	MO	L
F	NE	L
VL	NE	HU

=

1/5 VL	3/5 NE	1/5 HU
2/5 L	1/5MA	2/5 U
1/5F	1/5MO	2/5 L

=

3 x 3 x 3 = 27 rules

NO	**Degree**	**F^L**	**C^S**	**F^{CP}**	**Rule**	**P**	**F**	**A**	**G**	**VG**
1	(1/5) (3/5)(1/5)	VL	NE	HU	1					1
2	(1/5)(3/5) (2/5)	VL	NE	U	2				0.25	0.75
3	(1/5) (3/5)(2/5)	VL	NE	L	3			0.25		0.75
4	(1/5) (1/5)(1/5)	VL	MA	HU	6				0.4	0.6
5	(1/5) (1/5)(2/5)	VL	MA	U	7				0.65	0.35
6	(1/5) (1/5)(2/5)	VL	MA	L	8			0.25	0.4	0.35
7	(1/5) (1/5)(1/5)	VL	MO	HU	11			0.4		0.6
8	(1/5) (1/5)(2/5)	VL	MO	U	12			0.4	0.25	0.35
9	(1/5) (1/5)(2/5)	VL	MO	L	13			0.65		0.35
10	(2/5) (3/5)(1/5)	L	NE	HU	26				0.35	0.65
11	(2/5) (3/5)(2/5)	L	NE	U	27				0.6	0.4
12	(2/5) (3/5)(2/5)	L	NE	L	28			0.25	0.35	0.4
13	(2/5) (1/5)(1/5)	L	MA	HU	31				0.65	0.35
14	(2/5) (1/5)(2/5)	L	MA	U	32				1	
15	(2/5) (1/5)(2/5)	L	MA	L	33			0.25	0.75	
16	(2/5) (1/5)(1/5)	L	MO	HU	36			0.4	0.35	0.25
17	(2/5) (1/5)(2/5)	L	MO	U	37			0.4	0.6	
18	(2/5) (1/5)(2/5)	L	MO	L	38			0.65	0.35	
19	(1/5) (3/5)(1/5)	F	NE	HU	76		0.35			0.65
20	(1/5) (3/5)(2/5)	F	NE	U	77		0.35		0.25	0.4
21	(1/5) (3/5)(2/5)	F	NE	L	78		0.35	0.25		0.4
22	(1/5) (1/5)(1/5)	F	MA	HU	81		0.35		0.4	0.25
23	(1/5) (1/5)(2/5)	F	MA	U	82		0.35		0.65	
24	(1/5) (1/5)(2/5)	F	MA	L	83		0.35	0.25	0.4	
25	(1/5) (1/5)(1/5)	F	MO	HU	86		0.35	0.4		0.25
26	(1/5) (1/5)(2/5)	F	MO	U	87		0.35	0.4	0.25	
27	(1/5) (1/5)(2/5)	F	MO	L	88		0.35	0.65		

S4= [0P,0.0811F,0.1755A,0.3532G,0.3902VG]

Basic event 3

A	CR	HL
A	CT	L
L	CT	HL
VL	CR	HL
VL	CT	L

=

2/5 VL	2/5 CR	2/5 L
1/5 L	3/5CT	3/5 HL
2/5 A		

=

3 x 2 x 2 = 12 rules

NO	**Degree**	**F^{L}**	**C^{S}**	**F^{CP}**	**Rule**	**P**	**F**	**A**	**G**	**VG**
1	(3/5) (3/5)(2/5)	VL	CR	L	18		0.4	0.25		0.35
2	(3/5)(3/5) (3/5)	VL	CR	HL	19		0.65			0.35
3	(3/5) (2/5)(2/5)	VL	CT	L	23	0.4		0.25		0.35
4	(3/5) (2/5)(3/5)	VL	CT	HL	24	0.4	0.25			0.35
5	(3/5) (3/5)(2/5)	L	CR	L	43		0.4	0.25	0.35	
6	(2/5) (3/5)(3/5)	L	CR	HL	44		0.65		0.35	
7	(2/5) (2/5)(2/5)	L	CT	L	48	0.4		0.25	0.35	
8	(2/5) (2/5)(3/5)	L	CT	HL	49	0.4	0.25		0.35	
9	(3/5) (3/5)(2/5)	A	CR	L	68		0.4	0.6		
10	(3/5) (3/5)(2/5)	A	CR	HL	69		0.65	0.35		
11	(3/5) (3/5)(2/5)	A	CT	L	73	0.4		0.6		
12	(3/5) (3/5)(2/5)	A	CT	HL	74	0.4	0.25	0.35		

S3 = [0.1721P, 0.3993F, 0.2108A,0.99G, 0.118E]

Basic event 2

VL	CR	L
VL	NE	L
VL	CR	HL
VL	CR	L
VL	NE	L

=

5/5 VL	2/5 NE	4/5 L
	3/5 CR	1/5 HL

=

1 x 2 x 2 = 4 rules

NO	**Degree**	**F^{L}**	**C^{S}**	**F^{CP}**	**Rule**	**P**	**F**	**A**	**G**	**VG**
1	(5/5) (2/5)(4/5)	VL	NE	L	3			0.25		0.75
2	(5/5) (2/5)(1/5)	VL	NE	HL	4		0.25			0.75
3	(5/5) (3/5)(4/5)	VL	CR	L	18		0.4	0.25		0.35
4	(5/5) (3/5)(1/5)	VL	CR	HL	19		0.65			0.35

S2 = [0P, 0.2758F, 0.1980A, 0G, 0.5262E]

Basic event 1

L	MO	U
L	MO	U
AV	MO	HU
L	MO	HU
F	MO	U

=

3/5 L	5/5 MO	2/5 HU
1/5AV		3/5 U
1/5 F		

=

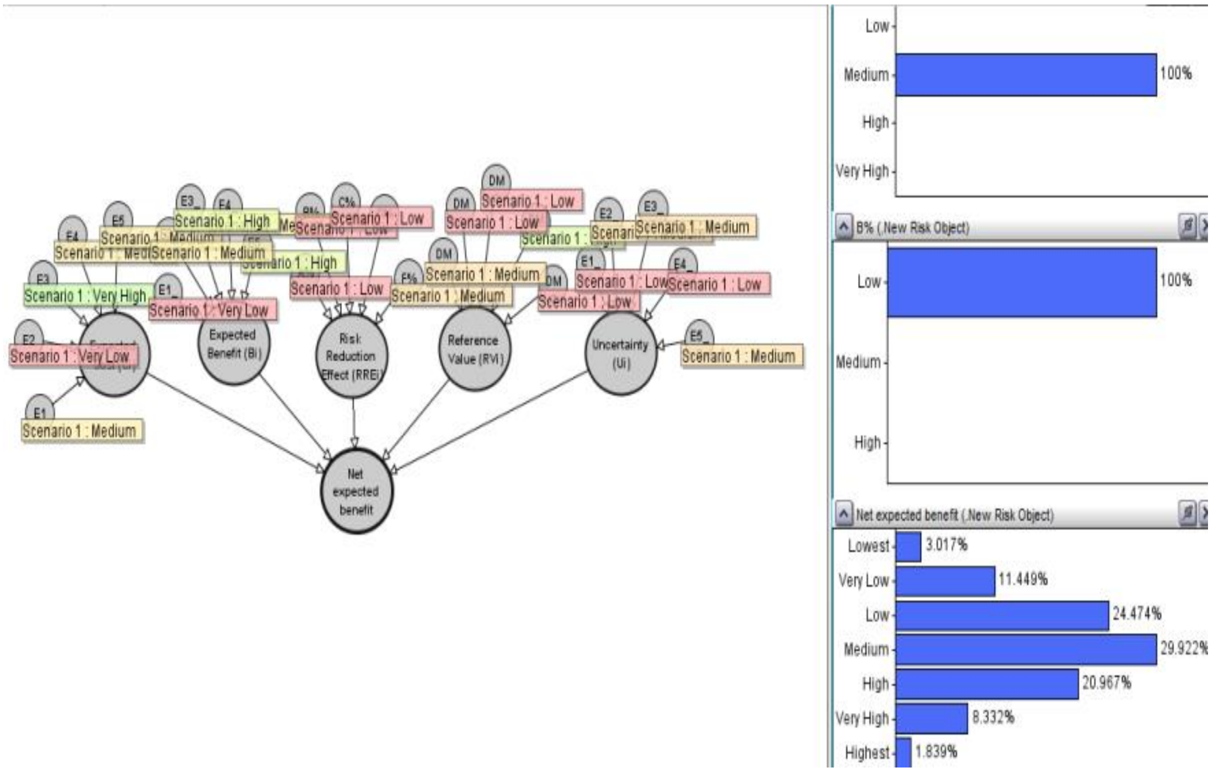
3 x 1 x 2 = 6 rules

NO	**Degree**	F^L	C^S	F^{CP}	**Rule**	**P**	**F**	**A**	**G**	**VG**
1	(3/5) (5/5)(2/5)	L	MO	HU	36			0.4	0.35	0.25
2	(3/5)(5/5)(3/5)	L	MO	U	37			0.4	0.6	
3	(1/5) (5/5)(2/5)	AV	MO	HU	61			0.75		0.25
4	(1/5) (5/5)(3/5)	AV	MO	U	62			0.75	0.25	
5	(1/5) (5/5)(2/5)	F	MO	HU	86		0.35	0.4		0.25
6	(1/5) (5/5)(3/5)	F	MO	U	87		0.35	0.4	0.25	

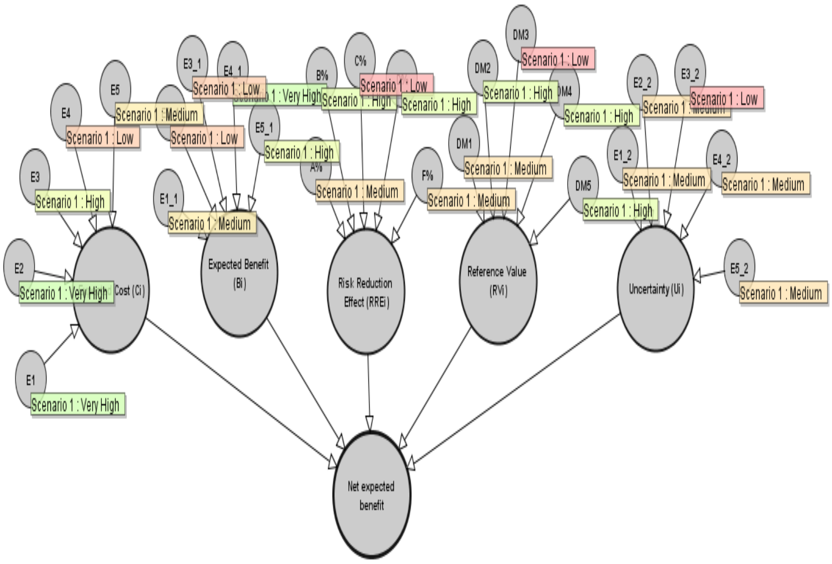
S1= [0P, 0.510F, 0.4915A, 0.37G, 0.809E]

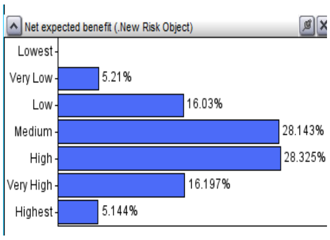
Appendix 7 – Cost benefit analysis result

RCOA1 Result

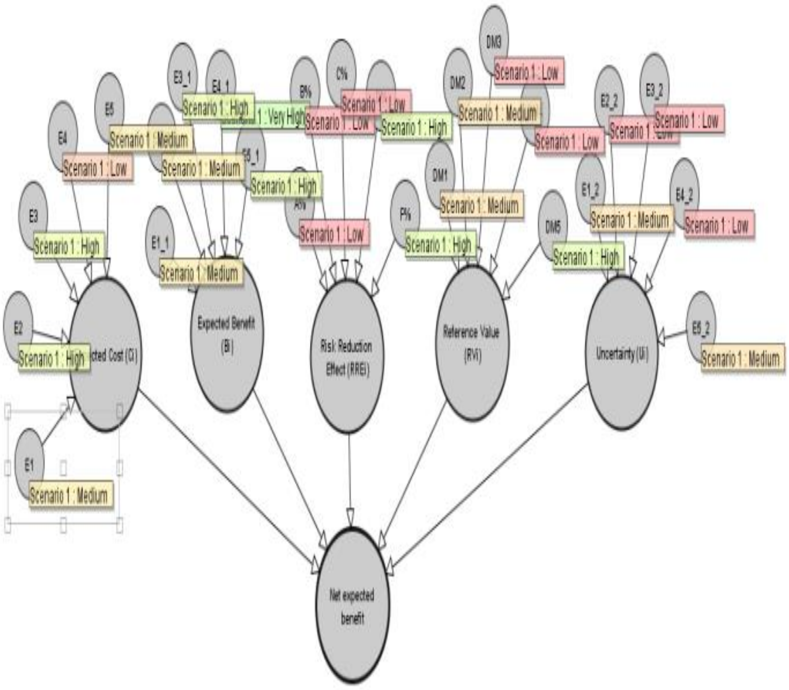


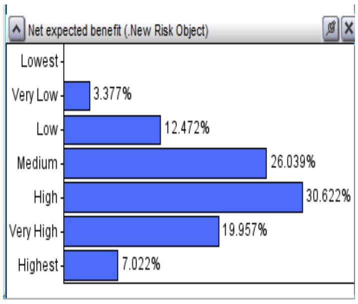
RCOA3 Result



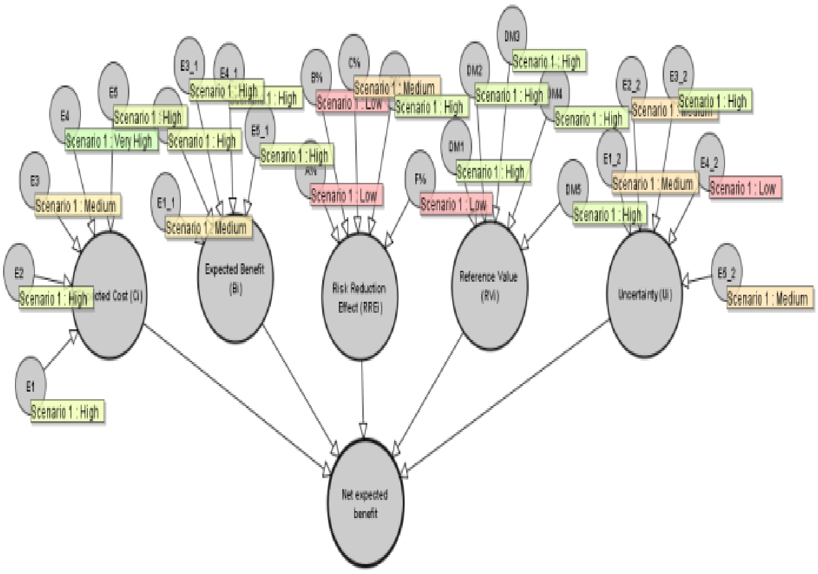


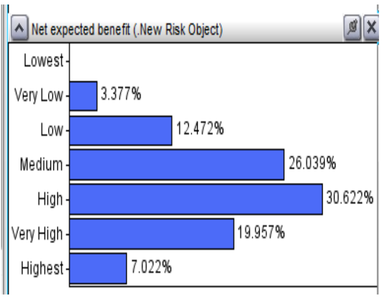
RCOA4 Result



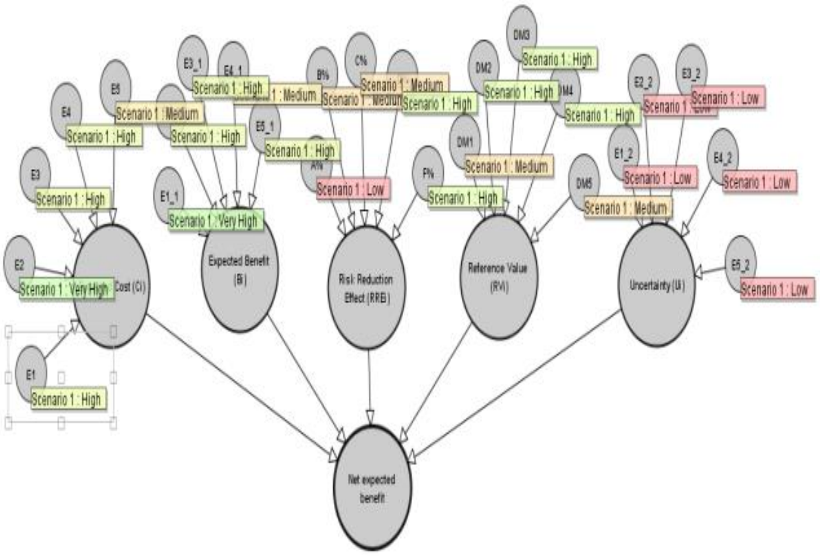


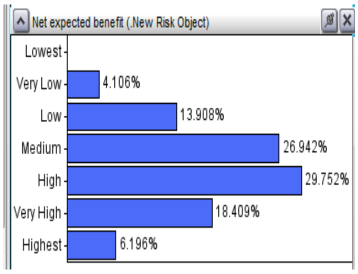
RCOA5 Result



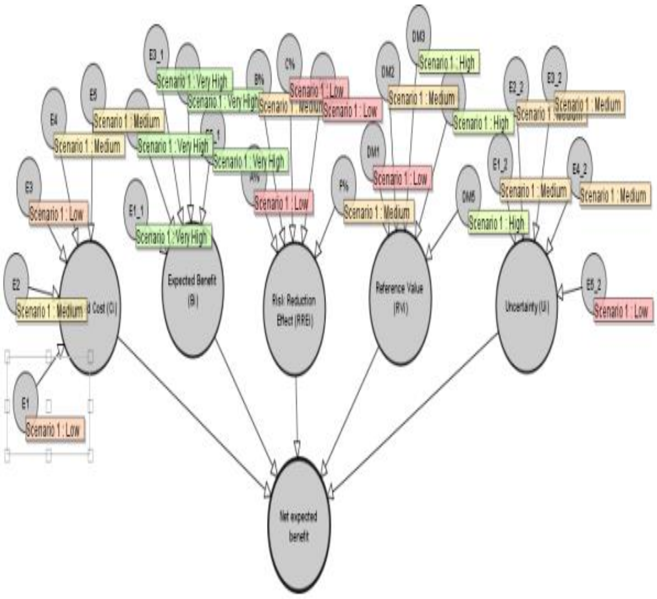


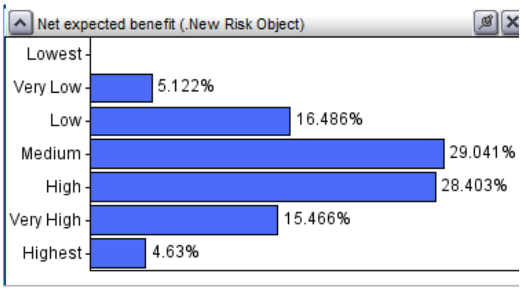
RCOA6 Result



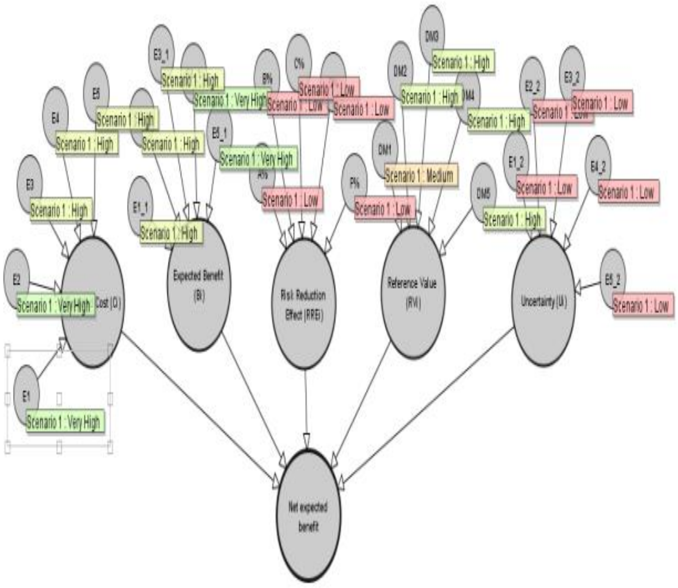


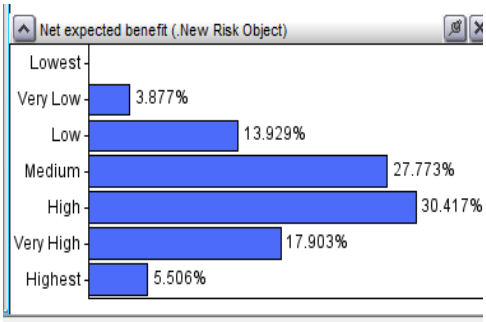
RCOB1 Result



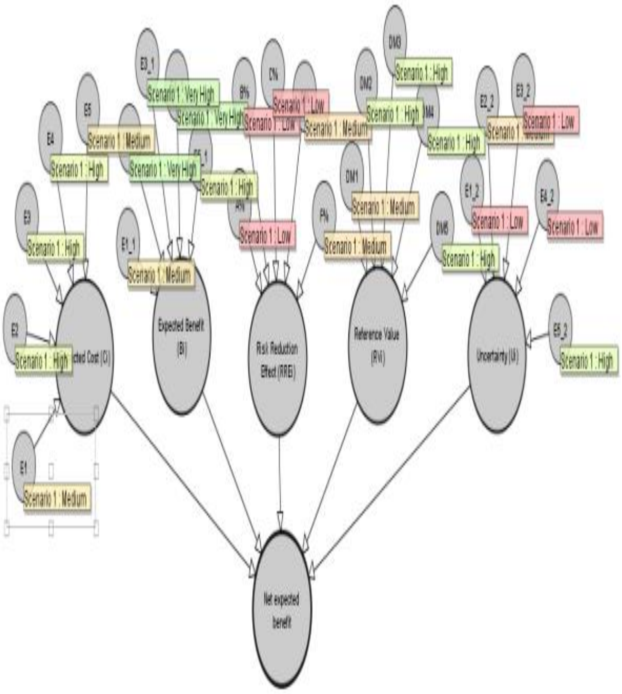


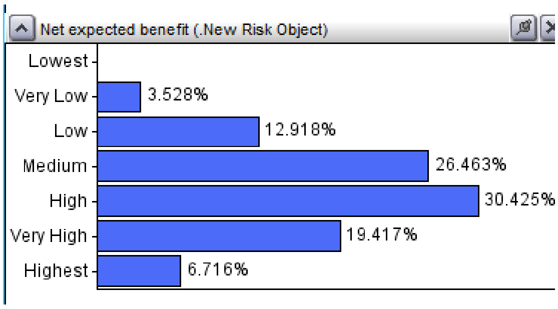
RCOB2 Result



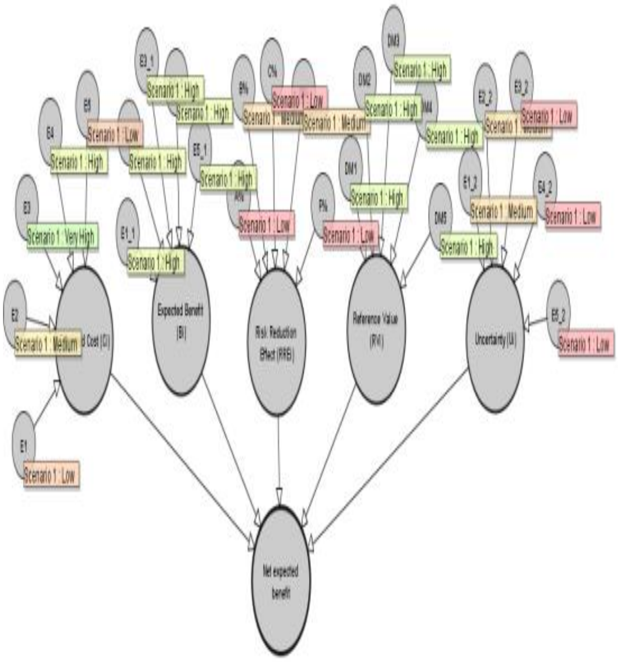


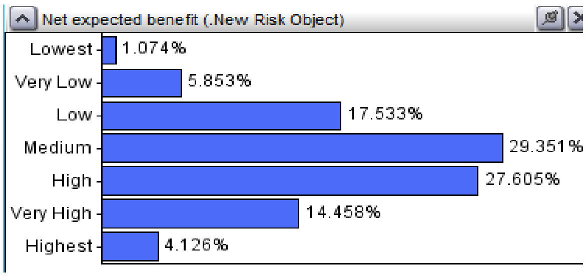
RCOB3 Result



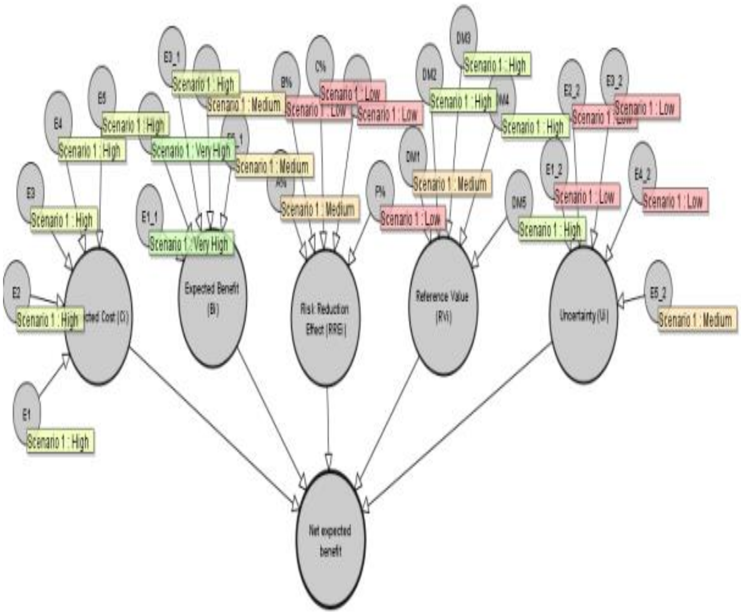


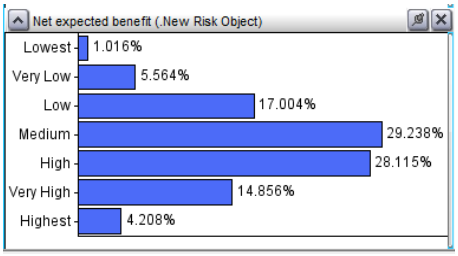
RCOB4 Result





RCOB5 Result





RCOB6 Result