RISK-BASED FRAMEWORK FOR BALLAST WATER SAFETY MANAGEMENT

By

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

March, 2010

Abstract

Ballast water has been identified as a major vector for the translocation of Non-Indigenous Invasive Species (NIS) and pathogens across zoogeographical regions and subsequent discharged into recipient port states/regions. This is bound to increase given factors like the globalization of trade and the economy of scale of the ship size. Established NIS has posed significant threat to the human health, economy, finances and marine bio-diversity of recipient regions and port states. The risks associated with the discharged NIS are uncertain and difficult to assess due to the stochastic nature of species assemblages and dispersal mechanism. The safest control measure advocated by the IMO is the conduct of ballast water exchange at sea while appropriate and effective proto-type treatment technologies are being developed and approved for future application.

This study has been conducted while recognizing the inability of probabilistic approaches applied in ballast water risk management to addressing uncertainty and inadequacy of data. A qualitative approach using powerful multi-criteria decision making techniques and the safety principles of the Formal Safety Assessment framework have been utilized in this research to develop three generic models for ballast water hazard estimation, risk evaluation and decision-making analysis respectively. The models are capable of being modified and utilized in the industry to address the problems of uncertainty and inadequacy of data in ballast water management. This is particularly useful as an interim measure for port states in developing economies (with insufficient data and technology) to developed robust ballast water management plans. While recognising the huge impact of ballast water pollution in recipient regions this study recommends that ballast water management programmes be given due recognition as an important element of sustainable development programmes at national and international levels.

The non-availability of a benchmark based on previous research on which to fully validate the research outcome was identified as a major limitation of this research study. The models developed will therefore be subject to modifications as new data become available.

Acknowledgements

This thesis represents the attainment of a profoundly personal goal in the life of the author. The academic voyage has been long and tortuous but to know that the desired goal is finally achieved lives the author with memories that will be cherished for the rest of his life. The author's interest in ballast water management as a subject of study dates back to 2001 - while studying for his Masters' degree in Maritime Operations at LJMU. This passion coincided with the 1st IMO International Ballast Water Treatment (R & D) Symposium (21 – 23, July, 2001) at the IMO Headquarters in London - which he attended. The wealth of knowledge and experience gathered from experts in the field who attended the symposium from all over the world gave the author a picture of what lay ahead in this chosen field of study. By the time the author attended the 2nd International Symposium in 2003 (kindly sponsored by the School of Engineering, LJMU) it was obvious that there was no going back on the subject. These symposia were quickly followed by ballast water risk assessment projects coordinated by the Globallast Programme in Demonstration Sites in six Pilot Countries. The risk assessment methodologies adopted by the Programme were species-specific and did not address the problems of uncertainties and inadequacy of historical data, hence, the choice of topic. This notwithstanding, the author would like to acknowledge the contributions and support of some of the experts in making this research successful.

The author would like to thank Steve Raaymakers (first Chief Technical Adviser of the IMO Globallast Programme) for his technical advice and the literature he gave to support the author's research. The following experts also supported with their published works: Dr. Keith Hayes, Dr. Tracy McCollin, Allegra Cangelosi, Dr. Geoff Rigby, Mr. Scott Smith and Dr, Stephen Gollasch. The author is particularly grateful to Dr. Moira McConnell for making available information on the Globallast Legislative Review even when it had not been published. The author also wishes to thank the Lloyd's Register for making available a copy of their Study, "Ballast Water Treatment Technology: Current Status". The document was of immense help during the study.

The author is particularly grateful to the LJMU School of Engineering, Technology and Maritime Operations for the Grant and financial support awarded to him during the course of this research. This research would not have been completed without the support and understanding of the School.

The author's special thanks and sincere gratitude go his supervisors, Dr. Alan Wall and Professor Jin Wang as well as Dr. Zaili Yang. Their support, friendship and encouragement during the long period of this research were unquantifiable and without them this research would never have come to fruition. I would like to thank the members of LJMU's LOgistics, Offshore and Marine (LOOM) Institute, for their support and encouragement during the study. They all proved to be productive team members and players.

The author would like to pay very special tribute to his soul-mate and the woman in his life, Mildred. For your love, care and encouragement, and for picking up the bills during this period of study, thank you so very much. For his children, Eugene (Jnr.), Solomon and Ann-Marie, you are very wonderful and special kids. A special tribute goes to the author's mother, Agatha who became a widow during the author's period of study. Mum, you are special.

Finally, the author wishes to pay tribute to all those supported him through their prayers and deeds. Special mention must however be made of the following people who stood out: Mr. Sunday Wang for your financial and moral support to the author and his family. Special gratitude also goes to my siblings – especially my sisters, Mrs. Christie Nyam and Miriam Shitery. Tribute is also paid to Grp. Capt. Chris Pam and Dr. William Musda.

May the Good Lord who began every good work in our lives bring them all to fulfillment. Amen.

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Abbreviations

AHP	Analytical Hierarchy Process
AI	Artificial Intelligence
ALARP	As Low As Reasonably Practicable
AQIS	Australian Quarantine and Inspection Service
BWM	Ballast Water Management
BWE	Ballast Water Exchange
BWEO	Ballast Water Exchange Options
BWRA	Ballast Water Risk Assessment
BWT	Ballast Water Treatment
CBA	Cost Benefit Analysis
CBD	Convention on Biological Diversity: United Nations
CI	Consistency Index
CR	Consistency Ratio
CSD	Commission for Sustainable Development: United Nations
DoB	Degree of Belief
DNV	Det Norske Veritas
D-S	Dempster Shafer Evidence Combination Rule
EMBLA	Integrated Ballast Water Risk Management Approach: DNV
ER	Evidential Reasoning
ETA	Event-Tree Analysis
FL	Fuzzy Logic
FMCDM	Fuzzy Multi-Criteria Decision-Making Methodology
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
FNIRP	Fuzzy Negative Ideal Reference Point
FPIRP	Fuzzy Positive Ideal Reference Point
FRB	Fuzzy-Rule Base
FSA	Formal Safety Assessment
FST	Fuzzy Set Theory
FTA	Fault-Tree Analysis
FUZIMEA	Fuzzy Infection Mode and Effect Analysis

GLoBALLAST	Global Ballast Water Management Programme
HAZID	Hazard Identification
HAZOP	Hazard and Operability
HSE	Health and Safety Executive (UK)
ICES	International Council for the Exploration of the Sea
ICS	International Chamber of Shipping
IDS	Intelligent Decision System
IMEA	Infection Mode and Effect Analysis
IMO	International Maritime Organization
INTERTANKO	International Association of Independent Tanker Owners
LLC	Lower Level Criteria
LRS	Lloyds Register of Shipping
MADA	Multi-Attribute Decision Analysis
MARPOL	Marine Pollution Convention (IMO)
MARTOB	European Research Project for On-board Treatment of Ballast Water and Application of Low Sulphur Fuels
MAFF	Ministry of Agriculture, Fisheries and Food (UK)
MCA	Maritime and Coastguard Agency (UK)
MCDA	Multiple Criteria Decision Analysis
MCDM	Multi-Criteria Decision Making
MEPC	Marine Environmental Protection Committee (IMO)
MPAs	Marine Protected Areas
MSC	Maritime Safety Committee (IMO)
NIS	Non-Indigenous Invasive Species
NIPR	Negative Ideal Reference Point
NRC	National Research Council (USA)
PFA	Priority for Attention
PIRP	Positive Ideal Reference Point
RI	Random Index
RCOs	Risk Control Options
RPN	Risk Priority Number
SOLAS	Safety of Life at Sea Convention: United Nations

SWIFT	Structured What-If Checklist Technique
TOPSIS	Technique for Order Performance by Similarity to Ideal Solution
UN	United Nations
UNCED	United Nations Convention on Environment and Development
UNCLOS	United Nations Convention on Law of the Sea Convention
USCG	United States Coast Guard
USEPA	United States Environmental Protection Agency
ULC	Upper Level Criteria
UVI	Ultra-Violet Irradiation Treatment
VLCC	Very Large Crude Oil Carriers
WMOM	Weighted Mean of Maximums

Dedication

This Ph.D. thesis is dedicated to my wife, Mildred Vou Pam, my children, Eugene Weng-Chomo Pam, Solomon Nyuah Pam and Ann-Marie Vou Noroh Pam.

Chapter One

Introduction

1.1 Background Analysis

Ships' ballast water and hulls have been recognised as major vectors for the transfer of NIS and pathogens across bio-geographical boundaries. Agenda 21(17.30) of the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro-Brazil (3- 14 June, 1992) recognised that for success to be achieved in the search for global prevention, reduction, and control of degradation of the marine environment from sea-based activities like shipping, there was a need for the adoption of appropriate rules on ballast water discharge to prevent the spread of non-indigenous organisms. In this regard, a major direct action was undertaken by the IMO aimed at minimising the introduction of NIS and pathogens (IMO, 1998). Voluntary (international) guidelines for preventing the introduction of unwanted aquatic organisms and pathogens from ships' ballast water and sediments discharges were subsequently introduced through Resolution A. 868(20) of 1997 (IMO, 1998). A significant approach in the IMO guidelines was the call for the development of prototype treatment technologies for on-board ballast water treatment. In response to this mandate numerous treatment technologies were developed to address this problem. Most of these technologies were derived from municipal and industrial (waste) water treatment applications and have been classified under two generic categories: physical solid liquid separation and disinfection (Lloyds Register, 2007). Technical, economic and ecological challenges to be sustained by the emerging ballast water treatment technologies include: vessel safety, fire hazards, corrosion, space limitations, vessel design limitations, inability to identify specific species type on a given donor or recipient port, inability to treat full volume during transit route, and "dead-spot" in ballast tanks that remain untreated (Lloyds Register, 2007). The IMO regulations unequivocally state that any emerging technology developed through research for on-board treatment of ballast water must be safe, environmentally acceptable, practicable, cost-effective, and biologically effective (Globallast, 2000). However, the absence of internationally acceptable standards and procedures for the evaluation and approval of new treatment technologies remains a constraint in the implementation of any developed treatment system. This is an issue that is currently being addressed by the IMO.

This research has been conducted whilst recognizing that current scientific and prototype technologies of ballast water treatment systems are under development. Despite technological progress the inadequacy of data on species types and assemblages creates an uncertainty that can result in the selection of inappropriate treatment systems for a wrong ship type and/or ballast voyage. This uncertainty could thus result in severe environmental and/or financial consequences. Classical subjective engineering safety models have been applied in this research as an alternative to a reliance on substantiated scientific facts about marine organisms and pathogens living in the world's bio-geographical regions. Principally, fuzzy sets theory and fuzzy rule-base have been applied in the ballast water risk evaluation while Evidential Reasoning (ER), Analytical Hierarchy Process (AHP) and TOPSIS approaches have been applied in the decision analyses processes. These safety models have been applied successfully in different specialized fields other than engineering with positive results. The models developed in this study are by no means conclusive, hence, they should be subject to further modification and subsequent applicability to decision-making analyses of related themes in ballast water safety management.

1.2 Research Problem and Research Question

The fact that NIS discharged through ships' ballast water and hulls impacts negatively on human health, social lives of maritime communities, economies of recipient port states, marine installations and the marine environments of recipient ports; coupled with the fact that inadequacy of data and uncertainties surround the stochastic nature of species assemblages within global bio-geographical regions posing a great threat to the success rate of on-board treatment systems for the management of NIS; and also the fact that there exist technical, economic and ecological challenges associated with the numerous technologies that have been developed for on-board ballast water treatment, the following research questions have been posed in this thesis:

i. Can the application of safety principles of the formal safety assessment (FSA) methodology to ballast water safety management minimize and control the translocation of NIS through ships' ballast water and hulls to recipient ports/coastal states?

ii. Can the application of advanced decision analysis techniques address the decision-making problems associated with the selection of appropriate ballast water treatment systems by an end-user?

1.3 Research Aim and Objectives

The aim of this research is to develop novel subjective risk management models (based on the safety principles of the Formal Safety Assessment (FSA) framework) that are capable of addressing ecological/environmental problems associated with discharged NIS in recipient ports/coastal states through ships' ballast water. The study is also aimed at addressing decision making problems that could be encountered in ballast water safety management processes.

The objective of the research is to minimise and control the risks associated with the NIS to As-Low-As-Reasonably-Practicable (ALARP) levels either at the ballast water upload stage, during the ballast water voyage stage or eventual period of discharge into recipient ports/coastal states.

The aims and objective of the research will be achieved through the following approaches:

- A review of methodologies and technologies for preventing the introduction of nonindigenous invasive species and pathogens through ships' ballast water and hulls.
- Development of a generic model for identification of invasive species and pathogens discharged into recipient ports through ships' ballast water and hulls.
- Development of a decision support system for decision-making analysis of evaluation criteria in ballast water safety management.

- Facilitating the transcription into national legislation of internationally acceptable ballast water management regulations and legislations in port and coastal states of developing countries.
- Contribution to knowledge and the global search for solutions to the growing bio-ecological hazards associated with translocated non-indigenous invasive exotic species and pathogens from the discharge of ballast water into brackish waters of recipient seaports.

1.4 Definition of Concepts Used in this Research

Ballast Water: Water with its suspended matter taken on board a ship to control trim, list, draught, stability or stresses of the ship (IMO, 2004).

Ballast Water Management: Mechanical, physical, chemical, and biological processes, either singular or in combination, to remove, render harmless, or avoid the uptake or discharge of harmful aquatic organisms and pathogens within ballast water and sediments (IMO, 2004).

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 (MSA, 1993).

Indigenous Species: A species with a long natural presence that extends into the pre-historic record (Awad *et al*, 2004).

Invasive Species: An established introduced species that remains localised within its new environment and shows minimal ability to spread despite several decades of opportunity (Awad *et al*, 2004).

Risk: A combination of the probability of occurrence (frequency) of an undesired event and the degree of its possible consequences (severity) (Wang & Trbojevic, 2007).

Risk Assessment: A comprehensive estimation of the probability and the degree of possible consequences in a hazardous situation in order to select appropriate safety measures (Yang, 2006).

Translocation: The transfer of an organism or its propagules into a location outside its natural range by a human activity (Awad *et al*, 2004).

Vector: The physical means or agent by which a species is transferred from one place to another (e.g. ballast water, a ship's hull, or inside a shipment of commercial oysters (Awad *et al*, 2004).

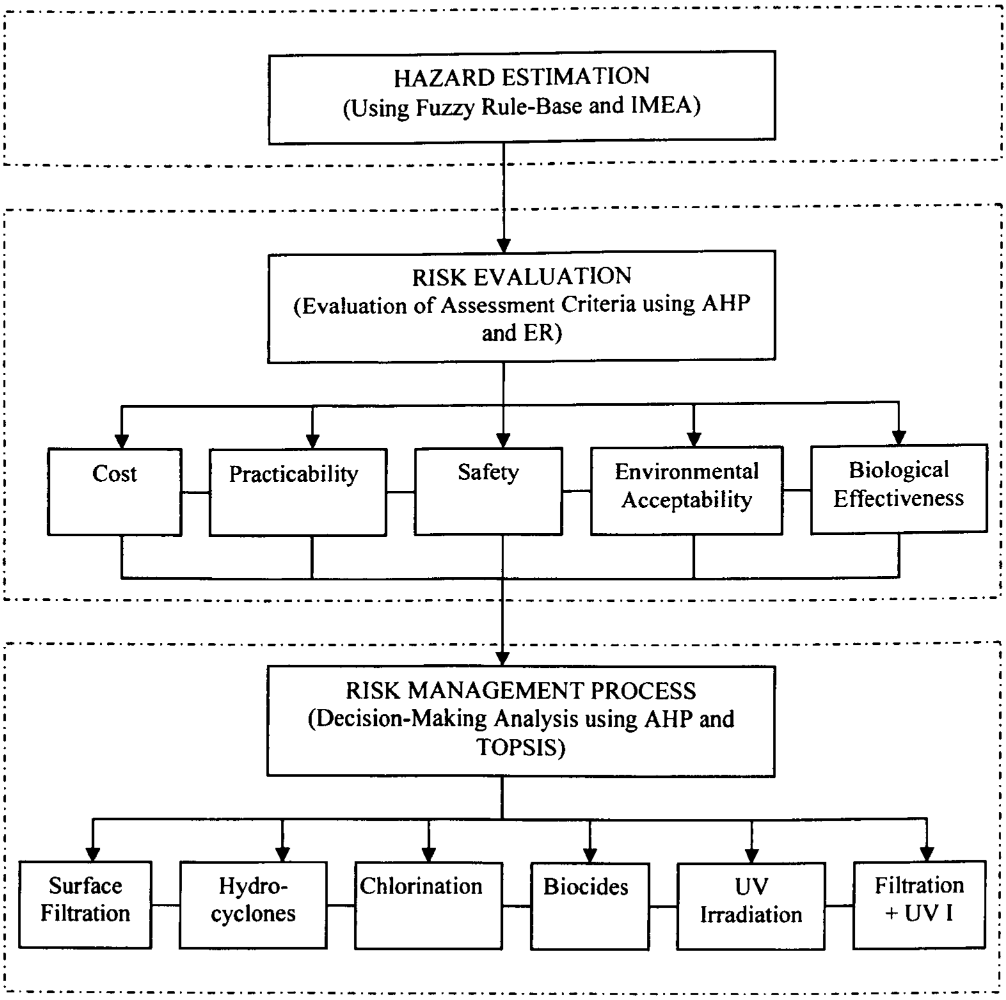
The concepts, "multi-attribute" and "multi-criteria" have been used interchangeably in this study to refer to a set of evaluation criteria.

1.5 Research Methodology

This research has been conducted taking into cognisance the fundamental principles of the Formal Safety Assessment (FSA). Generic models have been developed in this study capable of handling uncertainties and inadequacy of historical data for the evaluation of ballast water exchange options and treatment systems. This approach is an attempt to address the limitations of previous risk management methodologies that are case-specific or species-specific (See Section 2.5.2).

Fuzzy logic and multi-criteria (attribute) decision-making (MCDM) methodologies have also been utilised for the analysis of ballast water decision options. Consequently, the research methodology is divided into three unique sections and illustrated in Fig. 1.1.

Fig. 1.1 Thesis Research Methodology



1.5.1 Hazard Estimation

Discharged ballast water into brackish waters of recipient ports is identified as the primary hazard source and infection mode. Although ships' hulls have been identified as a secondary source, this research is limited to the primary infection mode. Chapter Two (Literature Review) discusses this subject and describes how the ballast water is transported in ships.

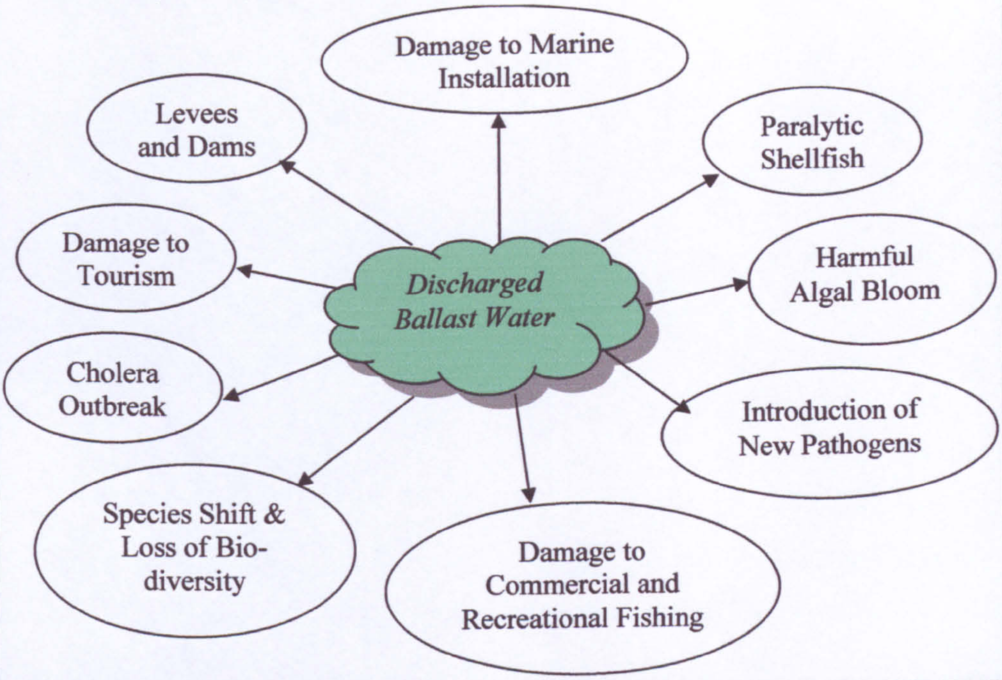
The Fuzzy-IMEA methodology applied in this thesis is based on components that outline the necessary procedure required for safety evaluation using Fuzzy Rule-Base (FRB). This is because the method does not require the use of a utility function to define the probability of occurrence, severity and detectability considered for the analysis and to avoid the use of traditional RPN (Pillay & Wang, 2003). The process is achieved through the utilisation of information and knowledge gathered from experts and integrating them in a formal way to reflect a subjective method of risk ranking. Details of this model are contained in Chapter Four.

1.5.2 Risk Evaluation

The hazard associated with discharged ballast water into recipient ports is the involuntary introduction of NIS and pathogens. Introduced species become invasive only after surviving the ballast intake, voyage and discharge processes. Added to these factors is the fact that the organisms would have settled and become established in the host environment. Once settled, these species develop and grow at exponentially devastating rates. In most cases they subdue and eliminate the indigenous organisms and take-over the new-found habitat. The consequences impact negatively on recipient port states. The major consequences include disruption of the social lives of maritime communities, human health, finance and economy of these states. Others include infestation of marine installations and environment (Fig. 1.2). Details of this subsection are contained in Chapter Two (Literature Review).

This study proposes a generic methodology for the evaluation of assessment criteria of ballast water management options using powerful multi-criteria decision making models (Analytic Hierarchical Process (AHP) and Evidential Reasoning (ER)). The criteria are: cost, practicability, safety, environmental acceptability and biological effectiveness. These criteria are fundamental principles of the IMO Guidelines for the control and management of ships' ballast water to minimize the transfer of harmful aquatic organisms and pathogens. The criteria are evaluated using subjective knowledge and judgement of multiple decision analysts. The AHP method has been applied to obtain the weights of these criteria while ER is applied for the assessment process of the criteria from a lower level to an upper level. The final output (decision options) from the data assessment process is synthesised using the evidential reasoning approach and IDS Software in order to select the best and most appropriate ballast water management option. The model described above is contained in Chapter Five.

Fig. 1.2 Some Identified Hazards Associated with Discharged Ballast Water
(Developed by author)



1.5.3 The Risk Management Process

In the risk management process, a hybrid methodology is developed to deal with the multi-criteria decision making (MCDM) problems encountered in the subjective analysis and selection of ballast water treatment systems under a group decision framework. The reality of selecting an acceptable ballast water treatment technology is a daunting task for end-users due to availability of numerous treatment options and their efficacy in given ship-types and ballast voyages.

For the purpose of this research study, six treatment systems have been selected from the two generic treatment technology groups (physical solid liquid separation and disinfection) and constitute the decision making alternatives in the proposed model. They are: surface filtration, hydro-cyclones, chlorination, biocides treatment, ultra-violet irradiation, and filtration + ultra-violet irradiation. Filtration + Ultra-Violet Irradiation (UVI) belongs to the treatment system group referred to as the hurdle technology (Lloyds Register, 2007).

The methodology proposed involves the application of fuzzy set theory and two powerful safety models (Analytical Hierarchy Process (AHP) and the Technique for Order Performance by Similarity to the Ideal Solution (TOPSIS)) in the decision-making analysis. A fuzzy-AHP methodology has been applied to determine the importance weights of the evaluation criteria while the Fuzzy-TOPSIS technique has been applied to obtain the performance ratings of decision alternatives using linguistic terms parameterised with triangular fuzzy numbers. The evaluation criteria and weights applied in this chapter are the same as those obtained in the previous chapter. This is to maintain a consistency in the subject matter of the research. In order to further validate this model, a sensitivity analysis is carried out under different criteria weights. The sensitivity analysis aims to identify the effects of changes in the input data and test the suitability of the developed model in decision-making analysis of ballast water treatment systems. This model is contained in a core technical chapter (Chapter Five).

1.6 Justification of Research

This Ph.D. research is a novel study that is aimed at addressing inherent problems associated with the management and control of discharged ballast water in recipient ports/ regions. It is apparent that the risk management process to address this problem can be limited due to inadequacy of historical data and uncertainties – in species inoculation and dispersal mechanisms. It also has to be observed that the quantitative risk assessment methodologies applied in ballast water risk management are end-point specific and based on environmental matching similarities. These approaches rarely address the problems of inadequacy of data and uncertainties which this research has set out to undertake. Through the introduction of the concept "safety" to ballast water management in this study, this research advocates the utilisation of effective and more robust approaches based on traditional engineering safety methodologies and possibilistic theories to conduct ballast water risk management. Ballast water pollution has been identified in this research as a bio-environmental problem which should be addressed holistically using powerful risk analysis and decision making analysis techniques. Fuzzy logic theory and MCDM techniques have been successfully applied in decision making and risk management problems in different fields that include: engineering; science and technology; corporate management and finance; education and training. The application of these techniques in ballast water safety management would not only address the problem of uncertainty and inadequacy of data in ballast water management but also be recognised as a novel approach to ballast water risk management.

1.7 Delimitation and Scope of Study

It should be understood that this research, while being conducted in line with the safety principle of FSA, does not exhaust the complete steps in the FSA flowchart which in full are: Hazard identification, Risk Assessment, Risk Control Options, Cost-Benefit Analysis and Decision Making Options. The study utilised hazard identification, risk assessment (evaluation) and decision making steps of the FSA. This is because the goal of the research is to explore the possibility and practicability of applying fuzzy logic and multi-criteria decision-making analysis methodologies to ballast water safety management. A complete study could be a subject of future research. Secondly, the absence of cost estimates in Chapter Five is as a result of unwillingness of the industry to disclose the cost of production and on-board application of developed products. The test scenarios have been generated using data obtained from the IMO (IMO, 2004) and Lloyds Register (Lloyds, 2007).

1.8 Structure of Thesis

The structure of this thesis is illustrated in Fig. 1.3. The thesis contains seven chapters and the breakdown is as follows:

1.8.1 Chapter One: Introduction

This chapter discusses the background of the research study. It identifies the research problem and questions, followed by identification of the research methodology, delimitation and scope of study. The chapter ends with a presentation of the structure of the thesis.

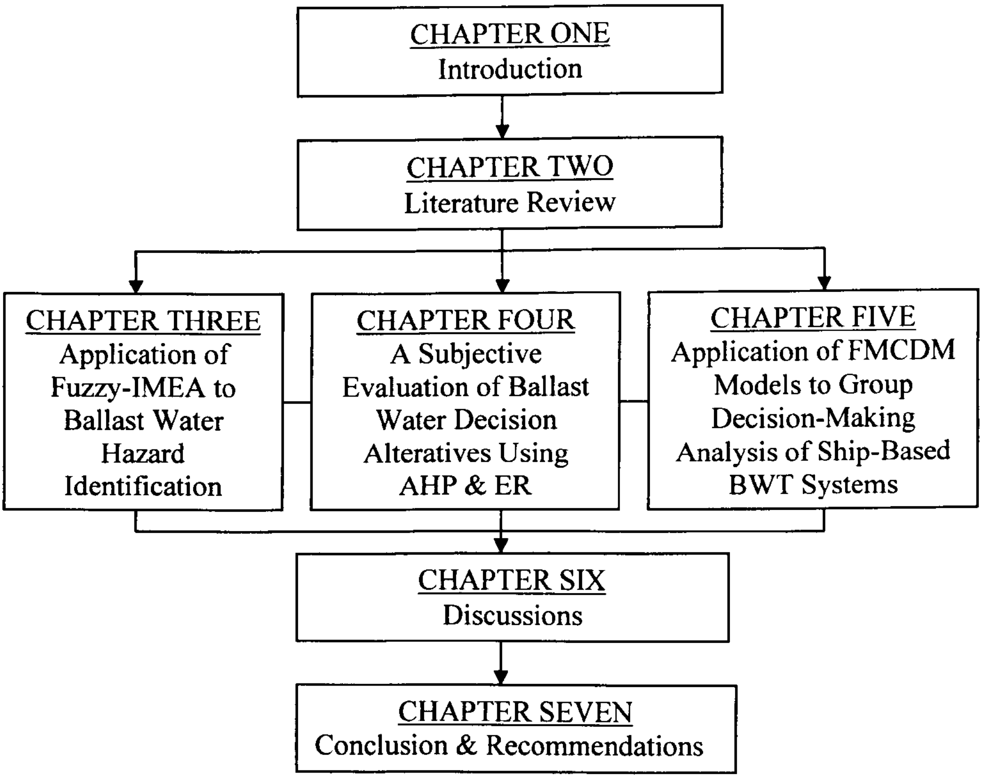
1.8.2 Chapter Two: Literature Review

This chapter reviews current data on research and development (R&D) on ballast water management, as well as a review of current legislations and management plans adopted by some selected Port States. The strengths and shortcomings of some of these management plans will be identified with a view to strengthening the case for the development and application of alternative methodologies for hazard identification, risk evaluation and decision-making analyses in ballast water safety management.

1.8.3 Chapter Three: Identification of Non-Indigenous Invasive Species (NIS) Infection Modes Using Fuzzy Rule-Base-IMEA

Chapter Three is a core technical chapter which contains the generic model for the estimation of NIS infection modes and vectors using fuzzy rule-base and infection mode and effect analysis (IMEA). The objective is to assess and identify infection modes and estimate priority for safety attention on infected vectors on the generic bulk cargo carrier.

Fig. 1.3 Structure of the Thesis



1.8.4 Chapter Four: A subjective Evaluation of Ballast Water Decision Alternatives Using AHP and ER Approaches

Chapter Four is another core technical chapter that discusses another proposed model that is capable of analysing ballast water assessment criteria. The model utilises subjective knowledge and judgement of multiple decision analysts as well as powerful multi-criteria decision analysis models (AHP and ER) in the assessment process. The objective is to identify the best option for implementation by end-users.

1.8.5 Chapter Five: Application of FMCDM Models to Group Decision-Making Analysis of On-Board Treatment Technologies

This technical chapter is closely connected with Chapter Four. The weight values obtained in Chapter Four are utilised in Chapter Five to analyse of the decision-making alternatives. The decision-making methodologies, AHP and TOPSIS have been applied in this model to evaluate decision alternatives for the treatment systems.

1.8.6 Chapter Six: Discussions

The research studies are verified and integrated in this chapter. The limitations of the entire research as well as the areas for further research either individually or collaboratively are also identified in this chapter.

1.8.7 Chapter Seven: Conclusion

Chapter Seven presents answers to the research problem and questions. The final conclusion and recommendations of the thesis are also drawn in Chapter Seven.

1.8.8 References

The references that are related to the research are presented in this section.

1.8.9 Appendices

Supplementary data connected to the various chapters are provided in this section.

Chapter Two

Literature Review

2.1 Introduction

This chapter is a review of literature on major subjects that have contributed to understanding the theme of this research. The chapter starts by reviewing the literature on ballast water operations (its function on the ship) and how ballast water has been identified as a major vector for the translocation of non-indigenous invasive aquatic species and pathogens from one ocean to the other. Prior to discussing the current IMO ballast water exchange plans and on-board treatment technologies, relevant international (United Nations) legislative interventions will be reviewed in order to establish the legal basis for the development of prototype ballast water treatment technologies. Six key treatment systems will be selected from these technologies and applied as evaluation criteria and decision alternatives in the hazard identification, risk assessment and decision-making models developed in this research.

Powerful multi-criteria decision making (MCDM) methodologies will be incorporated into the developed models based on the safety principles of the formal safety assessment (FSA) process. Consequently, a review of these MCDM models and the FSA will be conducted (Sections 2.5 and 2.6) to identify the *modus operandi* of these methodologies as well as their contributions to the development of the proposed generic ballast water safety management models in this research. FSA has been applied in maritime operations as a rational and systematic process for proactive management of safety. FSA has therefore been proposed in this research to support the decision making process on ballast water safety management. The Chapter ends with a justification of the research study, namely, why it is necessary to develop novel ballast water safety management techniques using fuzzy logic and MCDM models.

2.2 Ballast Water Operations and Non-Indigenous Invasive Species Voyages

The objective of this section is to describe the function of ballast water in a ship and its role as a major vector for the transfer of non-indigenous invasive species (NIS) from donor to recipient ports/regions. The transfer process, zoogeographical regions and the inhibiting factors for species establishment in recipient ports are discussed in this section.

Ballast water was first identified as a vector for the dispersal of aquatic NIS over 90 years ago (Chilton, 1910; Hallegraeff & Bolch, 1992). The scale and potential threats of this ecological and bio-environmental pollution were not fully recognised until the late 1980s through the works of marine biologists like Carlton (Carlton & Scanlon, 1985; Hallegraeff & Bolch, 1992). Ships' hulls and ballast tanks are the major vectors/pathways for the translocation of NIS across zoogeographical regions of the world. Principally, ballast water is used in a ship to increase the depth of submergence of the vessel in the sea water (the draft), change the trim, provide stability and manoeuvrability, and maintain its stress loads within acceptable limits during a voyage (NRC, 1996). Sea-water is pumped on-board into ballast tanks at a port when cargo is unloaded and usually discharged at another port when the ship receives cargo. In the event of unexpected inclement weathers during a voyage, the ship can be reballasted or deballasted to facilitate its stability and manoeuvrability. Ballast tanks capacities are proportionate to their cargo capacity (i.e. deadweight tonnage) although this varies given different ship types and sizes. On the average, the capacity is approximately 25 – 30% of the ship's deadweight (Det Norske Veritas (DNV), 2000). Human activities that include trade liberalisation, globalisation of commerce and a resultant growth/economy of scale of the ship size have contributed immensely to the discharge of more volumes of ballast water in countries/regions that are established suppliers of industrial raw materials and/or manufactured goods.

An estimated 3-5 billion tonnes of ballast water are transported via ships' ballast tanks and hulls every year (GEF-UNDP-IMO, 2009). About 42 million tonnes of ballast water are discharged annually into British waters (MAFF, 2001) while an estimated 21 billion gallons are discharged in port waters of the United States of America each year at the rate of over 2 million gallons per hour (USCG, 2001). A ballast-to-load-ratio of a medium size bulk cargo vessel (up to 60,000 dwt) is about 0.35 – 0.4 (Hay *et al.*, 1997). This means that for every 1000 tonnes of cargo to be loaded on board, an estimated 350 – 400 tonnes of ballast water is discharged.

Both the origin and history of myriad of aquatic species is uncertain (Carlton, 2001). However, the works of Ekman (1953) and Briggs (1974) constitute the basis for the classification of the global marine life zones into four zoogeographic regions and provinces (DNV, 1999). The regions (Fig. 2.1 and Table 2.2) include: tropical (comprising the Indo-West Pacific, Eastern Pacific, Western Atlantic and Eastern Atlantic regions), warm temperate (comprising the Carolina, California, Mediterranean-Atlantic and Japan regions in the Northern Hemisphere, and the Western South America, Eastern South America, Southern Africa, Southern Australia and Northern New Zealand regions in the Southern Hemisphere), cold temperate (comprising Eastern Pacific, Western Atlantic Boreal, Eastern Atlantic Boreal, Western Pacific Boreal regions in the Northern Hemisphere, and the Southern South America, Tasmania, Southern New Zealand and Sub-Antarctica regions in the Southern Hemisphere) and, finally, the cold zones (comprising the Arctic and Antarctica).

From the classification on the map (Fig. 2.1) and the description of the marine life zones (Table 2.1), it has been deduced that species are more likely to be established in environments that are similar to those of their origin (Gollasch & Leppakoski, 1999). In other words, the likelihood of organisms surviving and becoming established in a recipient port/region is very high if the donor and recipient ports/regions share the same zoogeographical characteristics. For example, the likelihood of NIS survival and becoming established is very high if the species are taken from a donor port located within the Eastern Atlantic Boreal region (say, the Port of Liverpool in the United Kingdom) and discharged into a location located within the Western Atlantic Boreal region (say, the Hudson Bay in Canada). This is because the United Kingdom and Western coasts of Canada belong to the same zoogeographical region (cold temperate region) and the establishment of the NIS within these regions is the result of a successful migration between the Eastern Atlantic and the Western Atlantic Boreal regions.

A survey conducted on species presence in ships' ballast tank showed that the density of zooplanktons could be within a range of 10,000 specimens per cubic metre of ballast water, while the density of phytoplankton could be within a range of 10 million per cubic metre of ballast water (Gollasch, 1997). A similar survey conducted on sediments from a ship's ballast tank discovered full dinoflagellate cysts at densities of 3 to 1300 cysts per cubic metre of sediments (Macdonald & Davidson, 1997). In Britain, 51 non-native marine species have been identified. These include 15 algae, 5 diatoms, 1 flowering plant and 30 invertebrates (Eno, *et al.*, 1997). These species evolve in the ballast tanks and develop a dispersal mechanism which allows them to exponentially expand their population.

Bio-invasions associated with discharged ballast water have been established. For example, Zebra Mussels *Dreissina polymorpha* and European river ruffe *Gymnocephalus cernuus* are said to have been translocated from Europe into the Great Lakes of North America through ballast water (Macdonald & Davidson, 1997). This has resulted in negative environmental, financial and social consequences. Similarly, different strains of Cholera *Vibrio cholerae* have been introduced to South America, the Gulf of Mexico and other areas through ballast water (IMO, 2006). Toxic dinoflagellates were also translocated from Asia to Australia through ballast water (Macdonald & Davidson, 1997). Ballast water is also described as the vector for the translocation of the Asian seastar *Asteras amuresis*, and the Japanese Oyster *Crassostrea gigas* from the pacific/Japan to New Zealand and Australia. The American jelly fish would have been translocated from America to the Black and Asov Seas through ballast water (Hay, *et al.*, 1997). Other examples of aquatic bio-invasions are contained in Appendix 2.

These introductions (bio-invasions) can be responsible for eutrophication in shore-based waters as well as algal blooms and red tides in mass ocean waters. A resultant effect would be an ecological degradation of the marine environment with huge consequences for the sustainable development of marine protected areas in particular and global marine environments in general.

2.3 Ballast Water Management

The objective of this section is to discuss ballast water management as a process designed by the IMO to minimise and control the transfer of NIS and other aquatic pathogens through ships' ballast water from one zoogeographical region to another. The issues addressed in this section include: legislative interventions; ballast water management plans and requirements; and, standards that should be complied with for ballast water exchange and performance.

Perturbed by the high propensity towards the bio-ecological degradation of marine environments, particularly from sea based activities, the United Nations (UN) at its conference on environment and development (UNCED, Agenda 21(17.30), Rio de Janeiro-Brazil, 1992) urged member-states and the international community to act individually, bilaterally, regionally or multilaterally and within the framework of the IMO and other relevant organisations, to determine whether sub-regional, regional or global authorities, as appropriate, should assess the need for additional measures to address the degradation of the marine environment (IMO, 2001). The conference recognised the need for a new legislative instrument to regulate the discharge of ballast water in order to control and minimise the translocation of non-indigenous aquatic species and pathogens. It should be noted that prior to this conference, there had been in place international legislations or regulations that recognised the need to protect the marine environment from environmental pollution through maritime activities, especially movement of cargo ships. Prominent among them was the International Convention for the Prevention of Pollution from Ships -1973, as modified by the Protocol of 1978 (MARPOL 73/78 Convention). The Convention was adopted to prevent operational pollution from ships that impact on the marine and coastal environments. It also identified "special areas" where maritime activities are regulated due to their vulnerability to pollution arising from maritime activities. Other legislations include: the United Nations Convention on the Law of the Sea (UNCLOS, Article 196) which enjoined states to ensure that they "take all measures to prevent, reduce and control pollution of the marine environment resulting from the use of technologies under their jurisdiction or control, or intentional or accidental introduction of species, alien or new, to a particular part of the marine environment, which may cause significant and harmful changes". The Convention on Biological Diversity (CBD), 1992 and Associated Instruments, specifically, Article 8 (h) states that contracting parties should, "prevent the introduction of, control or eradicate those alien species, which threaten ecosystems, habitats or species". Another relevant legislation is the International Convention for Safety of Life at Sea, 1974 (SOLAS) as amended (including the ISM Code), and the ICES Code of Practice on the Introduction and Transfer of Marine Organisms 1994. The most recent and widely acclaimed robust legislation that addresses the ballast water problem directly is the Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004. The activities of the United Nations Commission for Sustainable Development (CSD) and the IMO Global Ballast Water Management Programme (Globallast) contribute to the global support for the control and minimisation of ballast water environmental pollution.

The IMO is the UN Agency responsible for the standardisation of legislations and regulations related to marine and maritime activities. In the same vein, the Marine Environmental Protection Committee (MEPC) of the IMO is responsible for the development and implementation of maritime environmental pollution conventions. Specific UN legislation that centred on the control and minimisation of unwanted invasive species and pathogens include: Resolutions A. 774(18); A. 868(20) and the Ballast Water Convention 2004.

2.3.1 Resolution A. 774(18)

The first major effort by the IMO to prevent the introduction of non-native aquatic organisms and pathogens through ships' ballast water dates back to the MEPC 31st Session held from July 1 - 5 1991. The session adopted voluntary guidance (International Guidelines) for preventing the introduction of unwanted aquatic organisms and pathogens from ships' ballast water and sediment discharges (Resolution MEPC. 50(31)). The guidelines were subsequently adopted during the IMO General Assembly in 1993 as Resolution A. 774(18). This was the first major direct intervention by the IMO in line with the 1992 UNCED Rio Conference Agenda 21 mandate.

2.3.2 Resolution A. 868(20)

Resolution A. 774 (18) was reviewed and later adopted by the IMO General Assembly on November 27 1997 as Resolution A. 868(20). This Resolution repealed Resolution A. 774(18) and laid a foundation for the rapid development and implementation of a future international Convention. In this regard, the 1997 resolution maintained the directive issued to the Maritime Safety Committee (MSC) in resolution A. 774(18) - to keep the ballast water issue and the application of the guidelines open, with a view to developing them as a basis for a new legislation (either as an Annex to MARPOL 73/78 or an entirely new Convention). An important aspect of Resolution A. 868(20) is the fact that it stipulates guidelines for stake-holders towards the control and management of ships' ballast water. For example, section 7 of Resolution A. 868(20) enjoins port states to provide a specific ballast water management plan for specific ships that carry ballast water. It also requires port states to provide reception and treatment facilities for the discharge of ballast water and sediments from ships. However, the legislation cautions that any port wishing to provide reception facilities must ensure that such facilities are adequate. Records of ballast water loading and exchange – which should be made available to the port state authorities on request, are also to be maintained. Detailed information required from the ShipMaster is contained in Appendix 1. Port state authorities on their part are required to provide adequate information about their ballast water requirements, namely, exchange zones, contingency arrangements in the port, reception facilities and their charges (Section 8). They are to assist ships in undertaking precautionary measures during ballasting, and Masters are to be informed either directly or through their local agents about the ballasting areas/zones.

Section 9.2 describes four ballast water management options seen to be practicably possible. They include:

a. Ballast water exchange (in deep open ocean water and as far as possible from the shore).

b. Non-release or minimal release of ballast water (in the event of not being able to exchange or treat water on board).

c. Discharge to reception facilities on shore (if provided by the port state authority).

d. Utilisation of emergent and new technologies and treatments systems (subject to their viability and suitability as substitute to current the management options, the emerging technologies include: thermal methods, filtration, disinfection including ultra light and others acceptable to port states).

On option (d) above, the IMO unequivocally maintained that any control measure to be developed through research for on-board treatment of ballast water must be safe, environmentally friendly, cost-effective, and workable (Globallast, 2000). In consideration of the safety aspects of ballast water exchange at sea, the Guidelines recognised the need for future considerations and research on the option. Consequently, Section 12 enjoins researchers and ship designers to carry out research on all aspects of safety of the ship while undertaking ballast water exchange at sea. The need for ship-builders, owners and Classification Societies to take into consideration the guidelines in the course of designing new ships or remodelling old ones is stressed in Section 13.

2.3.3 Ballast Water Convention 2004

The Ballast Water Convention 2004, officially referred to as the, "International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004" was adopted as Agenda 8 of the International Conference on Ballast Water Management for Ships on 16th February, 2004 in London, England. The Convention enters into force 12 months after ratification by 30 nations, representing 35% of the world merchant shipping tonnage. The Convention recognised the importance of Resolutions A. 774(18) of 1993 and A. 868(20) of 1997 for addressing the problem of transfer of harmful non-indigenous aquatic organisms and pathogens.

Parties are urged by the legislation in the Convention to undertake to give full and complete effect to the provisions of the Convention and the Annex consistent with international law, while at the same time urged to ensure that ballast water management practices do not cause greater harm than they prevent to their environment, human health, property or resources, or those of other States.

Annex (A) of the Convention comprises 22 Articles that describe the general obligations for the application of the Convention as a voluntary legislation for the control and minimisation of non-indigenous invasive species translocation through ballast water. The role and support of the scientific and technical research and monitoring communities are also spelt out.

Annex (B) of the Convention contains 5 sections and a total of 23 regulations designed to enhance the control and management of ships' ballast water and sediments. Specific provisions of the Convention relevant to this research will be elaborated further in later sections of this Chapter. Relevant to this study are Regulations D-1 and D-2.

2.3.3.1 Ballast Water Management Plan and Requirements

The Ballast Water Convention 2004 requires all ships to carry a Ballast Water Record Book and implement a Ballast Water and Sediments Management Plan. Regulation B-3 contains specific requirements for ships' ballast water management. Any ballast water treatment systems to be installed on board ships must meet the standards stipulated in Regulation D-2 of the Ballast Water Management Convention 2004. A timetable for installation of treatment systems on board ships and their year(s) of construction are contained in regulation B-3 and illustrated in Table 2.2.

1. Ships constructed before 2009 with a ballast water capacity of between 1500 and 5000 cubic metres must conduct ballast water management that at least meets the ballast water exchange standards or the ballast water performance standards until 2014, after which time it shall at least meet the ballast water performance standard.
2. Ships constructed before 2009 with a ballast water capacity of less than 1500 or greater than 5000 cubic metres must conduct ballast water management that at

least meets the ballast water exchange standards or the ballast water performance standards until 2016, after which time it shall at least meet the ballast water performance standard.

3. Ships constructed in or after 2009 with ballast water capacity of less than 5000 cubic metres must conduct ballast water management that at least meets the ballast water performance standard.
4. Ships constructed in or after 2009 but before 2012, with a ballast water capacity of 5000 cubic metres or more shall conduct ballast water management that at least meets the standard described in regulation D-1 or D-2 until 2016 and at least the ballast water performance standard after 2016.

5. Ships constructed in or after 2012, with a ballast water capacity of 5000 cubic metres or more shall conduct ballast water management that at least meets the ballast water performance standard (IMO, 2004).

Other methods of ballast water management may also be accepted as alternatives to the ballast water exchange standard and ballast water performance standard, provided that such methods ensure at least the same level of protection to the environment, human health, property or resources are approved in principle by the Marine Environment Protection Committee (MEPC) of the IMO.

2.3.3.2 Ballast Water Management and Control Requirements for Ships in Certain Areas

Regulation B-4 (Ballast Water Exchange) identifies areas and depths where all ships using ballast water should / should not conduct ballast water exchange:

- Whenever possible, ships should conduct ballast water exchange at least 200 nautical miles from the nearest land and in water at least 200 metres in depth, taking into account the Guidelines developed by IMO.
- In cases where the ship is unable to conduct ballast water exchange as above, this should be as far from the nearest land as possible, and in all cases at least 50 nautical miles from the nearest land and in water at least 200 metres in depth (IMO, 2004).

However, given difficult ballast water exchange circumstances or situations where these requirements cannot be met, Regulation B-4 stipulates that areas may be designated for ships to conduct ballast water exchange. Similarly, all ships are required to dispose of sediments at spaces designated to carry ballast water in accordance with the provisions of the ships' ballast water management plan. Safety considerations should however determine compliance to this regulation.

2.3.3.3 Special Requirements in Regulation C-2

This section makes provision for parties, either individually or jointly with other parties, to impose additional measures on ships to prevent, reduce, or eliminate the transfer of harmful aquatic organisms and pathogens through ships' ballast water and sediments. It also identifies "no-go" areas for ballasting operations and urges parties to consult with adjoining or nearby states that may be affected by such measures. These areas include: areas that contain outbreak; infestation or population of aquatic organisms and pathogens like the toxic algal bloom; areas where harmful organisms are known to be present in the water column; areas where sewage is discharged; ballasting in darkness or at night when bottom-dwelling organisms migrate up to the water column; very shallow water or areas where the ship's propellers may stir up sediments and during seasons when organisms are obviously thriving (IMO, 2004).

As an additional measure, Regulation C-1 of the Convention states that any intention by the parties to establish additional measure(s) should be communicated to the IMO at least 6 months prior to the projected date of implementation, except in emergency or epidemic situations.

2.3.4 Standards for Ballast Water Management

The section identifies standards that should be complied with for ballast water exchange and ballast water performance. It also spells out the approval requirements for ballast water management systems and standards for the development of prototype treatment technologies.

2.3.4.1 Ballast Water Exchange Standard (Regulation D-1)

Ships performing ballast water exchange are expected to do so with an efficiency of 95% volumetric exchange of ballast water. For ships exchanging ballast water by the pumping-through method, pumping through three times the volume of each ballast water tank shall be considered to meet the standard described. Pumping through less than three times the volume may be accepted provided the ship can demonstrate that at least 95 percent volumetric exchange is met (IMO, 2004). A comprehensive review of the different types of ballast water treatment options is contained in Section 2.4.1 of this Chapter.

2.3.4.2 Ballast Water Performance Standard (Regulation D-2)

Regulation D-2 of the Convention stipulates that ships shall discharge less than 10 viable organisms per cubic metre greater than or equal to 50 micrometres in minimum dimension and less than 10 viable organisms per millimetre less than 50 micrometres in minimum dimension and greater than or equal to 10 micrometres in minimum dimension (IMO, 2004). Similarly, and to protect human health, the discharge of indicator microbes shall not exceed the following specified concentrations:

a. Toxicogenic *Vibrio cholerae* (01 and 0139) with less than 1 colony forming unit (cfu) per 100 millilitres or less than 1 cfu per 1 gram (wet weight) zooplankton sample.
b. *Escherichia coli* less than 250 cfu per 100 millilitres.
c. Intestinal Enterococci less than 100 cfu per 100 millilitres.

Any ballast water management treatment systems to be implemented must be approved by the Administration in accordance with the IMO Guidelines (Regulation D-3 - approval requirements for ballast water management systems). The systems shall include those that make use of chemicals or biocides, organisms or biological mechanisms, or those that alter the chemical or physical characteristics of the ballast water (IMO, 2004).

2.4 Research Projects on Ballast Water Management

The objective of this section is to discuss the research projects that have been undertaken on ships' ballast water as a vector for the transfer of non-indigenous species across oceans. The section also discusses current legislations that regulate the use of ballast water by ships, as well as research and development on ballast water management options and treatment technologies.

2.4.1 Ballast Water Management Options

The aim of this section is to review research and development projects on the different ballast water management options whose implementation minimises the quantity of ballast water that needs to be treated. This is imperative because a reduction in the amount of ballast water that needs to be treated and the number of ships that need to treat their ballast water will minimise the risk of non-indigenous species transfer and establishment in recipient ports/regions. The ballast water management options to be reviewed have been identified and recommended for use by the IMO. They include: ballast water exchange at sea; non-release or minimal release of ballast water; use of reception facilities; and the application of prototype treatment technologies (IMO, 2004).

2.4.1.1 Ballast Water Exchange at Sea

The rational behind ballast water exchange at sea (also referred to as mid-ocean exchange) is that coastal or fresh water species and organisms pumped into tanks during the ballasting process at donor ports rarely survive after being discharged at mid-ocean waters. The reasons are associated with these two bio-ecological factors:

a. The oceanic environment is inhospitable for fresh estuarine and inshore coastal planktonic organisms. Also, clear nutrient-exhausted open ocean water is usually characterised by a sparse plankton community. Similarly, oceanic organisms taken in-ballast and later discharged into fresh, estuarine, or onshore coastal waters encounter hostile conditions and are unlikely to survive.

b. It is extremely unlikely that the discharged viable organisms and pathogens would be transported back inshore from the mid-ocean by ocean currents (NRC, 1996).

Despite being identified as the most suitable ballast water treatment option, ballast water exchange at sea is not fool proof or a panacea for stopping the transfer of non-indigenous species across oceans. Firstly, however successful a mid-ocean ballast water exchange process is conducted some residual water, sediments and adhering marine life are still retained in the tanks. Secondly, mid-ocean ballast water exchange provides the animals retained in sediments or water residues with fresh supplies of oxygen and food Research findings in New Zealand confirmed that the rationale for mid-ocean exchanges is, “weakly based on scientific evidence or testing”, since it is expected that if the exchanges take place most coastal species will be removed, thus preventing them from becoming established on foreign shores (Cawthron, 1998). Thirdly, ballast water exchange at sea could be theoretically possible but practically ineffective for coastwise transit (Cangelosi, 1997; Hay, et al., 1997; Cawthron, 1998).

Despite the differences in opinion about mid-ocean ballast water exchange, it is currently upheld by the IMO and shipping community (International Chamber of Shipping/INTERTANKO, 1997) as the most suitable and safest means of minimising the transfer of non-indigenous species and organisms resident in ships’ ballast tanks from one fresh water region to the other.

IMO regulations stipulate that mid-ocean ballast water exchange must be conducted at least 200 nautical miles from the nearest land and in water at least 200 metres in depth (Regulation B-4 (2)) and must achieve an efficiency of at least a 95 % volumetric exchange (Regulation D-1). Where the distance and depth are not met, port states are expected to designate areas, in conjunction with adjacent or other states, a location where ships can conduct ballast exchange. In adverse weather, a ship’s master is not required to comply with this regulation if the exchange would threaten the safety or stability of the ship, its crew, passengers and/or cargo (Regulation B-4(4)).

Against this background, three methods of carrying out ballast water exchange at sea have been evaluated and accepted by the IMO (IMO, 2005). These are: Sequential (empty-refill), flow-through and dilution methods.

2.4.1.1.1 Sequential (Empty-Refill) Method

This is a process by which a segregated ballast tank intended for the carriage of ballast water is first emptied (individually or in sequence) and then refilled with replacement

open ocean water, as illustrated in Fig. 2.2. Approximately 70-90% of the ballast water is exchanged if the method is conducted properly.

This method was tested during a trial on board MV *Iron Whyalla*. From the results obtained it was discovered that a 90% efficiency can be achieved if ballast pumps are operated until tanks are empty, i.e., when pump suctions are lost (Rigby & Hallegraeff, 1994; AQIS, 2001). The system could take between 16 – 42 hours to complete. For example, a VLCC with deadweight of 300,000 tonnes, a ballast water pumping capacity of 8,000 cubic metres per hour, and a ballast water volume of 108,800 cubic metres would require approximately 28 hours to complete a sequential ballast water exchange (DNV, 1999; Pacific Ballast Water Group, 2004). Details of the time frame for sequential exchange for other ship-types are contained in Table 2.3. The difficulty in attaining maximum result however, is attributed to the positioning of the pipes which does not allow the ballast tanks to be completely emptied. Consequently, the process is unlikely to remove the sediments at the bottom of the ballast tanks, which serve as refuge for these organisms. In addition, the diverse shapes and sizes of ballast tanks are responsible for the retention of up to 5% of the original ballast water volume in a tank after "complete" emptying containing up to 25% of the resident viable organisms (AQIS, 1993). The "bending moment" and integrity of the ship might be compromised if the method has to be conducted when the ship is travelling in rough seas. Potential tank over-pressurization and water overflow on the deck are additional safety hazards associated with this ballast water exchange plan (Pacific Ballast Water Group, 2004). This process, notwithstanding, is required by a number of port states in order to provide a minimum of protection (ICS & INTERTANKO, 2000).

2.4.1.1.2 Flow-Through Method

This is the process by which replacement ballast water is pumped from the bottom (3 times the capacity of the ballast tank) through the ballast tank allowing the water to overflow through the air vents or deck hatches. The ballast tank remains full throughout the period of exchange. The goal of this method is to dilute the original in-port or near-shore ballast water with high volumes of deep, open-ocean ballast water, leaving a very small percentage of non-indigenous invasive species remaining in the tank as illustrated in Fig. 2.3. Approximately 95% of ballast water is exchanged during the process and 75% of original plankton and sediments are removed under optimal conditions (Pacific Ballast Water Group, 2004). The flow-through ballast water exchange does not alter the stability, stress and attitude of the ship. In this regard, the process can be accomplished in a wider range of weather conditions. However, while the operation could be applicable in some vessels, the practicality of such an operation in other vessels would require a modification to the tank piping and ballast water arrangements.

The advantage of this method is cost – it is relatively low compared to other treatment systems (about 5.8 – 8.1 cents per metric ton (ibid, 2004)). The disadvantage is that it is not suitable for shorter voyages as the exchange takes time to complete – between 3 to 4 days. For example, a VLCC with deadweight of 300,000 tonnes, a ballast water pumping capacity of 8,000 cubic metres per hour, and a ballast water volume of 108,800 cubic metres would require approximately 42 hours to complete a flow-through ballast water exchange (DNV, 1999; Pacific Ballast Water Group, 2004). Details for other ship types and sizes are contained in Table 2.3. Despite this time requirement, the system does not completely remove harmful species and sediments from the ballast tanks (AQIS, 2001).

2.4.1.1.3 Dilution Method

This is a process by which replacement ballast water is filled into the top of the ballast tank through a special deck while simultaneously discharging the old ballast water from the bottom at the same flow rate and maintaining a constant level in the tank throughout the ballast exchange operation. This is a modified version of the flow-through method that requires a three time exchange at a pumping rate of 2,000 tonnes per hour in order to achieve 90% replacement efficiency (AQIS, 2001).

2.4.1.2 Non-Release or Minimal Release of Ballast Water

In circumstances where ballast exchange or any treatment option is not possible, ships are expected to retain their ballast water in tanks or holds. Where this is not possible a ship should only discharge a minimum essential amount of ballast water in accordance with the port state's contingency strategy (Resolution A.868 (20). This management option demands that ships retain their ballast water or engage on minimal discharge at their destination ports. This option is also considered for ships that undertake ballast operations for the purpose of controlling list and trim during cargo operation (e.g. container, RoRo and passenger ships). However, this method would not suite oil tankers and bulk carriers considering the fact that they have to take in ballast water or deballast when discharging cargo or loading, respectively. When used, a plan for internal ballast water control should be developed that will minimise discharge of ballast water in the port (ICS & INTERTANKO, 2000).

2.4.1.3 Discharge to Reception Facilities

Reception facilities are shore based tanks and treatment facilities installed for the purpose of accommodating and treating ballast water from ships. The technology applied in municipal water treatment systems has been adopted for the treatment of ballast water in receptacles. However, for this method to be effective and practicable, it will require:

1. Retrofitting the vessel to allow discharge of ballast water through standardised wharf side connections.
2. Retrofitting of the wharf with piping connections, pumps and force mains to convey ballast water from vessels to onshore storage and treatment facilities.
3. Construction of storage tanks to handle peak discharge flows from multiple vessels that exceed ballast water treatment system flow rates.
4. Construction of ballast water treatment plant(s).
5. Construction of outfalls to discharge treated water and disposal of solids at a landfill site (DNV, 2004).

An Australian and US study on the utilization of reception facilities concluded that the option would be expensive and logistically demanding for the port state, and the fact that many ships deballast large amounts of water before entering ports makes land-based treatment systems an unattractive single option (DNV, 2004).

2.4.1.4 Ballast Water Treatment Technologies

Two recognised ballast water treatment processes have been identified: physical solid-liquid separation and disinfection (Lloyds Register, 2007).

The classification of the treatment systems is contained in Fig. 2.4. The physical solid-liquid separation is classified as a primary treatment process while the disinfection process is classified as a secondary treatment system. These treatment systems evolved essentially from municipal and industrial water treatment applications.

2.4.1.4.1 Physical Solid-Liquid Separation

This process is defined as the physical separation of suspended solid material, including larger suspended micro-organisms from ballast water, either by sedimentation (allowing the solids to settle out by virtue of their own weight), or by surface filtration (removal by straining; i.e. by virtue of the pores in the filtering material being smaller than the size of the particle or organism (Lloyds Register, 2007)).

Solid-liquid separation is conducted either through filtration (using discs or fixed screens) or hydrocyclones (providing enhanced sedimentation by injecting water at high velocity to impart a rotational motion which creates a centrifugal force which increases the velocity of the particle relative to the water). Schematic diagrams of filtration and hydrocyclone treatment systems are illustrated in Figs. 2.5(a) and 2.5(b). In the illustrated systems, clean water flows to the outlet pipe while the isolated sludge is returned to port water through the sludge pipe. Most of these technologies are at various stages of completion and/or final approval. An example of a prototype treatment system developed by Hamann AG is the SEDNA filtration and hydrocyclone treatment systems described in Fig. 2.6(a) and 2.6(b).

Results of the biological testing in the Great Lakes Project and further tests on board the passenger cruise vessel, *MV Princess,* revealed that filtration (using a 40 um filter) as a stand alone treatment system delivered substantial reduction in live zooplankton and some form of phytoplankton in the ballast water of ships. However it did not reduce total culturable bacteria and small sizes of phytoplankton (Cangelosi, 2001). Although the utilization of this process is safe for the ship and crew, it is inadequate in meeting the standards contained in regulation D-2. However, filtration could be used as a primary treatment system for an applicable secondary treatment system (disinfection). Filtration will be applied in this research as an evaluation criterion in the decision analysis.

2.4.1.4.2 Disinfection

Disinfection as a ballast water treatment system is the process that removes and/or inactivates micro-organisms using any of the following methods: chemical inactivation; physicochemical inactivation by irradiation with ultraviolet light; physicochemical disinfection through ultrasound or cavitation (microagitation); and, deoxygenation either by displacement of the dissolved oxygen with an inert gas injection or stripping it by means of a vacuum and thereby asphyxiating the micro-organism (Lloyds Register, 2007). Disinfection is classified under two generic treatment systems: chemical treatment and physical or mechanical treatments. Chemical treatment involves the application of the following technologies: chlorination, electrochlorination or electrolysis, ozonation, biocides, chlorine dioxide and peracetic acid (Fig 2.7). Physical or mechanical treatment system involves the use of ultraviolet (UV) irradiation, UV + Titanium Dioxide (TiO_2), deoxygenation, gas injection, ultrasonic treatment and cavitation. Disinfection can be applied as a stand-alone treatment system or as a secondary treatment following a primary treatment such as the solid-liquid separation using hydrocyclone or surface filtration.

A common physical treatment process adopted for secondary ballast water treatment technology is ultraviolet irradiation. This technology employs amalgam lamps surrounded by a quartz sleeve (Fig. 2.7) capable of providing UV light at different wavelengths and intensities, depending on the particular application. The system relies on good UV transmission through water, hence, requiring clear water and unfouled clean quartz sleeves to be effective (Lloyds Register, 2007). UV does not present any health or safety concerns for the crew or the vessel. However, a UV lamp can release toxic mercury if it breaks and if an organism irradiated with UV rays manages to survive the treatment, the possibility of genetic mutations exists (MARTOB, 2005). It is effective against a wide range of micro-organisms, including viruses and cysts. In most cases it is used in combination with other treatment systems (e.g. filtration) to produce a robust and effective treatment system.

This treatment method was tested on board the *MV Algonorth* (a trial platform for the Great Lakes Demonstration Project (Cangelosi, 1997)). The UV treatment system was also applied as a secondary treatment in the Velox prototype ballast water Management System - developed by Tech Trade A/S in Norway (Pacific Ballast Water Group, 2004). UV irradiation can be used as a stand-alone physical treatment system and as a secondary treatment (in combination with filtration) system. The technology is applied in this research as one of the evaluation criteria to be used in the analysis of ballast water decision options.

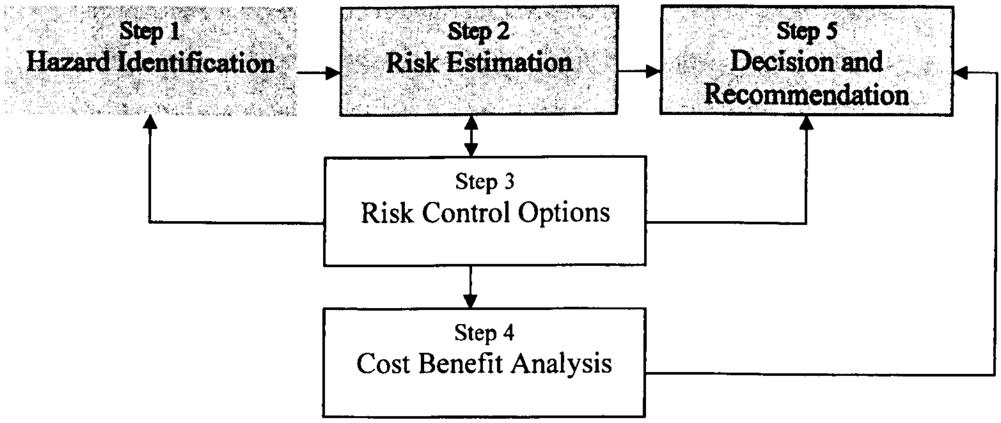
During the period of this research, a total of twenty-four (24) ballast water management treatment systems received both basic and final approval by the IMO in 2009 (IMO, 2009). The breakdown showed that 16 systems (including Peraclean Ocean and Ecochlor) received basic approval while 8 systems (including PureBallast System and Greenship Sedinox) received final IMO approval. The details of the approvals are contained in Appendix 3.

2.5 Formal Safety Assessment and Ballast Water Safety Management

The aim of this section is to discuss the fundamental structure of Formal Safety Assessment (FSA) and how it can be applied in ballast water safety management. FSA has been proposed in this research as a means of aiding and supporting the decision makers in the development of alternative ballast water management tools and to facilitate a more robust approach to ballast water safety management.

FSA is defined by the IMO as a "structured and systematic methodology, aimed at enhancing marine safety, including protection of life, health, the marine environment and property, based on risk and cost benefit assessments which lead to decisions" (IMO, 2002). It is a proactive approach to the management of safety based on the principles of hazard identification, risk estimation, risk control options, cost benefit analysis and decision making. The FSA flow-chart is illustrated in Fig. 2.8. The problem to be assessed is defined at the beginning of the process by decision makers. The boundaries or constraint for the assessment is also set by the decision makers. FSA has been adopted by the IMO to help evaluate the costs and benefits of options and for enhancing marine safety, including protection of life, health, the marine environment and property. The adoption of FSA for shipping represents a fundamental paradigm shift from it being a reactive approach to being an integrated, proactive and soundly based tool for the evaluation of risk. It is has also served as a systematic process for the management of safety. The FSA approach is employed to address safety issues common to a ship type such as bulk carriers, or to a particular hazard such as fire or grounding (Wang, 2002). The approach is capable of identifying commonalities and common factors that influence risk and its reduction. It is used in the marine industry to support decision-makers in developing new regulatory measures. Despite its success and widespread applicability in several research activities, the FSA approach still requires some levels of improvement. These areas include: risk criteria acceptance, cost-benefit estimates, uncertainty and expert judgement, human reliability and information availability (Wang, 2006).

Fig. 2.8 Flow Chart for Formal Safety Assessment



2.5.1 Ballast Water Hazard Identification

The objective of this section is to identify the vector hazards (components) on a generic cargo ship that constitute significant risk with potentially adverse consequences of the translocation and establishment of NIS into recipient ports/regions.

In formal ship safety assessment, hazard is defined as a physical situation with the potential to cause human injury and/or death, and/or damage to property and/or environment (MSA, 1993). Hazard identification is the process of systematically identifying hazards and their associated events that could have the potential to result in considerable negative consequences. The process has traditionally utilised the "brainstorming" techniques by trained and experienced personnel to determine the hazards (Wang, 2000). Techniques often used for hazard identification include: Hazard and Operability Studies (HAZOP), Preliminary Hazard Analysis (PHA), Failure Mode, Effects and Critical Analysis (FMECA), What-If Analysis, Checklist Analysis, Structured What-If Checklist Technique (SWIFT), Boolean Representation Method and Simulation Analysis (Wang *et al.*, 1995; Henley & Kumamoto, 1992; Smith, 1993).

A potential ballast water hazard exists when the following conditions are satisfied:

1. A vessel draws ballast water from a port which is contaminated with any of the species on the target list.
2. The vessel's ballast water is contaminated with any-one of these species.
3. At least one of these species is capable of surviving the vessel journey.
4. The vessel intends to deballast into a port which does not contain any of the species that survived the journey.
5. The vessel intends to deballast in a port with matching similarities in terms of climate and salinity, and/or belonging to the same zoogeographical region (Hayes, 1998).

Three categories of ballast water hazard have been identified (Hayes, 1998). They include: taxonomic hazard (a set of species available to vessels ballasting at a particular time and in a particular port, and capable of surviving the ballasting process and vessel's journey); vector hazard (vessels and their components that harbour viable non-native species); and, time hazard (the period of vessel operation and the distribution of target species at any moment in time during a specific voyage). This research is primarily associated with the vector hazard.

Hazard identification in ballast water risk analysis is conducted in order to identify the main risk contributors and their potential adverse impact on a recipient port/region. Multi-disciplinary group-based hazard identification techniques (such as those mentioned above) are often applied (DNV, 1999; Hayes, 2002a). Quantitative Risk Assessment (QRA) models (Fault-Tree Analysis (FTA) and Failure Mode and Effect Analysis (FMEA)) usually associated with complex engineering systems to identify the chain of events leading to a hazardous occurrence have been applied in hazard identification of complex ecological systems like ballast water introduction (Hayes, 2002a; Hayes, 2002b). The fault-tree hazard identification process focused on target-species and how they infect vectors. The process involves a physical and/or scientific identification of specific taxonomic specie groups that constitute the hazard. On the other hand, the FMEA hazard identification process involves the identification of system components that are likely to cause the undesired event (vector infection) (Hayes, 2002b). Computer aided user-friendly hazard screening techniques such as ArcView (loaded with the geographical information system (GIS) and EMBLA (a risk-based quantitative and qualitative ballast water decision support system that integrates biological and shipping knowledge in a structured risk assessment methodology) have been applied in ballast water hazard screening and assessment (DNV, 2000; Globallast, 2003). The non-availability of relevant data on which to base empirical techniques has, notwithstanding, posed a major difficulty in applying quantitative risk assessment methodologies to ballast water risk assessment (Hayes, 1998). Consequently the application of subjective linguistic variables to qualitative expressions of risk has become a more attractive option capable of being applied to ballast water hazard identification and risk estimation (Simberloff & Alexander, 1994; Gollasch & Leppäkoski, 1999). In recognition of these limitations this research has therefore utilised fuzzy sets theory (FST) and fuzzy rule-base (FRB) to estimate risks associated with the identified vector components.

The proposed process is aimed at facilitating the identification and representation of infection levels of vector components, thus culminating in the generation of fuzzy safety estimates. In this regard, components (identified as species hibernation and growth zones) of a generic bulk cargo vessel (Fig. 2.9) will be evaluated using fuzzy sets and membership functions to represent the risk levels. The components to be evaluated include: aft peak and fore peak tanks; topside and bottomside tanks; the fouling on anchors and chain, vessel hull, sea chest, propeller shaft and internal piping. Also included are: bilge water, propeller shaft cooling water, sanitary system water, fire control water, ballast water and incident water as illustrated in Fig. 2.9.

2.5.2 Ballast Water Risk Estimation

Once the hazards are identified, the next step in the FSA process is the evaluation of the associated risks in order to establish the level of risk. The likelihood and possible consequences of each hazard are estimated either on a qualitative or quantitative basis. Qualitative risk estimation can be conducted using historical data and judgement, or a combination of both. The results are often presented in the form of a risk matrix. The two classical techniques that are often applied in this process are Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) (Hayes, 1998).

In relation to ballast water risk estimation, the objective is to develop a process that can be used in the evaluation of risks associated with ships' ballast water, namely, transfer and discharge of NIS into recipient ports. The estimation of risks involves studying how hazardous events or states develop and interact to cause an accident. Risk in relation to NIS, is defined as the likelihood of undesired/unwanted invasive species establishing and causing biological, economic, safety or social damage in areas where the species did not occur naturally/historically (Haugom *et al.*, 2004).

Several ballast water risk assessment techniques have been developed and can be categorised under two fundamental options: Species-specific ballast water risk assessment and environmental similarity risk assessment (Barry *et al.*, 2008). Species-specific ballast water risk assessment is best suited to situations where the assessment can be restricted to a limited set of harmful species on journeys within bio-regions where ballast water is a small component of natural genetic exchange. The information required for this risk assessment method is largely driven by the assessment end-point. On the other hand, environmental similarity risk assessment is appropriate for journeys that start and end in locations which have very little or no natural genetic exchange, such as journeys between non-contiguous bioregions. This method is predicated on the premise that the likelihood of survival and establishment of any species that is repeatedly transferred between locations can be determined by the degree of physical similarity (e.g. matching climate and/or salinity) between these locations (Hilliard *et al.*, 1997).

The techniques that have been developed and applied in these methods include: EMBLA (developed by DNV as a tool for the identification of unacceptable ballast water risks on voyages and evaluating the need for treatment). EMBLA has also been applied to access the different ballast water management options (DNV, 2000; Haugom, *et al*, 2004; Gollasch & Leppakoski, 2007)); the Australian Decision Support System (a route-based quantitative approach for the identification of high risk voyages and vessels, for prioritising sampling on arriving vessels and evaluating the need for management measures (Hayes & Hewitt, 1998; DNV, 2000)); the IMO Global Ballast Water Programme (GloBallast) model (a route-based semi-quantitative risk assessment technique based on environmental matching between localities, weighted by target species presence in the donor location and inoculation factors (Globallast, 2002)). This technique is currently being used in the GloBallast pilot countries for ballast water risk assessment. This is because the technique is relatively quick and easy to conduct, and it maintains the two dimensions of risk (likelihood and consequence) in the final calculation. However, the technique does not address the prevalent problems of uncertainty and inadequacy of historical data.

The model proposed for the assessment of ballast water exchange options in this research is contained in Chapter Four. Two powerful techniques used in safety analysis of engineering structures and components (fuzzy AHP and Evidential Reasoning (ER)) have been applied in the technique. The Fuzzy AHP has been applied to determine the weights of the assessment criteria, while the ER algorithm will be utilised in the evaluation of the decision alternatives. A computer-based user-friendly software package (Intelligence Decision System (IDS)) is utilised for this purpose.

2.5.3 Ballast Water Risk Control Measures

The third step in the FSA process involves a consideration of alternative ways of managing the risks associated with the identified hazards. This also serves as the start of the risk management process and begins by identifying high-risk areas and events. Effective and practical risk control measures are proposed and selected for high risk areas based on the information gathered during the risk estimation process in Step 2. Risk control measures (either preventive or mitigating) are divided into three categories, namely (Canter, 1997):

a. Those relating to the fundamental type risk reduction (i.e. preventive or mitigating).

b. Those relating to the type of action required and its costs of the action (i.e. engineering/design/procedure/human).

c. Those relating to the confidence that can be placed in the measure (i.e. active or passive, single or redundant, quantitative or qualitative, etc).

An important aspect of this process is that it can reduce the frequency of failures and/or mitigate their possible effects and consequences.

Ballast water risk control measures are aimed at reducing the frequency rate of discharged NIS resident in ships' ballast water. These control measures include: ballast water exchange at sea; discharge of ballast water into reception facilities; application of treatment technologies; and non-release of ballast water. Both ballast water exchange at sea and treatment technologies are further divided into sub-sections. Details are contained in Sections 2.4.1 and 2.4.2 respectively. The RCOs are applied in this research as decision attributes for the evaluation of decision alternatives.

2.5.4 Ballast Water Cost Benefit Assessment

The aim of Cost Benefit Assessment (CBA) in the FSA process is to identify benefits from reduced risks and costs associated with the implementation of each risk control option for comparisons (Pillay & Wang, 2001). The process involves a comparison of the cost of implementing the measure with the benefits of the measure, in terms of the risks to be averted. To this end, the CBA should be able to establish whether the benefits of a measure outweigh its cost. Examples of these costs include: cost of equipment; redesign and construction; documentation; training; inspection; maintenance and drills; auditing; regulations; reduced commercial use (e.g. reduced deck space with commercial use); operational limitations (e.g. reduced loads, speed). Similarly, all benefits are to be the marginal benefits as compared to a base case established in Step 2. Examples of these benefits include: reduced probability of fatalities or number of fatalities; reduced number of injuries and severity of injuries; reduced negative effects on health; reduced probability of severity of pollution and environmental damage; and reduced economic losses (Dasgupta, 2003). Results obtained from the CBA can be applied for the decision-making process (for example, the appropriation of resources for identified RCOs identified in Step 3).

Any increase in risks to people, property and the environment as a direct result of BWM measures should be taken into account while calculating the cost of implementation and reduction of those risks. This is consistent with the "precautionary principle" reflected in Principle 15 of the Rio Declaration. However, to undertake this measure the damage risks from ballast water discharge must be established, together with the costs and benefits of possible risk control options. It is in this regard that efforts are currently being undertaken to place values to environmental damage associated with discharged ballast water in order to evaluate possible protection measures using CBA (Cangelosi, 1998). The measures include: surveys to estimate public preferences; determination of the effects of environmental changes to property prices; and calculation of the amount the public travels to enjoy environmental benefits like fishing and yachting (DNV, 2002). By and large, the stochastic nature of species assemblages and dispersal mechanism would make the determination of the losses arising from the discharge of NIS through ballast water very difficult. Similarly, the lack of in-depth research and historical data on the damages or hazards associated with ballast water pollution would affect the manner in which such risks can be quantified in terms of costs and benefits.

The cost benefit assessment of the ballast water RCOs in this research has not been effectively conducted as a single step within the FSA process. This is because the actual cost values associated with the developed prototype treatment systems could not be established due to unwillingness of manufacturers to disclose information on their products. The financial implications of the environmental damage associated with discharged ballast water were also difficult to obtain. Consequently, subjective qualitative data have been applied in the evaluation of the decision options.

2.5.5 Ballast Water Decision Making Analysis

The objective of decision making analysis in traditional FSA is to make decisions with regard to the selection of the appropriate RCOs and present recommendations for subsequent safety improvement. The information obtained from the steps of HAZID, risk assessment, RCOs and CBA is applied during this process. In the decision-making process, the decision maker ensures that the selected RCOs are fair to all stakeholders. Stake holders in the ballast water management system include: port state administrations, maritime safety agencies, ship management companies, classification societies, shipping and trade related groups.

Qualitative multi-criteria decision making techniques have been applied in the analysis of ballast water decision options for the purpose of identifying the options in their order of priority. The process in this research involves an analysis and rating of all decision options. Results obtained during the hazard estimation and risk assessment processes as well as subjective knowledge and judgement of experts involved in the analysis will be incorporated and utilised at this stage.

2.6 Proposed Ballast Water Risk Management Model

This section reviews the risk analysis and decision making techniques that have been applied in the generic models proposed in this thesis. Against the background that traditional engineering risk and reliability analyses provide a general framework for the identification of uncertainties and quantification of risks, the application of this process to ballast water safety management would facilitate the identification of stochastic variables and quantification of the associated risks in ballast water pollution. Fuzzy logic theory and multi-criteria decision analysis techniques have therefore been utilised in the generic models proposed in this research to conduct hazard identification/assessments of vector components and the analysis of decision making criteria/alternatives respectively. As observed in Section 2.5.2, the techniques applied so far in ballast water risk assessments have been based on assessment end-points that are either species-specific or based on environmental matching similarities. It is however pertinent to note that the likelihood of species establishment and dispersal in a recipient port/region is inarguably a subject of probability. This is because the boundaries of ecosystem, communities and populations are notoriously vague, and also because risk estimation in these ecosystems can be characterised by uncertainty and variability.

2.6.1 Generic Ballast Water Risk Analysis Model

The objective of this section is to discuss the generic ballast water risk analysis model that has been proposed in this Ph.D. thesis. The model utilises fuzzy logic in combination with the infection mode and effect analysis (IMEA) (hereafter, referred to as *Fuzzy Infection Mode and Effect Analysis* (*FUZIMEA*)) technique to identify hazards associated with the vector components of a generic bulk cargo vessel. Fuzzy logic theory has been applied in this model because the risk factors inherent in ballast water pollution are often incomplete and sometimes ill-defined for which traditional quantitative risk assessment approaches do not give adequate answers/solutions. IMEA has been utilised in this model to identify hazards and conduct risk estimations of the vector components. A more detailed discourse of this model is contained in Chapter Three.

2.6.1.1 Infection Mode and Effect Analysis

IMEA is a rigorous and systematic hazard analysis tool named after the engineering safety analysis tool, "failure mode and effect analysis (FMEA)". The technique was originally developed by Hayes and applied to investigate the potential spread of marine pests by small craft operating in local ports in south-eastern Australia (Hayes, 2002). This original approach was conducted through workshops attended by selected experts. The process involves: identifying the components and sub-components of infection vector; identifying all infection modes; description of the environmental conditions associated with the infection mode and scoring its suitability for marine organisms; listing the causes of each infection mode and scoring their likelihood; listing current controls to prevent infection mode and scoring the likelihood of detection; and calculating the risk priority numbers (RPN) (Hayes, 2002).

2.6.1.2 Fuzzy Logic

Fuzzy logic theory was developed in 1965 by Zadeh as an extension of classical Boolean logic from crisp sets to fuzzy sets and grew to become the first new method of dealing with uncertainty and problems that are too complex or ill-defined to be susceptible of analysis by convectional techniques. Aside from modelling the qualitative aspect of human knowledge and the reasoning process without employing precise quantitative analysis, fuzzy logic does not require an expert to provide a precise point at which a risk factor exists (Liu *et al.*, 2004). Fuzzy logic has been applied in many fields and applications that include: engineering; research and development projects; business management; information and control; economics and marketing; education; health and medicine; safety engineering; risk modelling and management; and decision making analysis (Wang *et al.*, 1995). Various fuzzy logic techniques have been used in uncertainty treatment. They include: fuzzy sets and fuzzy rule-base. Details on these theories are contained in Section 3.2.1.

2.6.1.2.1 Fuzzy Sets Theory

The use of natural language to express perception or judgement is always subjective, uncertain, imprecise or vague (Wang & Chang, 2007). Such uncertainty and imprecision have long been handled with probability and statistics (Dubois & Prade, 1997). Notable among the methods of representing and reasoning with uncertain knowledge are Bayesian probability theory (Pearl, 1988); Demspster-Shafer theory of evidence (Dempster, 1968, 1969; Shafer, 1976) and fuzzy set theory (Zadeh, 1965; Liu *et al*, 2002). Fuzzy sets theory (FST) was devised by Zadeh to provide an approximate and yet effective means of describing the behaviour of situations which are too complex to allow mathematical analysis. It employs human analysis and linguistic variables to represent risks and model uncertainty inherent in natural language (Zadeh, 1965). It is therefore complimentary to traditional safety analysis methodologies and can be an effective tool in dealing with ill-defined and imprecise information, especially linguistic information (Duckstein, 1994).

2.6.1.2.2 Fuzzy Membership Functions

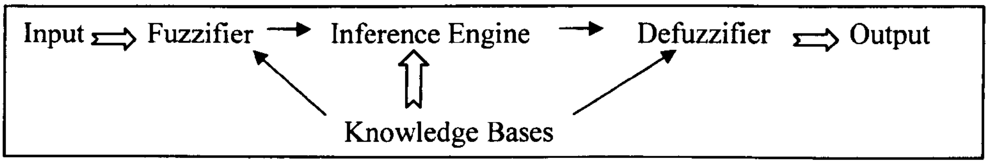
Fuzzy membership functions and linguistic terms are extensions of numerical variables which can represent the condition of an attribute at a given interval by taking fuzzy sets as their values (Wang, 1997). They are generated by utilising the linguistic categories identified in the knowledge acquisition stage and consist of a set of overlapping curves used to define the fuzzy input subset from an input variable. Examples of fuzzy membership functions are described in Section 3.2.1.

2.6.1.2.3 Fuzzy Logic System

Fuzzy logic systems or fuzzy inference systems are knowledge-based or rule-based systems that are constructed from human knowledge in the form of fuzzy *IF-THEN* rules, and describe the risk to the system for each combination of the input variables (Wang, 1997; Liu *et al.*, 2003). The system allows for the mapping of a number of fuzzy inputs into a number of fuzzy outputs. The inputs and outputs are represented by means of fuzzy variables capable of containing language terms and fuzzy hedges. The operation of the fuzzy inference system can be described as follows:

The system's input goes through a fuzzifier to the inference engine. The inference engine works with attribute values (with membership values attached). The engine provides a fuzzy output which may have to be defuzzified to produce a single "crisp" value. This is illustrated in Fig. 2.10.

Fig. 2.10 Fuzzy Inference Engine (Source: Liu, et al., 2003)



2.6.1.2.4 Fuzzy Rule-Base Method

Fuzzy rule-based method does not require a utility function to define the probability of occurrence, severity and detectability considered for the analysis (Pilay & Wang, 2003). However, each of the failure modes is assigned a linguistic term representing the three linguistic variables (probability of occurrence, severity and detectability). In order to generate a fuzzy rule-base for the proposed *FUZIMEA* model, the selected experts are asked to group the various combinations of linguistic terms describing the three factors considered into a category reflecting the *priority for attention.* The latter represents a risk ranking of all the failure modes identified for the vector components.

A fuzzy *IF-THEN* rule is an *IF-THEN* statement in which some words are characterised by continuous membership functions (Pillay & Wang, 2003). The first part of an *IF-THEN* rule is the input variables (including the elements of the probability of occurrence, severity and detectability). The second part is the consequence describing the risk level based on an established weight value and the linguistic priority term attached thereto by the experts. The following is an example of a fuzzy *IF-THEN* rule:

IF the probability of infection occurrence is *low*, the severity of the infection is *marginal*, *AND* the detectability of infection is *high, THEN* the priority for attention would be *low*.

2.6.1.2.5 Fuzzy Rule-Base with Belief Degree

Fuzzy rule-base with belief degree (or degree of belief (DoB)) is used when the experts involved in the assessment are unable to establish a strong correlation between the premise and the conclusion. In other words, the evidence available is not strong enough or the experts are not able to acquire a 100% certainty in the hypothesis, but only possess a certain degree of belief or credibility (Liu, *et al*, 2005). A fuzzy *IF-THEN* rule with belief degree can be described as follows:

IF probability of infection occurrence *low*, severity of the infection is *marginal*, *AND* the detectability of infection is *high*, *THEN* the priority for attention would be low (*0.7*) and fairly low (*0.3*).

The linguistic terms and belief degrees, *low* (*0.7*) and *fairly low (0.3)* are a belief distribution representing the priority for attention. This means that the experts are 70%

sure that the level of attention is low, and 30% sure that the level for attention is fairly low. The rule-base and belief degree will be used in the *FUZIMEA* to ascertain the priority for attention to the potential infection modes of vector components identified in the case study.

2.6.2 Generic Ballast Water Decision Analysis Model

This section describes the model that has been proposed for the evaluation of ballast water decision attributes. Since the reality of identifying the best ballast water exchange option and an appropriate ballast water treatment technology is constrained by the presence of uncertainty and inadequacy of data, there is need for the development of novel risk management and decision-making methodologies to address this problem. It is against this background that three powerful multi-criteria decision analysis (MCDA) techniques (traditionally applied in safety analysis of engineering systems) have been utilised in the development of two generic decision-making models in this research. These are: the evidential reasoning (ER) approach, the analytic hierarchy process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The reasons for their utilisation are two-fold. Firstly, the ballast water problem under investigation involves multiple criteria and large numbers of attributes and alternatives. Secondly, decision analysis of ballast water management problems can be limited due to uncertainties and inadequacy of historical data. Thus, by applying these powerful risk management techniques, it is expected that the problems often associated with ballast water risk management would be addressed.

Decision analysis can be understood as a systematic procedure adopted for the analysis of complex decision problems. The procedure includes dividing the decision problems into smaller more understandable parts, analysing the various parts, as well as integrating the parts into a logical manner to produce a meaningful solution. The MCDA methodology applied in this model is suitable for resolving the lack of precision by assigning importance weights to evaluation criteria as well as rating of the decision alternatives. The approach has helped decision-makers to solve complex decision-making problems with multiple criteria and alternatives (Wang & Chang, 2007).

Against the background that fuzzy logic theory can be combined with MCDA and other linear weighting techniques to obtain rather refined selection tools (Bottani & Rizzi, 2006), fuzzy logic theory, ER and AHP have been combined in the first decision analysis model to study the evaluation criteria. The approach has been adopted in this research in order to address the problem of uncertainty and inadequacy of data associated with the ballast water decision analysis problem. In the second model, a combination of AHP and Fuzzy-TOPSIS has been utilised to analyse and rank the different decision options. The details of these models are contained in two core technical Chapters (Four and Five) of this thesis. A brief description of the MCDA techniques applied in these models is briefly discussed in the following subsections:

2.6.2.1 The Evidential Reasoning (ER) Approach

The ER approach was developed in the 1990s to solve multi-attribute decision analysis (MADA) problems characterised by both qualitative and quantitative attributes with various types of uncertainties (Yang & Xu, 2002a). The ER technique has been successfully applied to solve MADA problems in the engineering and management fields. For example, it has been combined with fuzzy sets theory and fuzzy rule-base methods to conduct safety analysis and synthesis (Wang *et al.*, 1995, 1996; Liu *et al.*, 2004, 2005). It has also been applied in motorcycle assessment (Yang & Sen, 1994; Yang, 2001); general cargo ship design (Sen & Yang, 1995); retro-fit ferry design (Yang & Sen, 1997); organisational self-assessment (Yang *et al.*, 2001; Siow *et al.*, 2001) and contractor selection (Sonmez *et al.*, 2001, 2002). Details on this subject are discussed in Sections 4.2.4 and 4.3.6.

2.6.2.2 Analytic Hierarchy Process

The AHP is a technique suitable for dealing with complex systems that involve making a choice from several alternatives and providing a comparison of the considered options. It is capable of taking large quantities of decision making criteria of quantitative and qualitative nature into consideration and at the same time facilitating the construction of a flexible hierarchy to address a decision making problem (Cheng, 2002). AHP has been extensively used for modelling unstructured problems in different fields such as politics, economics, social and natural sciences (Berrittella *et al.*, 2007). For example, AHP has been applied to support decision-making in business functions such as accounting (Apostolou & Hassell, 1993), marketing (Dyer & Forman, 1991), production and logistics (Min, 1992). The method is based on the subdivision of a problem into a hierarchical form, thus, helping the analysts to organize the critical aspects of the problem into a hierarchical structure similar to a family tree (Satty, 1980). Other benefits of AHP include (Cheng, 2002):

1. Facilitating the decomposition of an unstructured problem into a rational decision hierarchy (similar to a decision tree).
2. Eliciting more information from the experts or decision makers by employing the pairwise comparison of individual groups of elements.
3. Assigning weights to the evaluation criteria.
4. Using the consistency measure to validate the consistency of the rating from the experts and decision makers.

A pairwise comparison matrix is developed to demonstrate the relative importance of one criterion over another. The scale developed for the pairwise comparisons enables the analysts incorporate experience and knowledge intuitively (Satty, 1980). By using the pairwise comparisons, the more important criterion is selected with a verbal judgement expressing the level of importance based on an agreed numerical rating between 1 (lowest) and 9 (highest) (Satty, 1980).

The numerical rating and comparative scale used in this paper is illustrated in Table 2.4. Using the comparative scale, a verbal judgement in a pairwise comparison can be represented with a numerical value to show the degree to which one criterion is more important than the other.

Table 2.4 Comparison Scale used for Numerical Rating (Satty, 1980)

Verbal Judgement	Numerical Rating
Extremely More Important	9
	8
Very Strongly More Important	7
	6
Strongly More Important	5
	4
Moderately More Important	3
	2
Equally Important	1

AHP is conducted in six major stages. The first stage involves a definition of the unstructured problem. The decision analysts must ensure that they have a clear understanding of the problem under investigation. The second stage is the decomposition of the problem into a systematic hierarchical structure. This process involves building a hierarchy (graphical representation of the problem in terms of the overall goal, criteria and decision alternatives). It is therefore important that the experts involved in the process clearly define the problems and specify their judgements about the relative importance of each criterion in terms of its contribution to the identification of the best and most appropriate ballast water treatment systems. The formation of the hierarchy is based on two assumptions: (a) each element of a level in the hierarchy would be related to the elements at the adjacent levels; (b) there is no hypothesized relationship between the elements of different groups at the same level (Cheng & Li, 2001). The third stage is the identification of a preference or priority for each decision alternative in terms of how it contributes to the upper level event. The process involves the employment of the pairwise comparison method to each group in the hierarchy to form a matrix and comparing each of the paired elements in the matrices. During this process, the analysts are expected to specify how their judgements on a lower level criterion contribute to the formulation of the upper level criteria or top level event. The fourth stage is the calculation of the consistency of the pairwise judgements. This involves carrying out a consistency measurement to screen out the inconsistency of responses. The fifth stage is the estimation of the relative weights of the components of each level in the hierarchy. Weighting methods are commonly used to objectify subjective multi-criteria decision making problems in such a way that qualitative comparisons are quantified and ranked (Zahedi, 1986; Su *et al.*, 2006). The attribute weights of evaluation criteria in MADA problems have also been determined using AHP (Sen & Yang, 1998). The final stage is the utilization of the obtained relative weights in the analysis or evaluation of the various decision options (Cheng & Li, 2002; Satty, 1980; 1994). AHP has been applied in this model to determine the weights of the evaluation criteria.

2.6.2.3 TOPSIS

TOPSIS is a linear weighting technique which was first proposed in its crisp version by Chen and Hwang with reference to Hwang and Yoon's work (Bottani & Rizzi, 2006). The technique was developed based on the concept that the chosen alternative should have the shortest distance from the positive ideal reference point (PIRP) and the farthest distance from the negative ideal reference point (NIRP) (Hwang & Yoon, 1981). Assume that each attribute in the decision matrix takes either a monotonically increasing or monotonically decreasing utility; it will be easier to locate the positive ideal solution, which is a combination of all the best attribute values attainable, while the negative ideal solution is a combination of all the worse attribute values attainable (Yoon & Hwang, 1995). TOPSIS has been proved to be one of the best methods in addressing rank reversal issue, that is, the change in the ranking of alternatives when a non-optimal alternative is introduced (Bottani & Rizzi, 2006). Moreover it has been proved to be insensitive to the number of alternatives and has its worst performance only in case of very limited number of criteria. TOPSIS has been applied in varied and robust fields such as: evaluation and selection of initial training aircraft (Wang & Chang, 2007); outsourcing of third party logistics service providers (Bottani & Rizzi, 2006); materials selection (Jee & Kan, 2000); evaluation of competitive companies (Deng *et al.*, 2000) and the assessment of service quality in the airline industry (Tsaur *et al.*, 2002).

2.7 Conclusion

The origin and history of many aquatic species remains uncertain. The identification and control of marine micro-organisms (including invasive species in recipient ports/regions) that constitute bio-environmental hazards to the maritime environment continue to be a subject of continuous research by scientists and stake-holders. Until this challenge is met the quest of scientific and technological solutions would continue. Notwithstanding the slow progress the IMO has undertaken articulated ballast water management legislative interventions. For example, the BWM Convention 2004 represents a major effort at international (UN) level to address the problem. These regulations are purely voluntary guideline with no punitive measures imposed on defaulters. However, concerted efforts have been made by different member states to introduce national and/or regional legislations, and, in some cases with severe penalties. A review of national ballast water management legislations has been deliberately avoided as it will constitute the subject of future research. Although some ballast water treatment systems have been approved for use by the IMO, it has to be observed that the different stages of review of these systems and their final approval should be devoid of excessive bureaucracy to facilitate faster availability of the products for end-users.

Both quantitative and qualitative techniques have been applied in previous ballast water risk assessment methodologies. However, these methodologies are limited as they are unable to address the problem of uncertainty and inadequacy of data inherent in the problem under investigation.

Some limitations have been associated with the models developed in this research. The principal constraint was the lack of data from the industry. Financial estimates and cost of producing most of the treatment systems utilised in this research were either inadequate for any quantitative analysis (e.g. cost benefit analysis) or deliberately not disclosed by manufacturers of prototype ballast water treatment technologies. The developed models are therefore subject to future modification given the availability of data.

Chapter Three

Application of Fuzzy-IMEA to Ballast Water Hazard Identification

3.1 Introduction

Non-indigenous invasive species (NIS) are usually uploaded into ballast tanks during ballast water intake. While in the ballast tanks the NIS evolve and increase exponentially during which time they develop dispersal mechanisms that enable them to populate any recipient marine environment. Once discharged, the NIS become established in the host (recipient) environment with high potential to cause a myriad of environmental problems ranging from parasitizing on important native species to an outright predation on important native species. In some cases the NIS alter the trophic level structure of the recipient's ecosystem. The established species also compete for food and space, and degrade habitats, food webs, water quality as well as transport. The NIS are also associated with spreading diseases and parasites thereby posing great threats to human health (IMO, 2004).

Concerted efforts have been undertaken at both local and international levels to manage this problem. The United Nations through the International Maritime Organization IMO) has promulgated the international Convention for the control and management of ships' ballast water and sediments (IMO, 2004). On the basis of this Convention, governments at national and regional levels have introduced legislations and regulatory regimes to address the problem. Section D of the Convention deals with standards for ballast water management. However, exemptions are granted by the Convention based on guidelines on risk assessment developed by the IMO (Regulation A-4 (4). In this regard, several ballast water risk assessment methodologies have been developed for the management of risks associated with the application of the different ballast water management plans and treatment systems (Barry et al., 2008). However, it has to be observed that a probabilistic assessment of bio-environmental variables is often constrained due to the inadequacy of historical data on species assemblages and dispersal mechanism. Another important factor is the fact that risk estimation in ecosystems is often associated with uncertainty and variability (Jooste, 2001).

In this chapter, a subjective hazard identification technique, "Fuzzy-Infection Mode and Effect Analysis (*FUZIMEA*)" has been developed capable of dealing with the problem of uncertainties and inadequacy of historical data on ballast water risk factors as well as identifying hazards associated with vector components. Previous hazard identification processes in ballast water risk analysis have been conducted for the purpose of identifying basic risk contributors and their potential adverse impact on recipient port/region. The methodologies utilised were species-specific and heavily dependant on quantitative data (as can be found in Chapters 4 and 5 of this research). Infection mode and effect analysis (IMEA) has been utilised in this model to identify hazards and conduct hazard screening of vector components. This study has however taken an alternative approach by applying FST and FRB for ballast water risk analysis and hazard estimation. This is because the risk factors inherent in ballast water pollution are often incomplete and sometimes ill-defined for which traditional quantitative risk assessment approaches do not give adequate answers/solutions.

Section 3.2 of this chapter discusses the possibilistic theories and hazard identification techniques that have been applied in the developed model. The methodologies include fuzzy logic, failure mode and effect analysis (FMEA) and infection mode and effect analysis (IMEA). The Section also discusses the ballast water invasion cycle and the methodologies that have been applied in various ballast water hazard analysis studies. Section 3.3 describes the flowchart and methodology of the proposed model. It introduces the fuzzy membership functions and fuzzy rule-base to be applied in the model. Vector components and potential infection modes of the generic bulk cargo vessel applied in the test scenario are identified in this Section. The hazard estimation and defuzzification processes are also discussed in this Section. In Section 3.4 the developed model is applied in a test scenario.

3.2 Background to the Proposed Methodology

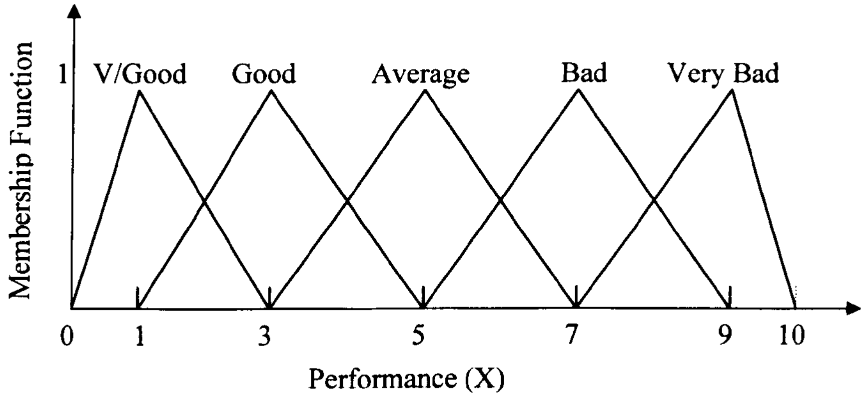
This section identifies and discusses fundamental artificial intelligence (AI) theories and hazard identification methodologies that constitute the framework for the development of the proposed model. The degree of uncertainty and inadequacy of historical data on species assemblages and dispersal mechanism as well as the impact of species introduction, severity of infection and infection detectability in recipient regions and port states necessitated the search for novel hazard identification techniques to address this marine environmental problem. Another intricate issue is the difficulty in understanding the interactions between species and species as well as between species and their physical environment. Consequently, fuzzy logic and IMEA have been proposed in the model to address this problem.

Techniques relevant to the development of this model will be briefly described in this section. It should however be stated here that these techniques have been discussed in Chapter 2. However, a brief description will be made in this section as a prelude to the model. Fuzzy Logic (Section 3.2.1) has been applied in this model to deal with the uncertainty and inadequacy of data. The traditional hazard identification technique, FMEA is discussed in Section 3.2.2. This technique was modified to generate an ecologically-based hazard identification technique IMEA (Section 3.2.3). The NIS invasion process is discussed in Section 3.2.4. The next section (3.2.5) reviews hazard analysis methodologies that have been developed and applied in major ballast water risk assessment methodologies. Ecological risk assessment is discussed in Section 3.2.6. This is necessary in order to understand the context in which *FUZIMEA* as a hazard identification model is applied.

3.2.1 Fuzzy Logic and Fuzzy Sets Theory

Fuzzy logic (FL) and fuzzy sets theory (FST) provide a systematic way of interpreting linguistic variables in a natural decision-making procedure (Zadeh, 1978). The goal is to establish linguistic variables which are used to develop fuzzy membership functions for representing risks. Fuzzy sets can be represented by membership functions in various shapes.

Fig. 3.1 Membership Function of Linguistic Variables for Measuring the Importance Weights and Performance of Evaluation Criteria



A membership function is a curve that defines how each point in the input space is mapped to a membership value (often indicated on the vertical axis) starting at 0 (no membership) and continuing to 1 (full membership). The shape of a specific fuzzy set depends on the best way to represent the data. The domain of a set is indicated along the horizontal axis as illustrated in Fig 3.1. The use of a numerical scale for the degree of membership provides a convenient way of representing gradation in the degree of the membership. Similarly, the use of linguistic variables (e.g. Very Good, Good, Average, Bad and Very Bad) provides a flexible modelling of imprecise data and information. The significance of fuzzy linguistic variables is that they facilitate a gradual transition between states and therefore are capable of dealing with objective observation and measurement of uncertainties as can be identified in the evaluation of ballast water management options.

Membership functions are represented in different shapes that include: triangular curves, trapezoidal curves, S curves, π curves, bell curves and Gaussian curves (Yen & Langari, 1999). The simplest membership functions are formed using straight lines. Examples of these are the triangular and trapezoidal membership functions (Figs. 3.2a & 3.2b). A triangular fuzzy number is a fuzzy set with three parameters (a_1, a_2, a_3), each representing a quantity of a linguistic value associated with a degree of membership of either 0 or 1. This is illustrated in Fig. 3.2a. A trapezoidal membership function (Fig. 3.2b) is defined by (a_1, a_2, a_4, a_5), where a_1 is the membership function's left intercept with a grade equal to 0; a_2 is the membership function's left intercept with a grade equal to 1; a_4 is the membership function's right intercept with a grade equal to 1; and a_5 is the membership function's right intercept with a grade equal to 0. The straight-line triangular membership function has been applied in this study because of its advantage of simplicity and its common use to describe risks in safety assessment (Wang, 1997).

Fig. 3.2a Triangular Membership Function and Fuzzy Numbers

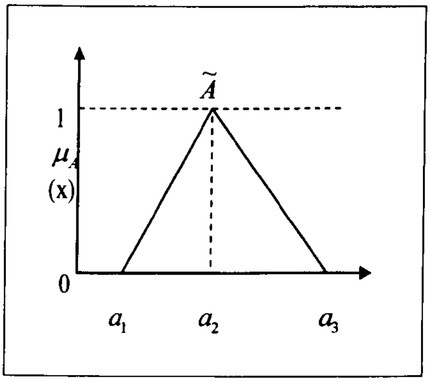
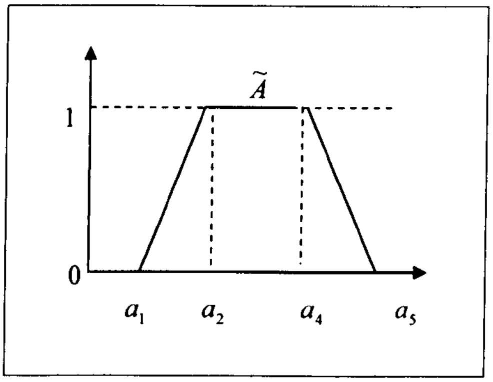


Fig. 3.2b Trapezoidal Membership Function and Fuzzy Numbers



3.2.2 Failure Mode and Effect Analysis (FMEA)

A powerful technique used in the marine industry to perform risk analysis of marine systems is FMEA. The technique examines the operating mode of a system and identifies the failure modes of each constituent component and the effects of failure on the other components and the overall function of the system (Ozog & Bendixen, 1987). The effect of this failure is therefore evaluated and the outcome of the analysis provides information for risk management decisions. A risk ranking is produced aimed at prioritising attention required for each level of failure mode identified. The technique utilises Risk Priority Numbers (RPN) for its ranking systems and adopts linguistic priority terms to rank the elements of probability of occurrence, severity and detectability, using a numeric scale of 1 – 10. Using the following mathematical formula.

$$\mathrm{RPN} = S_{\mathrm{f}} \times S \times S_{\mathrm{d}} \tag{3.1}$$

where S_{f} = Failure consequence probability

S = Failure consequence severity

S_{d} = Failure consequence detectability

This means that the higher the RPN of a failure mode, the higher the risk level and the higher the priority for attention. The process is divided into several steps as follows:

1. Identification and listing of all components.
2. Identification of all failure modes, considering all possible operating modes.
3. Listing of potential effects of each failure mode and their severity.
4. Listing of potential causes of each failure mode and scoring their likelihood.
5. Listing current controls to prevent the failure mode and scoring the likelihood of detection.
6. Calculation of the Risk Priority Number (RPN).

FMEA as the most widely applied safety analysis technique has been criticised and associated with some weaknesses (Ben-Daya & Raouf, 1996), (Gilchrist, 1993) (Deng, 1989). This is possibly due to the fact that:

- The various set of S_{f}, S and S_{d} may produce an identical value of RPN although the risk implication may however be totally different. For example, consider two different events having values of 1, 4, 5 and 2, 5, 2 for (S_{f}, S and S_{d}), respectively. Both events will record an RPN of 20 (RPN1 = 1 × 4 × 5 = 20 and RPN2 = 2 × 5 × 2 = 20). The risk implications of these two events may not necessarily be the same. The implication here would be a misjudgement and subsequent misallocation of funds or a likelihood of a high risk event going unnoticed (Pillay & Wang, 2003).

- The RPN ranking method neglects the relative importance among the three factors (S_f, S and S_d), as they are assumed to have the same importance. In practical applications of the FMEA this risk ranking may not be the same.

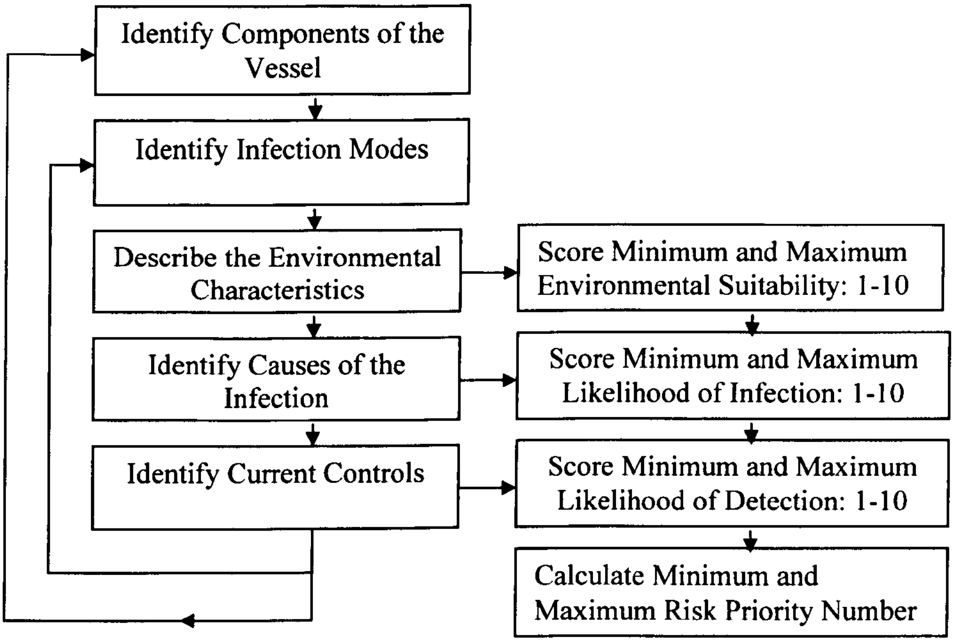
3.2.3 Infection Mode and Effects Analysis (IMEA)

This risk analysis tool was initially developed by Hayes (2002) to describe a vector hazard analysis tool based on FMEA. While being similar to FMEA the focus here is the identification of bio-invasion hazards - how marine species infect vectors (Hayes, 2002). The IMEA process is achieved in six steps as illustrated in Fig. 3.3 and described below.

1. Identifying and listing all components of the vessel that could be infected by marine organisms.
2. Identifying all "infection modes" on the components.
3. Description of environmental conditions associated with this infection mode and scoring its suitability for marine organisms.
4. Listing of causes of each infection mode and scoring their likelihood.
5. Listing of current control options to prevent the infection mode and scoring the likelihood of detection.
6. Calculation of Risk Priority Number (RPN).

Scores between 1 (minimum) and 10 (maximum) are allocated arbitrarily by the analysts to rate environmental suitability, likelihood of infection and likelihood of detection. It can be pointed out here that IMEA would likely suffer a similar setback as the traditional FMEA method. This is due to the fact that the IMEA process as a risk analysis methodology is essentially identical to the FMEA process (Hayes, 2002).

Fig. 3.3 Infection Modes and Effects Analysis (IMEA) (Source: Hayes, 2002)



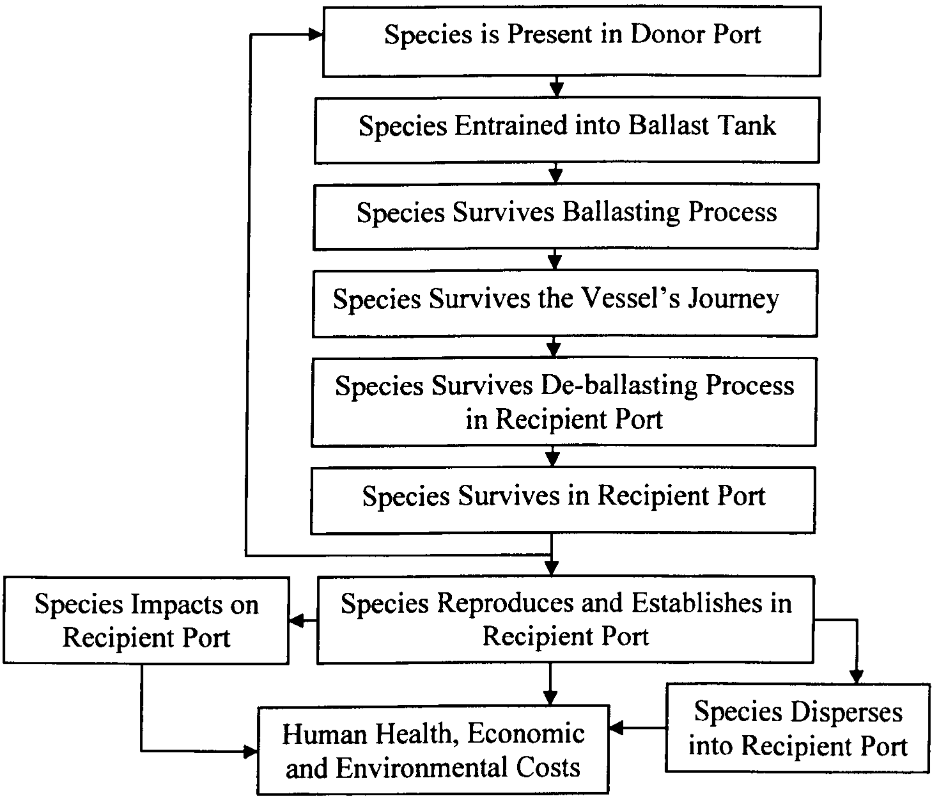
3.2.4 Non-Indigenous Aquatic Species Invasion Process

Every single vessel entering coastal waters has the potential to introduce unwanted NIS (Gollasch & Leppakoski, 1999), and the volume of introduced ballast water is an indication of the probability of future species introduction (Carlton, 1985). Ballast water invasion cycle (Fig. 3.4) is a complex process of stochastic events operating at a vector-species and site-specific level. The successful establishment of NIS in a recipient region is a culmination of a series of steps, each of which must be successfully negotiated by the invading species, and to which a probability of success can be assigned (Hayes, 1997). These steps are:

1. The probability of the organism being present in the body of water from which ballast water is drawn at the time of ballasting.
2. The probability of uptake of organism in the ballasting process.
3. The probability of the organism surviving the ballasting process.

4. The probability of the organism surviving the voyage in the ballast tank.
5. The probability of the organism surviving the de-ballasting process.
6. The probability that at the time of de-ballasting the recipient region provides a suitable habitat for the survivability of the introduced population.

Fig. 3.4 Ballast Water Introduction Cycle (Source: Hayes, 1997)



This chain of events and the fact that ecosystem patterns and processes are not easily or completely predictable are responsible for the non-predictability of arriving species. This uncertainty and associated unpredictability compound the problems of policy makers and managers in terms of management and resource allocation to address this problem.

3.2.5 Ballast Water Hazard Analysis Methodologies

In classical engineering, risk is a combination of probability or frequency of occurrence of a defined hazard and the magnitude of the consequences of its occurrence on lives, property and the environment. In relation to NIS however, risk can be understood as the likelihood of undesired/unwanted invasive species establishing and causing biological, economic, safety-related damage in areas where the species did not occur naturally/ historically (Haugom et al. 2001).

A comprehensive hazard analysis associated with discharged ballast water and sediments was as recent as the 1990s (Hayes, 1997). Prior to this, hazard analysis of invasive species had been undertaken from a robust ecological perspective to determine the impact of invasive species establishment on marine and coastal environments. Efforts in these projects were tailored towards the identification of hazards associated with any impending species invasions, financial estimates of specific introductions, identification of low risk routes, identification of vessels and tanks, and creation of baseline knowledge on the risk associated with NIS and shipping (ICES, 2005). The methodologies adopted in these projects were determined based on assessment end-points. Consequently, the methodologies applied included: environmental matching similarities (Gollasch, 1996; Gollasch & Leppäkoski, 1999; GloBallast: 2002-3; Barry *et al*, 2008), target species (DNV, 2002), and the Australian decision support systems (Hayes & Hewitt, 2000). The principle behind the probability of colonisation based on environmental matching similarities in donor and recipient regions is that species are more likely to become established in environments that are similar to those of their origin (Gollasch, 1996), and/or die or grow poorly when translocated to very dissimilar environments (Yarish *et al*, 1986). Hence, ecological (salinity) comparability of donor and recipient ports makes the risk of species introduction and establishment relatively high (Carlton, 1985).

From the risk matrix in Table 3.1, it can be stated that the probability of colonisation is high if a species is transported from a (donor) fresh water region and discharged into a comparable (recipient) fresh water region. The probability of species survival and colonisation is however medium if the fresh water is discharged into brackish water region. This is because the salinity level in fresh water columns is far less than the level in brackish water columns. For similar reasons, the probability of species survival and colonisation is low if fresh water species are discharged into a salt water region.

Table 3.1 Probability of Colonisation Based on Environmental Matching Salinity in Donor and Recipient Regions (Source: Carlton, 1985)

	Donor Region		
Recipient Region	Fresh Water	Brackish Water	Salt Water
Fresh Water	High	Medium	Low
Brackish Water	Medium	High	High
Salt Water	Low	High	High

The principle behind the probability of colonisation based matching climate in donor and recipient regions is that species are highly likely to become established in environments that are similar to their origin in terms of zoogeographical similarities (Gollasch, 1996). This principle is defined in the risk matrix described in Table 3.2.

Table 3.2 Probability of Colonisation of Invasive Species Based on Matching Climate in Donor and Recipient Regions (Source: Gollasch, 1996)

Recipient Region	Donor Region			
	Arctic & Antarctic	Cold-Temperate	Warm-Temperate	Tropics
Arctic & Antarctic	High	Medium	Low	Low
Cold-Temperate	Medium	High	Medium	Low
Warm-Temperate	Low	Medium	High	Medium
Tropics	Low	Low	Medium	High

The risk matrix shows that the probability of species survival and colonisation is high if the species is transported from the Arctic and Antarctic zones (donor regions) and discharged into a comparable recipient region within its zoo-geographic barrier. The probability of species survival and colonisation is medium if the species is transported from the Arctic and Antarctic region and discharged into the cold temperate region.

The probability of survival and colonisation is also low if the species is transported from the Arctic and Antarctic zones and discharged into the warm-temperate and tropical regions. Possible reasons for this are the fact that alien species cannot live in places that they could be reached by natural dispersal (e.g. tides and ocean currents) or distinguished by physical barriers that include ocean distances and depths, salinity and temperature.

3.2.6 Ecological Risk Assessment

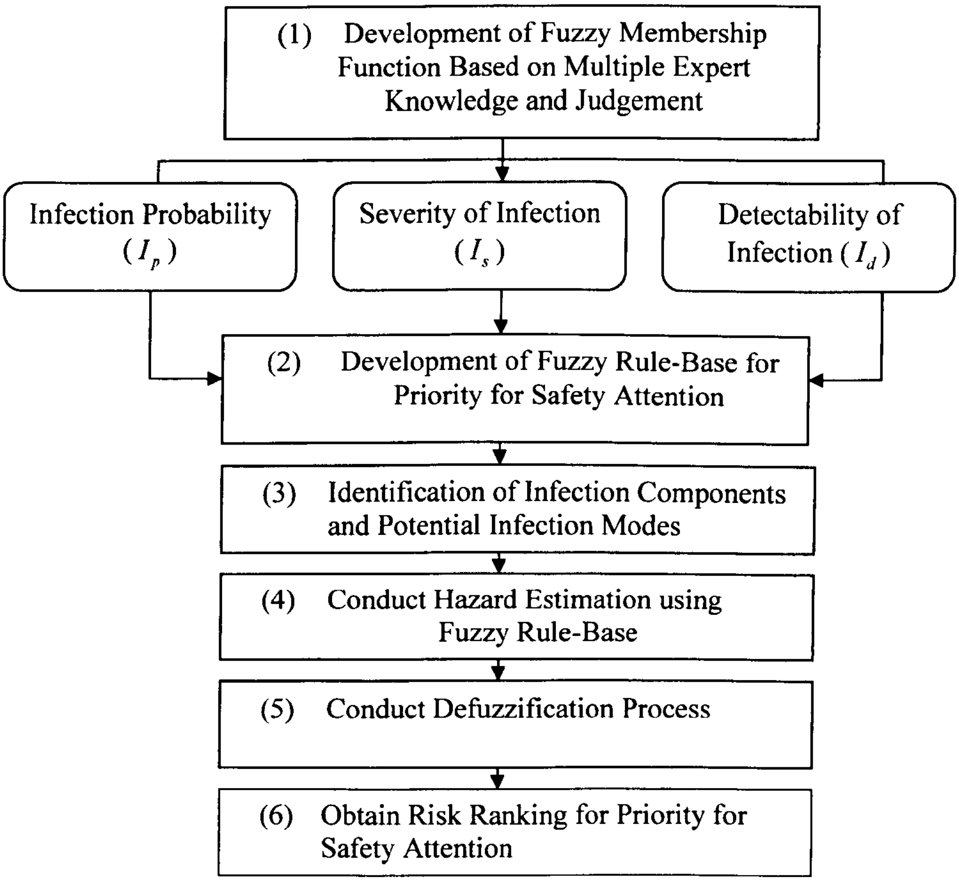
Ecological risk assessment has been defined as a "process that evaluates the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors" (USEPA, 1992). The stressor can be a chemical, an introduced species or any entity that affects the environment (Simberloff, 2005), and the system under stress can be an organism, a community, an eco-system or landscape (Suter, 1992). The interpretation of the likelihood of adverse ecological effect of translocated NIS should be entirely dependant on the endpoint of the assessment (Hayes, 1997). If the endpoint is the establishment of an invasive species in a recipient port or new location, then the risk is expressed in terms of the likelihood of establishment. If the endpoint is environmental damage, the risk must be defined as the likelihood of environmental damage arising from the introduction and establishment of invasive species (Hayes, 1997). The former classification best describes the subject of this research.

A risk assessment of potential hazards associated with NIS pollution requires a hazard identification and estimation of vector components. The criteria for the risk ranking will have to be established. It would also require the determination of the likelihood that species transferred from a donor area will survive if transferred to a recipient area (e.g. from temperate waters of the North Sea to the tropical waters of the Atlantic Ocean), the likelihood of the species surviving the ballasting process as well as surviving in the ballast water/tank throughout the duration of the voyage or between ballast water exchanges. This however is not the essence of this study.

3.3 Methodology of Research Model

The proposed modelling framework commences with an identification of on-board infection components with the necessary procedure required for safety evaluation using FST and FRB. The method does not require the use of a utility function to define the probability of occurrence, severity and detectability, and it avoids the use of traditional RPN (Pillay & Wang, 2003). Rather, it utilises the knowledge and experience of experts and integrates them in a formal way to reflect a subjective method of risk ranking. The framework of this methodology is illustrated in Fig. 3.5.

Fig. 3.5 Flowchart of Fuzzy-IMEA Research Methodology



The first step in the methodology is the development of fuzzy membership functions for the three linguistic priority terms associated with this model. The linguistic terms (infection probability, severity of infection and infection detectability) are developed based on the knowledge and experience of multiple experts. The second step is the development of a fuzzy rule-base that will be utilised during the hazard estimation process of infection modes. The third step is the identification of components and potential infection modes associated with a generic ship type. The fourth step is the estimation of hazards associated with the infection components using the developed fuzzy rule-base. The fifth step is the defuzzification process which transforms the fuzzy conclusion sets (i.e. range of output values from the aggregation process) into a single crisp ranking to express the inherent risk levels of infection. The final step in the methodology is to obtain risk ranking (values) for the priority for safety attention. The risk values are applied in the next stage of the ballast water safety management process, or utilised as a stand-alone result for a predetermined investigation.

3.3.1 Development of Fuzzy Membership Function

Fuzzy membership function is used to define the fuzzy input subset from an input variable (Wang, 1997). The membership functions considered in this study are based on the criteria for classical FMEA elements (probability of occurrence, severity and detectability) and generated using trapezoidal curves. A fuzzy membership function is developed for each of the three linguistic priority terms based on the knowledge and experience of multiple experts. The choice and selection of the experts for the risk analysis is carefully conducted to avoid non-biased and unrealistic membership functions (Kuusela *et al.*, 1998). The trapezoidal membership function is adopted here because it has a smooth transition from one linguistic priority term to the other. It is also used as generalisation of triangular membership functions and facilitates easy defuzzification of each linguistic priority term.

The membership function for each linguistic priority term is evaluated within its limits on an arbitrary scale from 0 to 1 and is obtained as follows.

Assume that there are z experts and each expert is asked to evaluate the proposition, 'x belongs to A' as either true or false. Suppose A is a fuzzy set on x that represents a linguistic priority term associated with a given linguistic variable and $a_i(x)$ is a value of scores within a certain range in x, i.e., $a_i(x) \in X$ (Klir & Yuan, 1995). In this study, X is defined with 10 categories (i.e., 0-10 categories).

In a situation where there are n experts and each of them has equal competence, Equation 3.2 is applied (Klir & Yuan, 1995):

$$A(x) = \frac{\sum_{i=1}^{z} a_i(x)}{z} \qquad (3.2)$$

where $A(x)$ is the final answer (value) after the judgements of z experts are synthesised and $a_i(x)$ is the answer (value) allocated by the i^{th} expert $i \in z$.

Should the experts have different degrees of competency, Equation 3.2 will be modified as:

$$\mathrm{A}(x) = \sum_{i=1}^{z} Com_i a_i(x) \qquad (3.3)$$

where Com_i is the degree of competency of the i^{th} expert, and

$$\sum_{i=1}^{z} Com_i = 1 \qquad (3.4)$$

It is important that the degree of competency for each expert should be determined based on his knowledge and experience in the relevant subjects that are associated with the analysis. It is also important that the degree of competence of each expert has to be agreed upon by all the experts involved in the analysis.

3.3.2 Development of Fuzzy Rule-Base for Priority for Safety Attention

This section discusses the fuzzy rule-base that is generated for hazard estimation of infection components. The rule-base is developed based on the membership functions established by the experts involved in the risk analysis. These experts are carefully selected to ensure a well balanced fuzzy rule base (Pillay & Wang, 2003). The experts involved in this analysis and their degrees of competency are tabulated in Table 3.3.

3.3.2.1 Fuzzy Rule-Base

A fuzzy rule-base describes the risk to the system for each combination of the input variables and is constructed from human knowledge in the form of fuzzy *IF-THEN* rules (Wang, 1996). Fuzzy logic systems are knowledge-based or rule-based systems constructed from human knowledge in the form of fuzzy *IF-THEN* rules (Liu *et al*, 2004). An important contribution of fuzzy logic theory is that it provides a systematic procedure for transforming a knowledge base into a non-linear mapping. The first part of an *IF-THEN* rule is the input variables, including the elements of the probability of occurrence, severity and detectability. The second part is the consequent describing the risk level based on a value of weight established by experts and a linguistic priority term. In this study, the consequent is referred to as the "priority for attention" and is described using five linguistic priority terms as follows: low, fairly low, moderate, fairly high and high.

A fuzzy *IF-THEN* rule is an *IF-THEN* statement in which some words are characterised by continuous membership functions (Pillay & Wang, 2003). For example, the following is a fuzzy *IF-THEN* rule:

***IF** the infection probability rate is **low**, the severity of the infection is **moderate**, **AND** the detectability of infection is **high**, **THEN** the priority for attention would be **low**.*

Linguistic variables *low, moderate and high* are characterised by the membership functions. The membership function for the "priority for attention" is determined by applying Equation 3.3. Although the membership function for the "priority for attention" is triangular in shape, it should be noted that the membership functions for the linguistic terms are not symmetrical. This is due to the difference in opinions of individual experts. However, the graph still provides a smooth transition between states.

3.3.2.2 Fuzzy Rule-Base with Belief Degree

Fuzzy rule-base with belief degree is used when the experts involved in the assessment are unable to establish a strong correlation between the premise and the conclusion. In other words, the evidence available is not enough or the experts are not able to acquire a 100% certainty in the hypothesis, but only to a certain degree of belief or credibility (Liu *et al*, 2004).

A fuzzy IF-THEN rule with belief degree is given as follows:

IF infection probability rate is very low, severity of the infection is marginal, AND the detectability of infection is unlikely, THEN the priority for attention would be low ***(0.8)*** *and fairly low* ***(0.2)***.

The linguistic terms and belief degrees, *low* ***(0.8)*** *and fairly low* ***(0.2)*** are belief distributions representing the priority for attention. The experts are 80% sure that the level of attention is *low*, and 20% sure that the level for attention is *fairly low*. The rule-base and belief degree will be used in the *FUZIMEA* to ascertain the priority for attention for the infection modes identified in the case study.

3.3.3 Identification of Vector Components and Potential Infection Modes

Vector components and potential infection modes of the primary infection vector (generic ship) will be identified in the section. The aim is to establish how the components of the ship sustain the survivability and growth of the invasive species, thus, becoming potential infection modes for ballast water pollution. The vector components identified in the generic ship in this study are: aft peak and fore peak tanks; topside and bottom-side tanks; the fouling on anchors and chain, vessel hull, sea chest, propeller shaft and internal piping. These components are graphically illustrated in Fig. 2.9. The potential infection modes of this generic ship include: ballast water, bilge water, incidental water, fire control water, engine cooling water, sanitary system water, propeller shaft water, ship hull, internal piping, ship's sea chest, propeller shaft as well as anchors and chains. These infection modes are capable of exacerbating the survivability of ingested NIS for the period of the ballast journey.

3.3.4 Hazard Estimation using Fuzzy Rule-Base

The generated rule-base will be applied in this section for the hazard estimation of the identified vector components of the generic ship. In order to generate a fuzzy rule-base for the proposed *FUZIMEA* model, the selected experts are asked to group the various combinations of linguistic terms describing the three factors considered into a category reflecting the *priority for attention*. The latter represents a risk ranking of all the failure modes identified for the vector components.

3.3.5 Conduct Defuzzification Process

In order to estimate inherent risk and express how corrective measures are to be prioritised, experts need to create a single assessment (crisp ranking) from the fuzzy conclusion set. Through the defuzzification process single crisp values are created based on the fuzzy conclusion set generated to describe the priority level to be assigned to the scenarios (infection components). Several defuzzification algorithms have been developed (Runkler & Glesner, 1993) of which the weighted mean of maximums (WMoM) is commonly used. This technique averages the points of maximum possibility of each fuzzy conclusion, weighted by the degree of truth at which the membership functions reach their maximum value (Andrews & Moss, 2002). The WMoM formula is.

$$WMoM = \frac{\sum w_i x_i}{\sum w_i} \tag{3.5}$$

where

w_i = degree of truth of the membership function, and
x_i = risk rank at maximum value of the membership function

Suppose the potential cause identified in the screening process has the following probability of infection occurrence, severity and detectability: Low, Moderate and Highly likely, respectively. Referring to the rule-base developed (See Appendix 3), Rule No. 39 will apply, with the priority of attention as, Low, with belief degree 0.4, and Fairly Low, with belief degree 0.6.

3.3.6 Formulation of Risk Ranking for Priority for Attention

In order to rank the safety estimates expressed by fuzzy sets, the fuzzy linguistic variables require to be defuzzified by giving each of them an "appropriate" utility value. Thus, by applying the WMoM defuzzification algorithm the weighted mean can be calculated.

3.4 Test Scenario: Application of *FUZIMEA* to a Generic Bulk Cargo Vessel

This generic model is applied on a generic bulk cargo vessel, and will involve the identification of vector components and determining the risk levels associated with these components. The vector components of the generic vessel have already been identified and discussed in Chapter Two (Section 2.2) and illustrated in Fig. 2.9. The components with the highest risk ranking will be assigned the highest priority for attention (in terms of the three evaluation variables: infection probability, severity, and detectability) and the components with the lowest risk ranking will be assigned the lowest priority for attention.

Table 3.3 Selected Experts and Assigned Degrees of Competence

Expert	Expertise and knowledge	Degree of Competency
1	Marine Biologist	0.3
2	Marine Ecologist	0.3
3	Ship Captain / Engineer	0.15
4	Port Manager/ Harbour Master	0.15
5	Environmental Risk Assessor	0.1

For the purpose of this research five experts were selected to undertake this hazard identification process. The identified experts are not necessarily exhaustive but utilised in this study for evaluation purposes. They include: Marine Biologist; Ecologist; Ship Captain; Harbour Master and Environmental Risk Assessor. Their degrees of competence have been agreed on by the experts themselves and assigned as shown in Table 3.3. Each degree of competency represents the knowledge and experience of these experts in dealing with maritime transport and marine environmental management problems.

3.4.1 Development of Fuzzy Membership Function

Each of *probability of infection (*I_p*), infection severity (*I_s*) and infection detectability (*I_d*)* is described under five linguistic priority terms, as follows: probability of infection: *very low, low, moderate, high and very high*; infection severity: *negligible, marginal, moderate, critical and catastrophic;* infection detectability: *highly unlikely, unlikely, likely, highly likely and definite.*

The interpretation of the linguistic terms describing each scenario has been defined in Tables 3.4 - 3.6.

Table 3.4 Description for Probability of Infection (I_p) and General Interpretation

Linguistic Term for Infection Probability Rate (I_p)	General Interpretation
Very Low	The probability of introduction is remote and highly unlikely
Low	The probability of introduction is marginal
Moderate	There is occasional occurrence of introduction
High	There is high occurrence of introduction
Very High	There is very high and continuous introduction

Table 3.5 Description for Infection Severity (I_s) and General Interpretation

Linguistic Terms for Infection Severity Rate (I_s)	General Interpretation
Negligible	The environment is not suitable for species survival and no risk of infection
Marginal	The environment is suitable for survival of only tolerant species with a slight risk of infection
Moderate	The environment is suitable for the survival of most species and a low risk of infection
Critical	The environment is suitable for the survival and growth of tolerant species and high risk of infection
Catastrophic	The environment is suitable for the survival, growth and reproduction of most species, and very high risk of infection

Table 3.6 Description for Infection Detectability (I_d) and General Interpretation

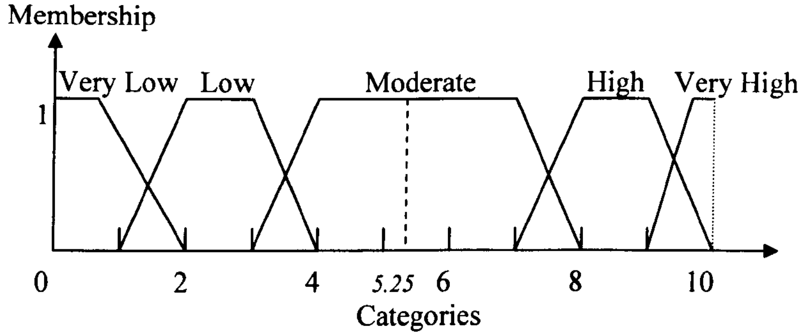
Linguistic Terms for Infection Detectability Rate (I_d)	General Interpretation
Definite	The infection is virtually certain to detect without significant impacts on the recipient port
Highly likely	There is high likelihood to detect infection without significant impacts on the recipient port
Likely	There is an average chance of detecting the infection without significant impacts on the recipient port
Unlikely	There is very slight chance of detecting infection without significant impacts on the recipient port
Highly unlikely	It is almost impossible to detect the infection without significant impacts on the recipient port

The fuzzy membership functions for the hazard screening in this study consist of trapezoidal curves generated using the linguistic categories identified in the knowledge acquisition stage and applied using the fuzzy Delphi method (Bojadziev & Bojadziev, 1995). The membership function for each linguistic priority term can be obtained using Equation 3.3. For example, the full membership for "Moderate" is obtained using Equation 3.3 (provided that there are five experts with the weights of 0.3, 0.3, 0.15, 0.15 and 0.1, associated with their individual answers as to the value that can fully describe the linguistic term "Moderate" when the membership function reaches 1, which are 5.0, 5.0, 5.5, 5.5 and 6.0, respectively) as follows.

$$0.3 \times 5.0 + 0.3 \times 5.0 + 0.15 \times 5.5 + 0.15 \times 5.5 + 0.1 \times 6.0 = 5.25$$

This is graphically illustrated in Fig. 3.6 where at 5.25 (in Categories) “moderate” has a full membership.

Fig. 3.6 Membership Function for Linguistic Terms Describing Infection Occurrence, Severity and Detectability



Consequently, the membership functions and associated fuzzy numbers of the continuous fuzzy sets describing the probability of infection, infection severity and infection detectability have been generated and described in Figs. 3.7 – 3.9.

Fig. 3.7 Membership Function for Linguistic Terms Describing Infection Probability

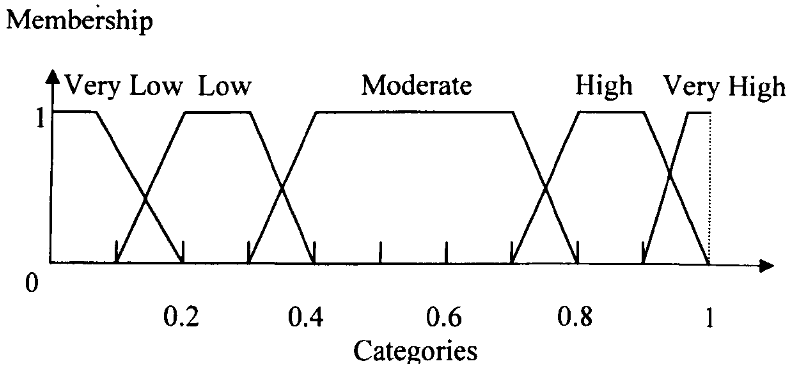


Fig. 3.8 Membership Function for Linguistic Terms Describing Infection Severity

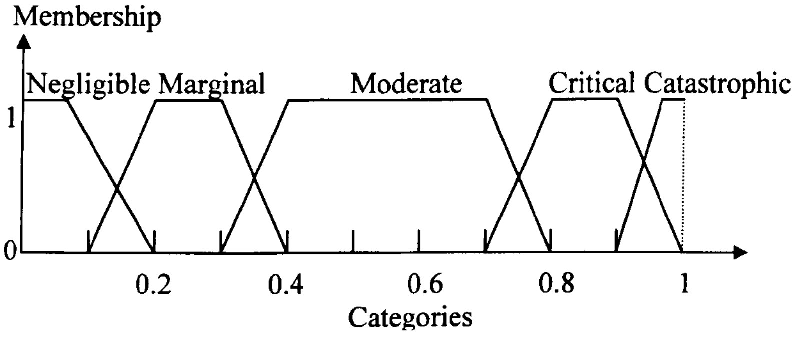
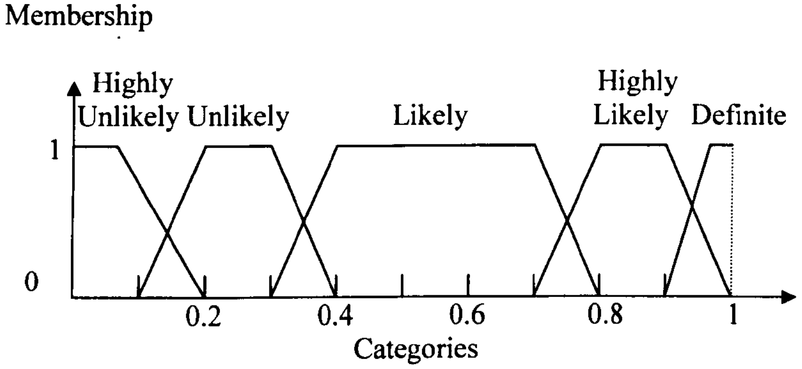


Fig. 3.9 Membership Function for Linguistic Terms Describing Infection Detectability



3.4.2 Development of Fuzzy Rule-Base

In order to generate the fuzzy rule-base the experts were asked to group the various combinations of linguistic terms describing the three evaluation criteria (probability of infection occurrence, severity and detectability) into the five linguistic priority terms that reflect the level of attention priority, namely; low, fairly low, moderate, fairly high and high). Equal weights were assigned to the three criteria. Equations 3.3 and 3.4 were applied to determine the membership functions of the linguistic terms that represent the priority level of attention of each rule as shown in Fig. 3.10. In view of the fact that there are three elements associated with the five linguistic priority terms, a total of 125 (5 × 5 × 5) rules were developed. The generated rule-base is contained in Appendix 3.

3.4.3 Identification of Vector Components and Potential Infection Modes

The vector components to be analysed in this model have been identified in Section 3.3.3. The components and infection modes of the generic ship have been identified in Table 3.7. These infection modes are primarily loaded ballast water and sediment retention in the identified ballast tanks. Ballast water and sediments pumped in during the ballasting process at the donor port provide a safe haven for the NIS to hibernate and develop dispersal mechanism until they are discharged at recipient ports/regions.

Table 3.7 Result of IMEA of Bulk Carrier using Fuzzy Rule-Base

Scenario	Description	Component	Infection Mode	I_p	I_s	I_d	Priority for Attention
1	Holding Tank	Ballast water	Water & sediment retention	Very High	Catastrophic	Highly Likely	Fairly High (0.1) High (0.9)
2	Holding Tank	Bilge water	Water & sediment retention	Low	Marginal	Unlikely	Low (0.7) Fairly Low (0.3)
3	Holding Tank	Incidental water	Water & Sediment retention	Very High	Catastrophic	Highly Likely	Fairly High (0.1) High (0.9)
4	Holding Tank	Fire control water	Water & Sediment retention	Moderate	Moderate	Likely	Fairly Low (0.6) Moderate (0.4)
5	Holding Tank	Engine cooling water	Water & Sediment retention	Moderate	Moderate	Likely	Fairly Low (0.6) Moderate (0.4)
6	Holding Tank	Sanitary system water	Water & Sediment retention	Very Low	Marginal	Unlikely	Low (0.8) Fairly Low (0.2)
7	Holding Tank	Chain locker water & sediment	Water & Sediment retention	Moderate	Moderate	Highly likely	Fairly Low (0.5) Moderate (0.5)
8	Holding Tank	Propeller shaft cooling water	Water & Sediment retention	High	Critical	Highly likely	Moderate (0.4) Fairly High (0.6)
9	Topside Tanks	Ballast water	Water & Sediment retention	Very High	Catastrophic	Highly Likely	Fairly High (0.1) High (0.9)
10	Bottom-side Tanks	Ballast water	Water & Sediment retention	Very High	Catastrophic	Highly Likely	Fairly High (0.1) High (0.9)
11	Fore Peak Tank	Ballast water	Water & Sediment retention	Very High	Catastrophic	Highly Likely	Fairly High (0.1) High (0.9)
12	Aft Peak Tank	Ballast water	Water & Sediment retention	Very High	Catastrophic	Highly Likely	Fairly High (0.1) High (0.9)
13	Fouling	Vessel hull	External fouling	High	Critical	Highly Likely	Moderate (0.5) Fairly High (0.5
14	Fouling	Sea Chest	External fouling	High	Critical	Highly Likely	Moderate (0.5) Fairly High (0.5)
15	Fouling	Internal Piping	Internal fouling	Moderate	Moderate	Likely	Fairly Low (0.6) Moderate (0.4)
16	Fouling	Propeller Shaft	External fouling	High	Critical	Highly Likely	Moderate (0.5) Fairly High (0.5)
17	Fouling	Anchors & Chain	External fouling	High	Critical	Highly Likely	Moderate (0.5) Fairly High (0.5)

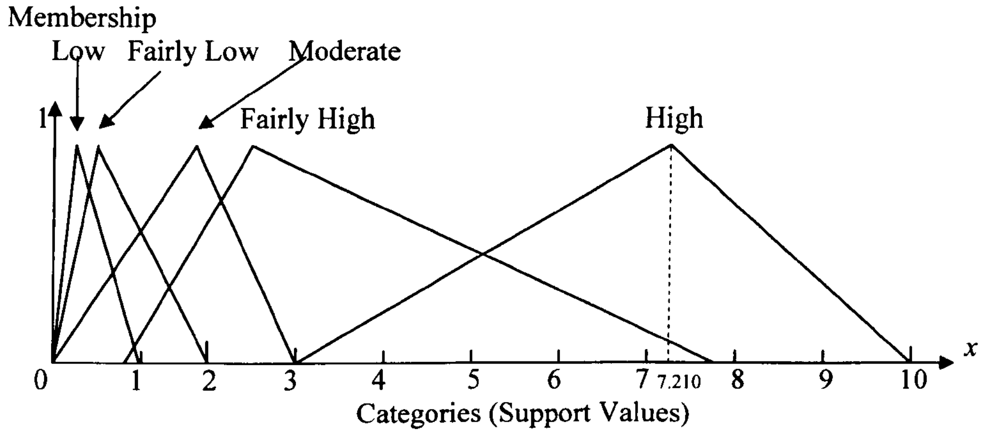
3.4.4 Conduct Hazard Estimation using Fuzzy Rule-Base

The hazard estimation process is conducted by applying the membership functions and fuzzy rule-base developed for the process. As observed in Section 3.3, the linguistic terms describing the three evaluation criteria (probability of infection occurrence, severity of infection and infection detectability) will be grouped into the five linguistic priority terms that reflect the priority level for attention.

The support values for the linguistic terms describing the priority for attention are acquired by taking the weighted average of the support values as assigned by the experts. The values have been calculated on an arbitrary scale between 1 and 10 and represented on the "x" axis when the membership function for a particular linguistic term reaches 1. Fig. 3.10 shows the full membership values for the linguistic terms describing the priority for attention. Such values associated with these linguistic terms have been determined using Equation 3.4 as follows.

Low - 0.045
Fairly Low - 0.571
Moderate - 0.822
Fairly High - 2.121
High - 7.210

Fig. 3.10 Membership Function for Priority for Attention



3.4.5 Conduct Defuzzification Process

As observed previously, the aim of this process is to create a single crisp value/ranking from the fuzzy conclusion set to express the inherent risk of the failure (infection) mode. Consequently, the algorithm was applied for the defuzzification process. The combination of belief degrees (0.1 and 0.9) and the corresponding support values (2.210 and 7.210) representing the linguistic priority terms, *fairly high* and *high* in Fig. 3.8 will be defuzzified to generate a single crisp value for Scenario 3 as follows.

The three variables describing the infection components associated with Scenario 3 (i.e. Holding Tank for Incident Water) in Table 3.3 are described as follows:

Infection probability (I_p) = Very High

Severity of infection (I_s) = Catastrophic, and

Infection detectability (I_d) = Highly Likely

Matching this event and the linguistic terms to the fuzzy rule-base developed, it can be seen that Rule 124 (in Appendix 4) applies as follows.

If *infection probability* is *very high*, and *severity of infection* is *catastrophic*, and *infection detectability* is *highly likely*, then the *priority for attention* will be fairly high,with a belief degree (0.1) and, high, with a belief degree (0.9).

Table 3.8 Defuzzified Values of the Test Scenarios

Scenario	Defuzzified Values	Ranking for Priority for Attention
1	6.701	1
2	0.203	6
3	6.701	1
4	0.672	5
5	0.672	5
6	0.150	7
7	0.697	4
8	1.601	2
9	6.701	1
10	6.701	1
11	6.701	1
12	6.701	1
13	1.472	3
14	1.472	3
15	0.672	5
16	1.472	3
17	1.472	3

Equation 3.5 (Section 3.3.5) is applied in the next step to generate a single defuzzified (crisp) value that represents the *priority for attention* of the scenario. The process involves adding the obtained belief degrees (0.1 and 0.9) of Scenario 3 with the corresponding support values (2.21 and 7.210) representing the linguistic priority terms fairy high and high (Fig. 3.10). Thereafter the sum is divided by the belief degrees of the scenario as follows.

$$\frac{[(0.1)(2.121)+(0.9)(7.210)]}{[(0.1)+(0.9)]}=6.701$$

Following this process, the crisp value representing the *priority for attention* for Scenario 3 is 6.701. The defuzzified values for the other Scenarios in this estimation process were obtained using the same process and presented in Table 3.8.

3.4.6 Obtain Risk Ranking for Priority for Attention

From the obtained defuzzified values in Table 3.8 it can be seen that Scenarios 1, 3, 9, 10, 11 and 12 (Aft Peak, Fore Peak, Topside and Bottomside Tanks) returned the highest risk ranking value (6.701) representing the infection modes that would require the maximum level of priority for attention. Scenario 6 (Holding Tank for sanitary system water) returned the lowest risk ranking value (0.150) representing the infection modes that would require the minimum level of priority for attention. The second highest risk ranking value (1.601) is associated with Scenarios 8 (Holding Tank for propeller shaft cooling water). This is followed by the infection modes in Scenarios 13, 14, 16 and 17 having returned a risk ranking value of 1.472. Scenario 7 returned the fourth highest risk value (0.697) and priority for attention level. Scenarios 4, 5, 7 and 15 returned the fifth highest risk ranking (0.672). Scenario 2 returned the sixth highest ranking (0.203).

3.5 Sensitivity Analysis and Partial Validation of Model

In order to test the robustness and sensitivity of the model to change, a sensitivity analysis is conducted under different criteria weights. The outcome of the analysis will ascertain the suitability of the model in identifying the priority for attention levels of the infection modes in the case study. In this regard, 2 Conditions have been generated for the conduct of this sensitivity analysis. In Condition 1, the linguistic variables for describing the three evaluation variables (infection probability (I_p), infection severity (I_s) and infection detectability (I_d)) for each of the 17 Scenarios will be changed to the next level (in the fuzzy rule-base) leading to a higher priority for attention (PFA). In Condition 2, the linguistic variables for describing the three evaluation variables (infection probability (I_p), infection severity (I_s) and infection detectability (I_d)) for each of the 17 Scenarios will be changed to the next level (in the fuzzy rule-base) leading to a lower PFA. The outcome of this analysis will be compared with the results in Table 3.8 to establish the reasonableness of the model.

Table 3.9 Results of Sensitivity Analysis (by Changing the Linguistic Variables for Describing Infection Probability (I_p), Severity (I_s) and Detectability) (I_d))

		Defuzzified Values	
Scenario	Main Defuzzified Values	Condition 1 (Higher PFA)	Condition 2 (Lower PFA)
1	6.701	7.210	6.192
2	0.203	0.255	0.150
3	6.701	7.210	6.192
4	0.672	0.697	0.646
5	0.672	0.697	0.646
6	0.150	0.255	0.098
7	0.697	0.722	0.671
8	1.601	1.731	1.472
9	6.701	7.210	6.192
10	6.701	7.210	6.192
11	6.701	7.210	6.192
12	6.701	7.210	6.192
13	1.472	1.601	1.342
14	1.472	1.601	1.342
15	0.672	0.697	0.646
16	1.472	1.601	1.342
17	1.472	1.601	1.342

From the obtained results (Table 3.9) it can be seen that the main output values of the three evaluation variables (I_p, I_s and I_d) for each of the 17 Scenarios increased in value when I_p, I_s and I_d were exchanged for the next level (in the fuzzy rule-base) leading to a higher priority for attention (PFA) in Condition 1. For example, in Scenario 1 the main output value of 7.210 was obtained compared to the original value of 6.701. Similarly, the main output values of the three evaluation variables (I_p, I_s and I_d) for each of the 17 Scenarios decreased in value when I_p, I_s and I_d changed for the next level (in the fuzzy rule-base) leading to a lower PFA in Condition 2. For example, in Scenario 6 the main output value of 0.098 was obtained compared to the original value of 0.150. This pattern is to be expected since the analysis maintains a consistent process. The results show that despite the change in values leading to either higher or lower PFA, the Scenarios still maintain their rankings as shown in Table 3.8. In this regard, it can be stated that the model is sensitive to change and therefore reasonable.

3.6 Conclusion

FUZIMEA was proposed in this study as a model that is capable of identifying infection modes and generating risk rankings for the identified infection components using powerful multi-criteria decision making methods. It is therefore capable of being utilized to conduct hazard screening of vector components. The outcome of the hazard identification process is also expected to facilitate the conduct of the next step in the risk management process. A sensitivity analysis was conducted to partially validate the developed model and establish its reasonableness and ability to respond to change. The model is also capable of being modified and applied in related ecological risk management processes characterised by uncertainties.

Economies of recipient ports and coastal states have suffered due to NIS colonisation as large sums of money have to be earmarked for their control and management. Equally threatened are endangered species in marine protected areas (MPAs) around the world. The Ballast Water Management Convention 2004 is a major step at controlling and minimizing the transfer of NIS around the globe. Several risk management methodologies have been developed for the different ballast water plans and treatment technologies currently available. However, these methodologies are of quantitative nature and are either species-specific or based on environmental matching similarity. These methodologies do not address the problems of uncertainty and inadequacy of data often associated with NIS assemblages and dispersal mechanism.

The subjective model (*FUZIMEA*) developed in this chapter is capable of being incorporated into a BWM plan and utilized in port states of developing economies in the absence of a robust management plan. The benefits of the model include the fact that it is generic and capable of being applied in multiple circumstances. In other words, the model is not limited to target species or specific environmental matching similarities.

Chapter Four

A Subjective Evaluation of Ballast Water Decision Alternatives Using Analytic Hierarchy Process and Evidential Reasoning Approaches

4.1. Introduction

The evaluation of maritime environmental issues can be complex and intractable due to inherent trade-offs (in port states or regional blocks) that are predicated by socio-political, ecological, financial and economic factors. These trade-offs inadvertently affect the process of selecting the most appropriate option for the management of ballast water management problems. The inadequacy of data on species assemblages, invasion mechanisms and species establishment in some donor or recipient ports/coastal states also contributes to the decision-making problem. Despite these limitations, the decision analysis and selection process would have to consider stochastically related IMO standards that require any exchange system to be safe, cost effective, operationally practicable, environmentally acceptable and biologically effective.

A generic model for the evaluation of ballast water decision-making alternatives in ballast water management using powerful multi-criteria decision analysis models (Analytic Hierarchical Process (AHP) and Evidential Reasoning (ER)) has been developed in this chapter. AHP and ER have been widely used to solve complex multi-attribute/multi-criteria decision problems of quantitative and qualitative nature under uncertainty (Satty, 1980; Yang, 2001; Yang & Xu, 2002a). The concepts, "multi-attribute" and "multi-criteria" have been used interchangeably in this study to refer to a set of evaluation criteria. The final output (decision options) from the data assessment process is synthesised using an evidential reasoning approach and the IDS Software package in order to establish the best and most appropriate option to be selected. The proposed model takes into consideration the prevalence of multi-criteria (attributes) decision-making problems which have to be evaluated using subjective knowledge and judgement of multiple decision analysts. Thus, by eliminating the complexities associated with rigorous quantitative data assessments (often associated with traditional engineering safety analysis) the model addresses a fundamental problem of uncertainty and inadequacy of data on species assemblages, survivability and establishment in recipient ports/coastal states.

Section 4.2 discusses the multi-criteria decision analysis methodologies that constitute the background to the model. These include fuzzy logic, multi-attribute decision analysis (MADA), analytic hierarchical process (AHP) and the evidential reasoning (ER) approaches. The framework for the proposed model is contained in Section 4.3. The proposed model is demonstrated in a test scenario in Section 4.4. A sensitivity analysis to partially validate the proposed model has been conducted and presented in Section 4.5 of this chapter.

4.2. Background to the Proposed Methodology

This section discusses the MCDM methodologies that constitute the background for the development of the proposed model.

4.2.1 Fuzzy Sets Theory

Fuzzy sets theory was described previously. For detailed information, visit Sections 2.6.1.2.1 and 3.2.1.

4.2.2 Multi-Attribute Decision Analysis (MADA)

Multi-Attribute Decision Analysis (MADA) is widely used in ranking decision alternatives with respect to multiple, usually conflicting attributes. MADA problems are often characterised by both qualitative and quantitative attributes. For instance, the purchase of a car may require an evaluation of attributes such as price, comfort, style and miles per gallon. Similarly, the design evaluation of an engineering product may require the simultaneous consideration of several attributes such as cost, quality, safety, reliability, maintainability and environmental impact. Qualitative attributes are usually assessed using human judgments which are subjective in nature and inevitably associated with uncertainties arising from the human being's inability to provide complete judgments or adequate information about the attributes and their assessments.

A decision problem is said to be complex and difficult where the following conditions apply:

- Multiple criteria exist, which can be both quantitative and qualitative in nature.
- There may be multiple decision makers.
- Uncertainty and risk are involved.
- Decision (input) data may be vague, incomplete or imprecise (Hipel *et al.*, 1993).

In order to achieve an effective and logical evaluation process, MADA problems are broken down into simpler or smaller sub-problems. The process involves the application of a hierarchical framework of attributes to guide the overall evaluation of the multi-attributes in the decision problem. Attributes are evaluated (based on an ER framework) through a distributed assessment using the Degree of Belief (DoB) method along with the associated evaluation grades. In this regard, both subjective judgement with uncertainty and precise data will be modelled under a unified framework.

4.2.3 Analytic Hierarchy Process

AHP has already been defined in Section 2.6.2.2. The process is conducted in six major stages. The first stage involves the definition of an unstructured problem. In this section, decision analysts must ensure that they have a clear understanding of the problem under investigation. The second stage is the decomposition of the problem into a systematic hierarchical structure. This stage in the AHP process involves building a hierarchy (graphical representation of the problem in terms of the overall goal, criteria and decision alternatives). It is therefore important that the experts involved in the decision analysis clearly define the problems and specify their judgements about the relative importance of each criterion in terms of its contribution to the identification of the best and most appropriate ballast water management option. The formation of the hierarchy is based on two assumptions: (a) The expectation that each element of a level in the hierarchy would be related to the elements at the adjacent levels; (b) The fact that there is no hypothesized relationship between the elements of different groups at the same level (Cheng & Li, 2001). The third stage involves the identification of a preference or priority for each decision alternative in terms of how it contributes to the upper level event. The process involves the employment of the pair-wise comparison method to each group in the hierarchy to form a matrix and comparing each of the paired elements in the matrices. During this process, the decision analysts are expected to specify how their judgement on a lower level criterion contributes to the formulation of the top level event. The fourth stage is the calculation of the consistency of the pairwise judgement. This involves carrying out a consistency measurement to screen out the inconsistency of responses. The fifth stage involves estimating the relative weights for the components of each level of the hierarchy. Weighting methods are commonly used to objectify subjective multi-criteria decision making problems in such a way that qualitative comparisons are quantified and ranked (Zahedi, 1986; Shim, 1989; Suh *et al.*, 1994; Huang *et al.*, 2003; Su *et al.*, 2006; Isiklar & Buyukozkan, 2007). The attribute weights of evaluation criteria in MADA problems have also been determined using AHP (Barron & Barrett, 1996; Sen & Yang, 1998). The final stage involves the utilization of the obtained relative weights in the analysis or evaluation of the various decision options (Cheng and Li, 2002; Satty, 1980, 1994). AHP has been applied in the proposed model presented in this chapter to determine the weights of the evaluation criteria.

4.2.4 The Evidential Reasoning (ER) Approach

The ER approach has been used to aggregate attributes of a multi-level structure (Yang & Sen, 1994; Yang & Xu, 2002a). The DoB in ER can be described as the degree of expectation that an alternative will yield an anticipated outcome on a particular criterion. An individual's DoB depends on his knowledge of the subject and his experience. The use of the DoB can be justified by the fact that human decision making involves ambiguity, uncertainty and imprecision. That is, individuals can convey judgements in probabilistic terms with the help of their knowledge and real life experience (Sönmez *et al.*, 2001).

The process involves the application of a hierarchical framework of attributes to guide the overall evaluation of the multi-attributes in the decision problem. The attributes are evaluated (based on an ER framework) through a distributed assessment using the Degree of Belief (DoB) method along with the associated evaluation grades. In this regard, both subjective judgement with uncertainty and precise data will be modelled under a unified framework. The approach is based on the ER algorithm developed on the basis of a multi-attribute evaluation framework and evidence combination rule of the Dempster-Shafer (D-S) theory. The D-S theory of evidence (Dempster, 1968; Shafer, 1976) shows great potential where an ER approach for MADA under uncertainty has been developed on the basis of a distributed assessment framework and the evidence combination rule (Yang & Xu, 2002a).

After all the criteria are transformed to a common utility space, the ER approach is applied to synthesise the transferred criteria and establish the best and most appropriate option to be selected. The IDS software package is a powerful user-friendly Windows-based software and computer interface which incorporates the ER algorithm and facilitates information collection, processing and display. It records assessment information including evidence and comments in organized structures, and provides systematic help at every stage of the assessment including guidelines for grading criteria (Xu & Yang, 2003). The technique has the following advantages (Yang & Xu, 2002a):

1. It is difficult to deal with both quantitative and qualitative criteria under uncertainty but ER provides an alternative way of handling such information systematically and consistently.
2. The uncertainty and risk surrounding the problem can be represented through the concept of "Degree of Belief (DoB)."
3. Both complete and incomplete information can be aggregated and modelled using a belief structure.
4. The ER algorithm is integrated into a software package called "Intelligence Decision System (IDS)." It is a graphically designed decision support tool that allows decision makers to build their own models and input their own data.
5. The IDS software enables users to provide results of evaluation both in tabular and graphical forms which is very useful for future use, especially in industries.

While recognising the fact that evaluation of safety systems are often conducted by multiple experts, it is pertinent to note here that this study does not place emphasis on the number of experts involved in the evaluation or decision making process. Rather it is an evaluation of multiple criteria/attributes. An evaluation of multi-attribute and multi-expert decision making approach could be a subject of a future study.

4.3 The Methodology of Proposed Model

The model framework is illustrated in Fig.4.1 and the methodology is conducted in the following stages:

Stage 1	Identification of decision-making criteria for the selection of a ballast water management option.
Stage 2	The development of a decision-making model of this study.
Stage 3	Establishment of weights of each criterion using AHP.
Stage 4	Converting lower level criteria to upper level criteria using Evidential Reasoning Assessment Transformation Process.
Stage 5	Conducting synthesis process of all decision options using an evidential reasoning approach and the IDS Software package.
Stage 6	Application of the model to a case scenario.

4.3.1 Identification of Decision-Making Criteria for the Selection of a Ballast Water Exchange Option

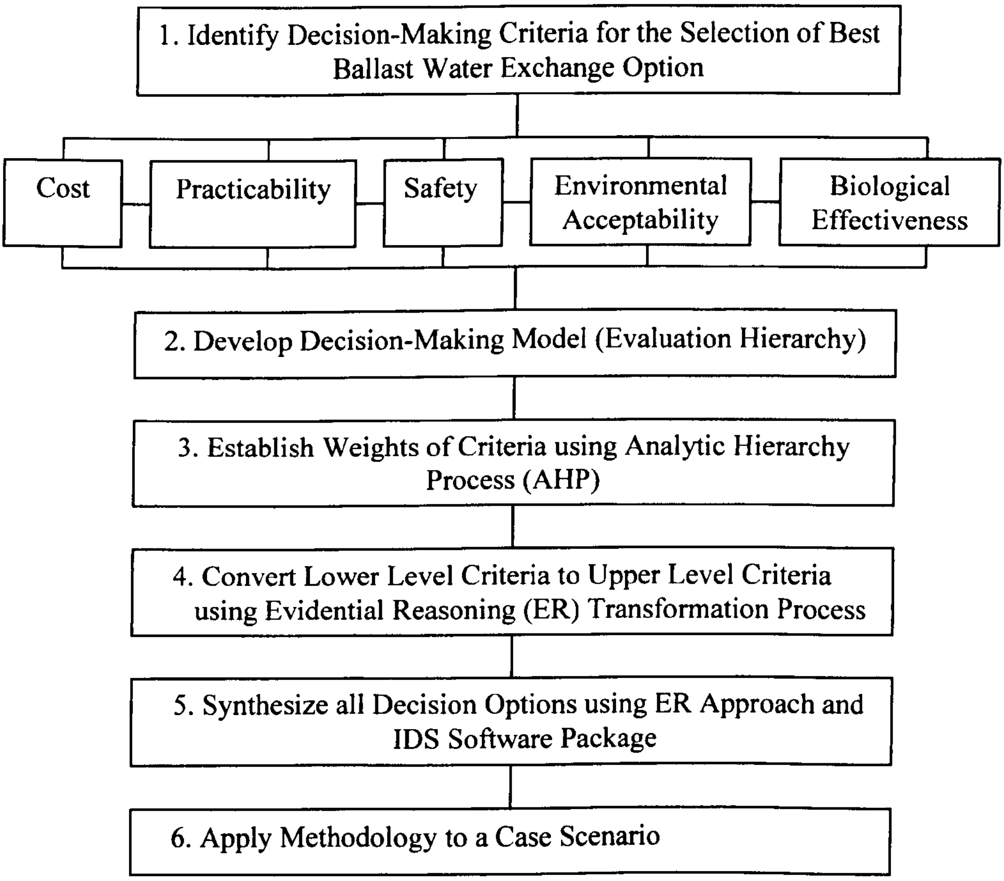
Five assessment criteria have been considered in this generic ballast water management decision analysis. These are:

- Cost effectiveness, i.e., economic viability.
- Practicability, i.e., compatibility with ship design and operations.
- Safety consideration relating to the safety to the ship, cargo and crew.

- Environmental acceptability, i.e., not causing more or greater environmental impacts than they solve.
- Biological effectiveness in terms of removing, or otherwise rendering not viable, harmful aquatic organisms and pathogens in ballast water.

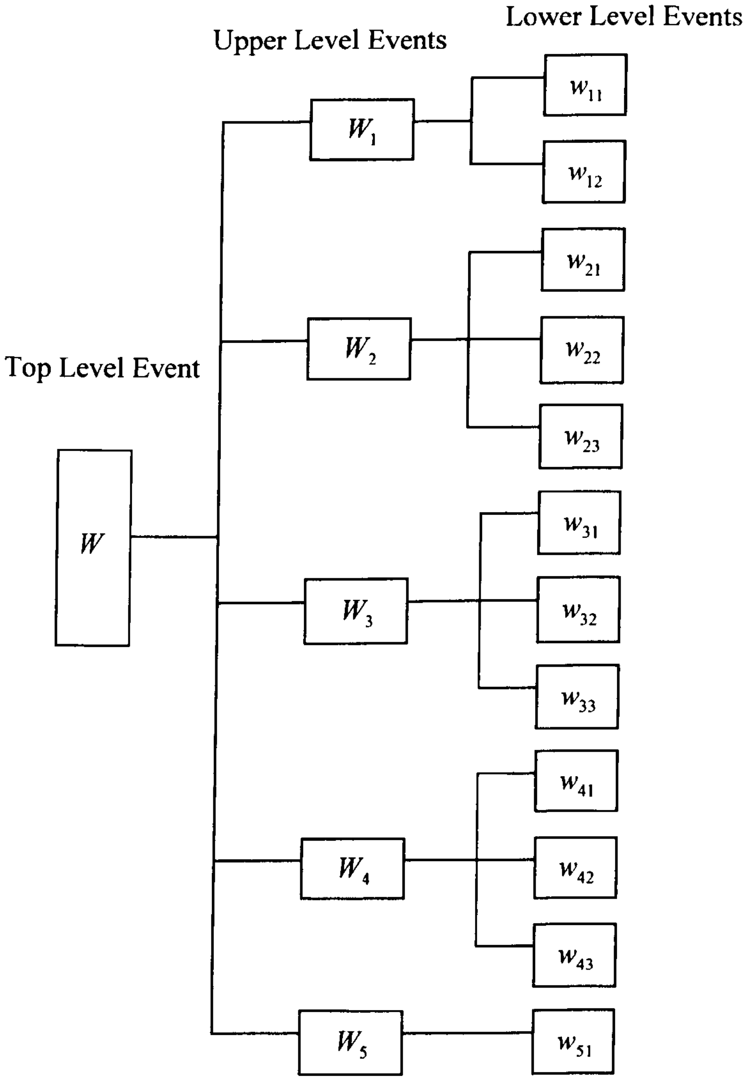
These criteria are statutory IMO standard requirements for the development of any proto-type ballast water treatment technology (Resolution A.868 (20) and IMO International Convention for the control and management of ships' ballast water and sediments (Regulation D-5 (2), 2004)). The decision analysis will be conducted through brainstorming by carefully selected experts who are assigned equal ratings.

Fig. 4.1 Outline of Methodology



The main event in the evaluation hierarchy of this study is ballast water management option (BWMO). This is represented as (W) in the decision model illustrated in Fig. 4.2. This means that the primary objective of the decision-making analysis is the identification of the best, appropriate and acceptable ballast water exchange option to be adopted by a port state or end-user.

Fig. 4.2 Hierarchical Diagram of the Decision Making Model



4.3.3 Establishment of Weights of each Criterion using AHP

The five assessment criteria (W_1, W_2, W_3, W_4 and W_5) constitute the Upper Level Events. The Upper Level Events are further subdivided into twelve sub-criteria that constitute the Lower Level Events and represented as (w_{11}, w_{12}, etc.). Linguistic terms have been used to describe the criteria in this study. A maximum of five and a minimum of four linguistic terms have been used to describe the assessment grades.

Having identified the evaluation criteria of this decision analysis, the next step in the methodology is establishment of importance weights of the evaluation criteria using the AHP approach. The obtained weights will be used for propagating the lower level criteria assessments to their respective upper levels. The importance weights of criteria in the real world are often subjective, reflecting the preference of decision analysts (Wang & Chang, 2007). The algorithm for this model is described below.

Suppose the quantified judgement on the pairs of criteria W_i and W_j is represented by an $n \times n$ single value comparison matrix A (Pillay & Wang, 2003). Then

$$A = (a_{ij}) = \begin{bmatrix} 1 & a_{12} & .... & a_{1n} \\ 1/a_{21} & 1 & .... & a_{2n} \\ . & . & .... & . \\ 1/a_{n1} & 1/a_{n2} & .... & 1 \end{bmatrix} \tag{4.1}$$

where each a_{ij} is the relative importance of the criteria W_i and W_j.

The weighting vector indicating the priority of each element in the pairwise comparison matrix in terms of its overall contribution to the decision making process can be obtained through a synthesization process that involves:

i. Summation of the values in each column of the pairwise comparison matrix.
ii. Dividing each element of the matrix by its column.
iii. Establishing the average of the elements in each row.

This process is described in Equation 4.2 as follows.

$$w_1 = \frac{1}{n}\left[\left(\frac{a_{11}}{\sum_{i=1}^{n} a_{i1}}\right) + \left(\frac{a_{12}}{\sum_{i=1}^{n} a_{i2}}\right) + \ldots. + \left(\frac{a_{in}}{\sum_{i=1}^{n} a_{in}}\right)\right] \tag{4.2}$$

The mathematical expression of the synthesization process is described in the following equation.

$$w_k = \frac{1}{n}\sum_{j=1}^{n} \frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}} \tag{4.3}$$

where w_k is the weighing of a specific element k (i.e criterion k) in the pairwise comparison matrix, and $k = 1, 2, 3, \ldots.n$.

The method has been proposed in this study because of:

i. Its suitability for analysing both quantitative and qualitative decision making criteria.
ii. Its ability to take a large quantity of criteria into consideration.
iii. Its ability to facilitate the construction of a flexible hierarchy to address the decision making problem.

The importance weights obtained in the pairwise comparison matrix are checked for consistency using a Consistency Index (CI). Consistency check is a stage in the AHP process where the degree of consistency among the pairwise comparisons provided by the analysts is measured. This is necessary because with numerous pairwise comparisons, a perfect consistency is often difficult to achieve. The CI is defined as follows.

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{4.4}$$

where n is the number of items being compared and $\lambda_{\max}$ is the maximum Eigen value of an $n \times n$ comparison matrix that is calculated using the following equation.

$$\lambda_{\max} = \frac{\sum_{j=1}^{n} \frac{\sum_{k=1}^{n} w_k a_{kj}}{w_k}}{n} \tag{4.5}$$

The next step in the process is the computation of the Consistency Ratio (CR) which is defined as.

$$CR = \frac{CI}{RI} \tag{4.6}$$

where the Random Index (RI) is the CI of a randomly generated pairwise comparison matrix.

The value of the RI depends on the number of items being compared and takes on the values presented in Table 4.1. A CR of 0.10 or less is considered acceptable (Satty, 1980).

Table 4.1 Average Random Index value

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.33	1.41	1.45	1.49

n = Size of the Pairwise Comparison Matrix

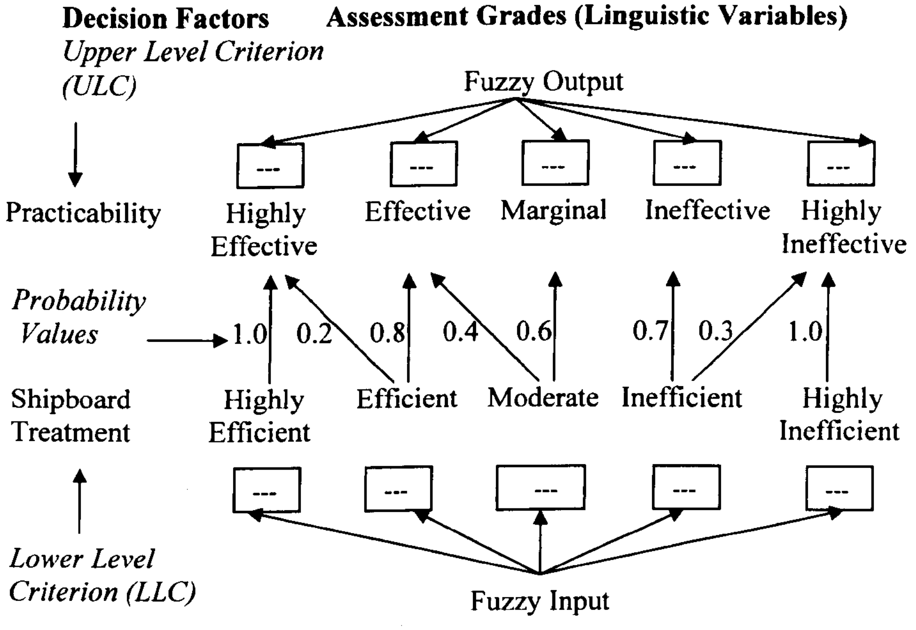
4.3.4 Convert Lower Level Criteria to Upper Level Criteria using Assessment Transformation Process

After determining the weights of the evaluation criteria, the next phase in this process is to convert lower level criteria (LLC) to upper level criteria (ULC) using the assessment transformation process. The transformation process is based on a fuzzy rule-base theory where the LLC (fuzzy inputs) are transformed to UPC (fuzzy output). In Fig. 4.3 the main criterion is at the upper level while the sub-criterion is at the lower level. The criterion, "Practicability" (ULC) is assessed using the following grades: Highly

Effective, Effective, Marginal, Ineffective and Highly Ineffective. The sub-criterion "Shipboard Treatment" (LLC) is assessed using the following linguistic terms: Highly Efficient, Efficient, Moderate, Inefficient and Highly Inefficient. The assessment grades for all the evaluation criteria are presented in a hierarchical structure in Tables 4.2 to 4.4.

A two-level transformation process is used in this model because it enables the decision analysts to easily convert lower level criteria to upper level criteria and obtain quantitative data that can be used for each level during the decision analysis. The transformation process and aggregating calculations (quantification) are described as follows.

Fig. 4.3 The Process of Transforming Lower Level Criteria (Fuzzy Input) to Upper Level criteria (Fuzzy Output)



Assume that each LLC^{ST} ($ST = 1, 2, \ldots, 5$) highlights the fuzzy input of the lower level criterion and that each ULC^{P} ($P = 1, 2, \ldots, 5$) represents the corresponding fuzzy output (upper level). Then Equation 4.7 can be constructed as:

$$ULC^{P} = \sum_{ST=1}^{5} LLC^{ST} P_{ST}^{\ P} \qquad P = (1, 2, ..., 5) \tag{4.7}$$

where $\sum_{P=1}^{5} ULC^{P} = 1.0$, and

$P_{ST}^{\ P}$ represents the relationship between the different level criteria as shown in the values attached to the arrows in Fig. 4.3.

In Fig. 4.3 the main criterion "Practicability" is the upper level criterion (ULC) while the sub-criterion "shipboard treatment" is at the lower level (LLC). The ULC is assessed using the following grades: Highly Effective, Effective, Marginal, Ineffective and Highly Ineffective. The LLC is assessed using the following linguistic grades: Highly Efficient, Efficient, Moderate, Inefficient and Highly Inefficient. The assessment grades for all the evaluation criteria are presented in a hierarchical structure in Tables 4.2 to 4.4. In Table 4.4, the sub-criteria, "New Technology" and "Treatment Options" belong to the criterion, "Cost", while the sub-criteria, "Exchange at Sea", "Shipboard Treatment" and "Discharge to Reception Facilities" are associated with the criterion, "Practicability". The criterion, "Safety" is associated with the sub-criteria, "Crew", "Vessel" and "Cargo" while the criterion, "Environmental Acceptability" is associated with the sub-criteria, "Human Habitat", "Marine Environment" and "Marine Installations".

Table 4.2 Assessment Grades for the Main Criterion

Main	Assessment Grades				
BWSM	Highly Preferred	Preferred	Moderate	Less Preferred	Least Preferred

Table 4.3 Assessment Grades for the Upper Level Criteria

Upper Level Criteria	Assessment Grades				
Cost	Very Low	Low	Average	High	Very High
Practicability	Excellent	Good	Average	Poor	Very Poor
Safety	Highly Acceptable	Acceptable	Unacceptable	Critical	Catastrophic
Environmental Acceptability	Highly Suitable	Suitable	Marginal	Unsuitable	Highly Unsuitable
Biological Effectiveness	Highly Acceptable	Acceptable	Marginal	Unacceptable	Highly Unacceptable

Table 4.4 Assessment Grades for the Lower Level (Sub) Criteria

Lower Level Criteria	Assessment Grades				
New Technology	Very Effective	Effective	Marginal	Less Effective	Least Effective
Treatment Option	Very Low	Low	Average	High	Very High
Exchange at Sea	Highly Likely	Likely	Marginal	Unlikely	Highly Unlikely
Shipboard Treatment	Highly Efficient	Efficient	Moderate	Inefficient	Highly Inefficient
Reception Facilities	Highly Likely	Likely	Unlikely	Highly Unlikely	
Crew	Very Low	Low	Marginal	Likely	Definite
Vessel	Very Insignificant	Insignificant	Marginal	Significant	Very Significant
Cargo	Highly Unlikely	Unlikely	Likely	Definite	
Human Habitat	Very Low	Low	High	Very High	
Marine Environment	Very Minimal	Minimal	Moderate	Likely	Very Likely
Marine Installations	Very Low	Low	Moderate	High	Very High
Species Survivability	Very Low	Low	Moderate	Critical	Catastrophic

The definitions of the five upper level criteria are contained in Tables 4.3 to 4.10. In Table 4.5, for example, the assessment grade (very low) of the "cost" criterion is assessed as "highly reasonable" if the cost of procurement, installation and running of the treatment system is very low. The assessment grade (low) is of the "cost" criterion assessed as "reasonable" if the cost of procurement, installation and running of the treatment system is low. The assessment grade (average) of the "cost" criterion is assessed as "fairly reasonable" if the cost of procurement, installation and running of the treatment system is average. The linguistic variable "high" of the "cost" criterion is assessed as "unreasonable" if the cost of procurement, installation and running of the treatment system is high. Finally, the linguistic variable "very high" of the "cost" criterion is assessed as "highly unreasonable" if the cost of procurement, installation and running of the treatment system is very high.

Table 4.5 Assessment Grades and Definitions for the Cost Criterion

Criterion	Assessment Grade	Definition
Cost	Very Low	The cost of procurement, installation and running of treatment system is very low, consequently, the system is highly reasonable
	Low	The cost of procurement, installation and running of treatment system is low, consequently, the system is reasonable
	Average	The cost of procurement, installation and running of treatment system is average, consequently, the system is fairly reasonable
	High	The cost of procurement, installation and running of treatment system is high, consequently, the system is unreasonable
	Very High	The cost of procurement, installation and running of treatment system is very high, consequently, the system is highly unreasonable

Table 4.6 Assessment Grades for the Practicability Criterion

Criterion	Assessment Grade	Definition
Practicability	Excellent	The compatibility of the treatment system to ship design and operations is highly effective, consequently, the practicability of the system is excellent
	Good	The compatibility of the treatment system to ship design and operations is effective, consequently, the practicability of the system is good
	Average	The compatibility of the treatment system to ship design and operations is marginal, consequently, the practicability of the system is average
	Poor	The compatibility of the treatment system to ship design and operations is ineffective, consequently, the practicability of the system is poor
	Very Poor	The compatibility of the treatment system to ship design and operations is highly ineffective, consequently, the practicability of the system is very poor

Table 4.7 Assessment Grades for the Safety Criterion

Criterion	Assessment Grade	Definition
Safety	Highly Acceptable	The risk level to crew, vessel and cargo arising from the installation of the treatment system is very low, consequently, the system is highly acceptable
	Acceptable	The risk level to crew, vessel and cargo arising from the installation of the treatment system is low, consequently, the system is tolerable
	Unacceptable	The risk level to crew, vessel and cargo arising from the installation of the treatment system is marginal, consequently, the system is unacceptable
	Critical	The risk level to crew, vessel and cargo arising from the installation of the treatment system is likely, consequently, the system is highly unacceptable
	Catastrophic	The risk level to crew, vessel and cargo arising from the installation of the treatment system is definite, consequently, the system is extremely unacceptable

Table 4.8 Assessment Grades and Definitions for the Environmental Acceptability Criterion

Criterion	Assessment Grade	Definition
Environmental Acceptability	Highly Suitable	The impact of the treatment system on the marine environment and installations is very low, consequently, the system is highly suitable
	Suitable	The impact of the treatment system on the marine environment and installations is low, consequently, the system is suitable
	Marginal	The impact of the treatment system on the marine environment and installations is moderate, consequently, the system is marginal
	Unsuitable	The impact of the treatment system on the marine environment and installations is high, consequently, the system is unsuitable
	Highly Unsuitable	The impact of the treatment system on the marine environment and installations is very high, consequently, the system is highly unsuitable

Table 4.9 Assessment Grades and Definitions for the Biological Acceptability Criterion

Criterion	Assessment Grade	Definition
Biological Effectiveness	Highly Acceptable	The efficacy of the treatment system to remove or render unviable ballasted harmful aquatic species is very high, consequently, the system is highly acceptable
	Acceptable	The efficacy of the treatment system to remove or render unviable ballasted harmful aquatic species is high, consequently, the system is acceptable
	Marginal	The efficacy of the treatment system to remove or render unviable ballasted harmful aquatic species is average, consequently, the system is marginal
	Unacceptable	The efficacy of the treatment system to remove or render unviable ballasted harmful aquatic species is low, consequently, the system is unacceptable
	Highly Unacceptable	The efficacy of the treatment system to remove or render unviable ballasted harmful aquatic species is very low, consequently, the system is highly unacceptable

Table 4.10 Assessment Grades and Definitions for Ballast Water Management Option

Main Criterion	Assessment Grade	Definition
Ballast Water Management Option	Highly Preferred	The ballast water treatment system is very safe and highly effective in the minimisation and control non-indigenous invasive species
	Preferred	The ballast water treatment system is safe and effective in the minimisation and control non-indigenous invasive species
	Moderate	The ballast water treatment system is marginally safe and averagely effective in the minimisation and control non-indigenous invasive species
	Less Preferred	The ballast water treatment system is unsafe and less effective in the minimisation and control non-indigenous invasive species
	Least Preferred	The ballast water treatment system is very unsafe and least effective in the minimisation and control non-indigenous invasive species

4.3.5 Conduct Synthesization Process using Evidential Reasoning Approach

After transforming all the criteria to a common utility space, the ER approach (Yang & Xu, 2002a; Xie *et al.*, 2006) is applied to synthesise the transferred criteria. The synthesization process is applied as follows:

Suppose there are L basic criteria associated with a general criterion y.

a). Define a set of L basic criteria as follows:

$$E=\{e_i,\ i=1,2,3\ ....,\ L\} \tag{4.8}$$

Suppose the L basic criteria consist of all factors that influence the assessment of the associated general criterion. Suppose the weights of the criteria are given as $\omega = \{\omega_1 \dots \omega_i \dots \omega_L\}$, where ω_i is the relative weight of the ith basic criterion with

$$0 \le \omega_i \le 1 \text{ and } \sum_{i=1}^{L} \omega_i = 1 \tag{4.9}$$

The weights of the evaluation criteria in this assessment will be established through a pairwise comparison involving AHP.

b). Define N distinctive (mutually exclusive) evaluation grades H_n (n = 1, ..., N) as a complete (collectively exhaustive) set of standards for assessing each alternative on all criteria as represented by:

$$H = \{H_n,\ n=1, \ldots\ldots, N\} \tag{4.10}$$

c). Model the multi-criteria decision making problem using the following expectations for alternatives $a_l = (l = 1, \ldots., M)$ on criteria e_i (i = 1,...., L).

$$S(e_i\,(a_l)) = \{(H_n,\ \beta_{n,i}\,(a_l)),\ n = 1, 2, \ldots., N\},\ i = 1, \ldots.\ L, \quad l = 1, 2, \ldots., M, \tag{4.11}$$

where $\beta_{n,i}\,(a_l)$ is a degree of belief. $\beta_{n,i}\,(a_l) \geq 0$ and $\sum_{n=1}^{N} \beta_{n,i}(a_1) \leq 1$.

An expectation for e_i and a_l as shown in Equation 4.11 reads that a criterion e_i at an alternative a_l is assessed to a grade H_n with a Degree of Belief of $\beta_{n,i}\,(a_l)$ (n = 1, 2,......, N).

Let β_n be a degree of belief to which the general criterion y is assessed to the grade H_n, then β_H is the uncertain degree of belief for the assessment.

$$\beta_H = 1 - \sum_{n=1}^{N} \beta_n\ , \quad 0 \leq \beta_n \leq 1, \quad \sum_{n=1}^{N} \beta_n + \beta_H = 1 \tag{4.12}$$

The aggregation problem is to generate β_n (n = 1, 2 3, ..., N) by aggregating the assessments for all the associated basic criteria e_i (i = 1,...., L) as given in Equation 4.11.

4.3.6 The Evidential Reasoning Algorithm

The set S (E) = $\{(H_n,\ \beta_n),\ n = 1, \ldots, N\}$ represents the synthesis of a set of L criteria which is assessed to grade H_n with degree of belief β_n, n = 1, ..., N. Let $m_{n,i}$ be a basic probability mass representing the degree to which the ith basic criterion e_i supports the hypothesis that the criterion y is assessed to the nth grade H_n. Therefore $m_{n,i}$ can be represented as follows (Yang & Xu, 2002b):

$$m_{n,i} = \omega_i \beta_{n,i} \qquad n = 1, 2, \ldots, N; \quad i = 1, 2, \ldots, L \tag{4.13}$$

$m_{H,i}$ is the remaining probability mass that can be stated as:

$$m_{H,i} = 1 - \sum_{n=1}^{N} m_{n,i} \qquad i = 1, 2, \ldots, L \tag{4.14}$$

The remaining probability mass $m_{H,i}$ is spilt into two parts, $\bar{m}_{H,i}$ and $\tilde{m}_{H,i}$, and is calculated using the following equations:

$$\bar{m}_{H,i} = 1 - \omega_i \qquad i = 1, 2, \ldots, L \tag{4.15}$$

$$\tilde{m}_{H,i} = \omega_i \left(1 - \sum_{n=1}^{N} \beta_{n,i}\right) \qquad i = 1, 2, \ldots, L \tag{4.16}$$

$\bar{m}_{H,i}$ is the first part of the remaining probability mass that is not yet assigned to individual grades due to the fact that criterion i (denoted by e_i) only plays one part in the assessment relative to its weight. $\tilde{m}_{H,i}$ is the second part of the remaining probability mass unassigned to individual grades, which is caused due to the incompleteness in the assessment $S(e_i)$.

To obtain the combined degrees of belief of all the basic criteria, $E_{I(i)}$ is firstly defined as the subset of the first i basic criteria as follows:

$$E_{I(i)} = \{e_1, e_2, \ldots, e_i\}$$

Let $m_{n,I(i)}$ be a probability mass defined as the degree to which all the i criteria in $E_{I(i)}$ support the hypothesis that E is assessed to the grade H_n and let $m_{H,I(i)}$ be the remaining probability mass unassigned to individual grades after all the basic criteria in $E_{I(i)}$ have been assessed. Equations 4.17 and 4.18 are obviously correct when $i = 1$.

$$m_{n,I(1)} = m_{n,1} \qquad \text{for } n = 1, 2, \ldots\ldots, N \tag{4.17}$$

$$m_{H,I(1)} = m_{H,1} \tag{4.18}$$

By using Equations 4.17 and 4.18, Equations 4.19 – 4.23 can be constructed for $i = 1, 2, \ldots, L$-1 to obtain the coefficients $m_{n,I(L)}$, $\bar{m}_{H,I(L)}$ and $\tilde{m}_{H,I(L)}$ as follows (Yang & Xu, 2002b).

$$K_{I(i+1)} = \left[1 - \sum_{t=1}^{N} \sum_{\substack{j=1 \\ j \neq t}}^{N} m_{t,I(i)} m_{j,i+1}\right]^{-1} \tag{4.19}$$

where $K_{I(i+1)}$ is a normalizing factor.

$\{H_n\}$:

$$m_{n,I(i+1)} = K_{I(i+1)}[m_{n,I(i)} m_{n,i+1} + m_{H,I(i)} m_{n,i+1} + m_{n,I(i)} m_{H,i+1}] \quad n = 1, 2, \ldots, N \tag{4.20}$$

$$\tilde{m}_{H,I(i+1)} = K_{I(i+1)}[\tilde{m}_{H,I(i)} \tilde{m}_{H,i+1} + \bar{m}_{H,I(i)} \tilde{m}_{H,i+1} + \tilde{m}_{H,I(i)} \bar{m}_{H,i+1}] \tag{4.21}$$

$$\bar{m}_{H,I(i+1)} = K_{I(i+1)} \bar{m}_{H,I(i)} \bar{m}_{H,i+1} \tag{4.22}$$

$\{H\}$:

$$m_{H,I(i)} = \tilde{m}_{H,I(i)} + \bar{m}_{H,I(i)} \qquad i = 1, 2, \ldots, L - 1 \tag{4.23}$$

Finally, after all the L assessments have been aggregated, the combined DoBs are generated by assigning $\bar{m}_{H,I(L)}$ back to all the individual grades proportionately using the following normalization process (Yang & Xu, 2002b).

$$\{H_n\}: \beta_n = \frac{m_{n,I(L)}}{1 - \bar{m}_{H,I(L)}} \qquad n = 1, 2, \ldots, N \tag{4.24}$$

$$\{H\}: \beta_H = \frac{\tilde{m}_{H,I(L)}}{1 - \bar{m}_{H,I(L)}} \tag{4.25}$$

where β_n denotes the degree of belief with which E is assessed to H_n and β_H is the unassigned degree of belief representing the extent of the incompleteness in the overall assessment.

4.3.7 Synthesis of all Decision Options using Evidential Reasoning Approach and IDS Software Package

The final step in this methodology is the synthesis of all decision options using the IDS software package (Yang & Xu, 2000). The IDS software is a powerful user-friendly window based software package and computer interface which incorporates the ER algorithm and facilitates information collection, processing and display. It records assessment information including evidence and comments in organized structures, and provides systematic help at every stage of the assessment including guidelines for grading criteria (Xu & Yang, 2003). The package has been used in a variety of applications that include motorcycle assessment (Yang & Sen, 1994), general cargo ship design (Sen & Yang, 1995), marine system safety analysis and synthesis (Wang *et al.*, 1995, 1996), executive car assessment (Yang & Xu, 1998), project management (Sonmez *et al.*, 2001) and organizational self-assessment (Yang *et al.*, 2001; Siow *et al.*, 2001).

4.4 Case Scenario

The aim of this section is to demonstrate how the methodology can be applied in the analysis of ballast water management decision alternatives. The evaluation criteria and decision attributes have been generated from the IMO Ballast Water Management Convention 2004 as observed in Section 4.3.1. However, the values assigned to these criteria were based on expert knowledge and judgement.

4.4.1 Establishment of Weights of Each Criterion using Analytic Hierarchy Process (AHP)

The evaluation criteria in this decision analysis are: cost, practicability, safety, environmental acceptability and biological effectiveness. The following linguistic terms and numerical values have been utilised to express the decision analysts' preference for each pair of elements: More Important (1-2), Moderately More Important (3) and Strongly More Important (4). The descriptive preferences and numerical values would then be used to establish the importance weight of each criterion.

4.4.1.1 Conduct Pairwise Comparison

The pairwise comparisons of the evaluation criteria were conducted as shown in Table 4.11.

Table 4.11 Scale for the Pairwise Comparison of Evaluation Criteria

Pairwise Comparison	More Important Criterion	How Much More Important	Numerical Rating
Cost - Practicability	Practicability	Moderately more important	3
Cost - Safety	Safety	Strongly more important	4
Cost - Environmental Acceptability	Environmental Acceptability	Moderately more important	3
Cost - Biological Effectiveness	Biological Effectiveness	Moderately more important	3
Practicability - Safety	Safety	Moderately more important	3
Practicability - Environmental Acceptability	Environmental Acceptability	Moderately more important	3
Practicability – Biological Effectiveness	Practicability	Moderately more important	2
Safety - Environmental Acceptability	Safety	Moderately more important	2
Safety - Biological Effectiveness	Safety	Moderately more important	3
Environmental Acceptability - Biological Effectiveness	Environmental Acceptability	Moderately more important	2

Given the numerical ratings and the associated assessment criteria in Table 4.11, a 5 × 5 pairwise comparison matrix was constructed using Equation 4.1 as follows.

Table 4.12 Pairwise Comparison Matrix

Criterion	Cost	Practicability	Safety	Environmental Acceptability	Biological Effectiveness
Cost	1	⅓	¼	⅓	⅓
Practicability	3	1	⅓	½	2
Safety	4	3	1	2	3
Environmental Acceptability	3	2	½	1	2
Biological Effectiveness	3	½	⅓	½	1
Sum	14	6.833	2.416	4.333	8.333

4.4.1.2 AHP Synthesis Process

The next stage in the AHP process is the synthesis process. This was conducted using Equations 4.2 and 4.3 as follows.

i. Summation of the values in each column of the pairwise comparison matrix. The process was conducted using Equation 4.2 as developed below.

Cost	Practicability	Safety	Env. Acceptability
1 ÷ 14 = 0.071	⅓÷ 6.833 = 0.049	¼ ÷ 2.416 = 0.103	⅓ ÷ 4.333 = 07
3 ÷ 14 = 0.214	1 ÷ 6.833 = 0.146	⅓÷ 2.416 = 0.183	½ ÷ 4.333 = 0.115
4 ÷ 14 = 0.286	3 ÷ 6.833 = 0.439	1 ÷ 2.416 = 0.414	2 ÷ 4.333 = 0.462
3 ÷ 14 = 0.214	2 ÷ 6.833 = 0.293	½ ÷ 2.416 = 0.207	1 ÷ 4.333 = 0.231
3 ÷ 14 = 0.214	½ ÷ 6.833 = 0.073	⅓÷ 2.416 = 0.138	½ ÷ 4.333 = 0.115

Biological Effectiveness

⅓÷ 8.333 = 0.040
2 ÷ 8.333 = 0.240
3 ÷ 8.333 = 0.360
2 ÷ 8.333 = 0.240
1 ÷ 8.333 = 0.120

ii. To determine the weight of each evaluation criterion, the average value of the elements in each row was obtained and divided by the total number of criteria (i.e. 5). Equation 4.3 was applied and the results are presented in Table 4.13.

Table 4.13 Evaluation Criteria and their Determined Weight Values

Criterion	Cost	Practicability	Safety	Environmental Acceptability	Biological Effectiveness	Weight Values
Cost	0.071	0.049	0.103	0.077	0.040	0.068
Practicability	0.214	0.146	0.138	0.115	0.240	0.171
Safety	0.284	0.438	0.414	0.462	0.360	0.392
Environmental Acceptability	0.214	0.293	0.207	0.231	0.240	0.237
Biological Effectiveness	0.214	0.073	0.138	0.115	0.120	0.132

4.4.1.3 Calculate the Consistency of the Pairwise Judgement

After obtaining the weight values of the evaluation criteria, the next stage in the AHP process is the calculation of the Consistency of the pairwise judgement. Equations 4.4 and 4.5 were applied in the process as follows.

Step *i*: Each value in the first column of the pairwise comparison matrix was multiplied by the priority of the first item as follows.

$$0.068\begin{bmatrix}1\\3\\4\\3\\3\end{bmatrix}+0.171\begin{bmatrix}1/3\\1\\3\\2\\1/2\end{bmatrix}+0.392\begin{bmatrix}1/4\\1/3\\1\\1/2\\1/3\end{bmatrix}+0.237\begin{bmatrix}1/3\\1/2\\2\\1\\1/2\end{bmatrix}+0.132\begin{bmatrix}1/3\\2\\3\\2\\1\end{bmatrix} \tag{4.26}$$

Consequently, the following sums were obtained.

$$\begin{bmatrix}0.068\\0.204\\0.272\\0.204\\0.204\end{bmatrix}+\begin{bmatrix}0.057\\0.171\\0.513\\0.342\\0.086\end{bmatrix}+\begin{bmatrix}0.098\\0.131\\0.392\\0.196\\0.131\end{bmatrix}+\begin{bmatrix}0.079\\0.119\\0.474\\0.237\\0.119\end{bmatrix}+\begin{bmatrix}0.044\\0.264\\0.396\\0.264\\0.132\end{bmatrix}=\begin{bmatrix}0.346\\0.889\\2.047\\1.243\\0.672\end{bmatrix} \tag{4.27}$$

Step *ii*: Each $\sum_{k=1}^{n} w_k a_{kj}$ (j = 1, 2, 3, 4, 5) in Equation 4.5 is calculated as follows.

$$\frac{0.346}{0.068}=5.088;\ \frac{0.889}{0.171}=5.199;\ \frac{2.047}{0.392}=5.222;\ \frac{1.243}{0.237}=5.245;\ \frac{0.672}{0.132}=5.091 \tag{4.28}$$

Step *iii*: Using the results obtained in step *ii*, the $\lambda_{\max}$ was obtained using Equation 4.5 as follows.

$$\lambda_{\max}=\frac{5.088+5.199+5.222+5.245+5.091}{5}=5.169 \tag{4.29}$$

Step *iv*: The CI is obtained as follows.

$$\frac{5.169-5}{5-1} = \frac{0.169}{4} = 0.042 \qquad (4.30)$$

Step *v*: Since there are 5 items in the first level of the hierarchy resulting in the corresponding RI of 1.12, the CR was calculated using Equation 4.6 as follows.

$$\frac{0.042}{1.12} = 0.038 \qquad (4.31)$$

The result of the pair-wise comparison for the weights of the evaluation criteria shows a CR of 0.038. This means that the degree of consistency in the pairwise comparisons is acceptable because the CR is less than 0.10.

Based on this result the obtained importance weights for the evaluation criteria are certified as follows.

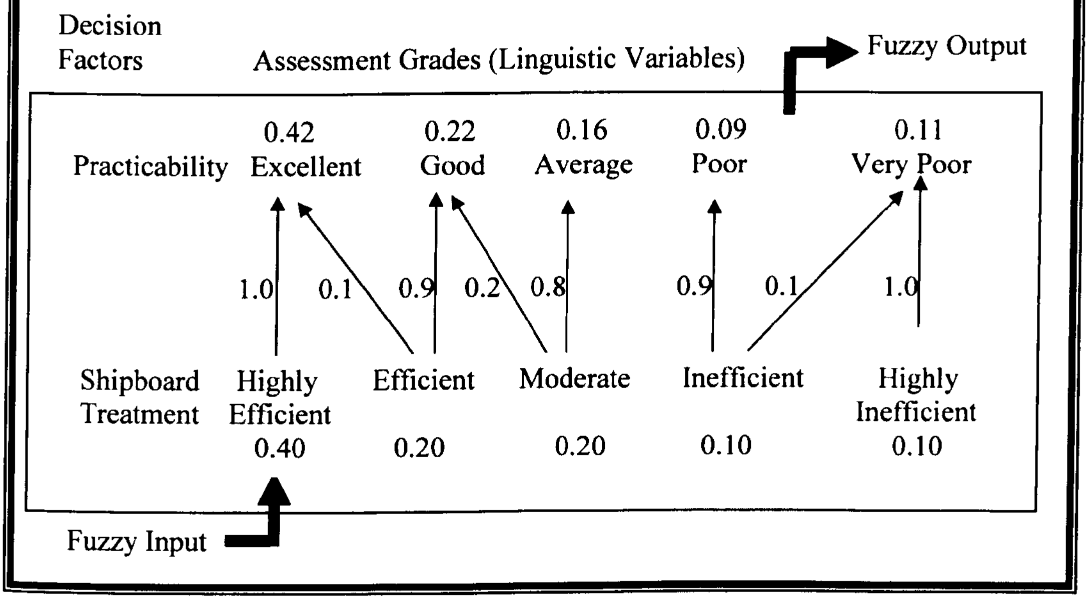
Cost = 0.068
Practicability = 0.171
Safety = 0.392
Environmental Acceptability = 0.237
Biological Effectiveness = 0.132

The results also indicate that the criterion "Safety" recorded the highest weight (0.392), whereas the lowest weight (0.068) is associated with the criterion, "Cost". These weight values will be applied in the next stage of the proposed model in order to establish the fuzzy performance ratings of the evaluation criteria. The weight distributions for the evaluation criteria of the other levels in the hierarchy were obtained using a similar process and presented in Appendix 4.

4.4.2 Convert Lower Level Criteria to Upper Level Criteria using Evidential Reasoning Assessment Transformation Process

In order to apply the ER algorithm in this evaluation process it is necessary to transform the lower level criteria to their upper level criteria. The assessment grades and values of the lower level criteria (fuzzy input) were assigned by the experts involved in the assessment process and based on their knowledge and judgement. However, the assessment values for the upper level criteria (fuzzy output) are obtained after the transformation of the lower level criteria. The assessment transformation (mapping) process for the attribute, "Practicability" is demonstrated in Fig. 4.4 as an example. The transformation processes for the other criteria are contained in Appendix 5.

Fig. 4.4 Assessment Transformation Process for Practicability



A subjective fuzzy rule-base with belief degree principle is applied to describe the mapping process as follows:

1. If Shipboard Treatment is Highly Efficient, then Practicability is Excellent (1.00).
2. If Shipboard Treatment is Efficient, then Practicability is Good (0.90) and Excellent (0.10).

3. If Shipboard Treatment is Moderate, then Practicability is Average (0.80) and Good (0.20).
4. If Shipboard Treatment is Inefficient, then Practicability is Poor (0.90) and Very Poor (0.10).
5. If Shipboard Treatment is Highly Inefficient, then Practicability is Very Poor (1.00).

The output values for the assessment grades of the upper level criterion, "Practicability" (having been transformed from the values and corresponding assessment grades of the lower level criterion "Shipboard Treatment" in Fig. 6 were obtained using Equation 4.27 as follows.

Excellent = (0.40 ×1.0) + (0.20 × 0.1) = 0.40 + 0.02 = 0.42
Good = (0.20 × 0.9) + (0.2 × 0.2) = 0.18 + 0.04 = 0.22
Average = 0.20 × 0.8 = 0.16
Poor = 0.10 × 0.9 = 0.09
Very Poor = (0.10 × 1.0) + (0.10 × 0.10) = 0.1 + 0.01 = 0.11

The values, 0.42, 0.22, 0.16, 0.09 and 0.11 associated with the linguistic terms "Excellent", "Good", "Average", "Poor" and "Very Poor" respectively, constitute the input values for the assessment of the upper level criterion "Practicability" in the next level of the mapping process. The output values of all sub-criteria to be applied in the next level in the assessment transformation process have been obtained using the same process and contained in Tables 4.14 – 4.18.

Table 4.14 Output Values of Cost Criterion

Cost	Very Low	Low	Average	High	Very High
New Technology	0.20	0.29	0.21	0.15	0.15
Treatment Option	0.30	0.25	0.20	0.10	0.15

Table 4.15 Output Values for Practicability Criterion

Practicability	Excellent	Good	Average	Poor	Very Poor
Exchange at Sea	0.40	0.20	0.20	0.09	0.11
Shipboard Treatment	0.42	0.22	0.16	0.09	0.11
Reception Facilities	0.45	0.20	0.08	0.12	0.15

Table 4.16 Output Values for Safety Criterion

Safety	Highly Acceptable	Acceptable	Unacceptable	Critical	Catastrophic
Crew	0.35	0.20	0.20	0.15	0.10
Vessel	0.30	0.25	0.18	0.17	0.10
Cargo	0.40	0.27	0.07	0.16	0.10

Table 4.17 Output Values of Environmental Acceptability Criterion

Environmental Acceptability	Highly Suitable	Suitable	Marginal	Unsuitable	Highly Unsuitable
Human Habitat	0.33	0.27	0.12	0.12	0.16
Marine Environment	0.30	0.25	0.20	0.12	0.13
Marine Installations	0.25	0.20	0.25	0.15	0.15

Table 4.18 Output Values for Biological Effectiveness Criterion

Biological Effectiveness	Highly Acceptable	Acceptable	Marginal	Unacceptable	Highly Unacceptable
Species Survivability	0.30	0.20	0.18	0.14	0.18

4.4.3 Synthesis of all Decision Options using Evidential Reasoning Approach and IDS Software Package

To obtain the input values for the upper level assessment, the output values obtained from the mapping process of the lower level criteria (Tables 4.13 – 4.18) are combined with the weight values obtained for these criteria using the AHP method (Table 4.12) and synthesised using the IDS Software package. This process continues until the input values for the assessment of the main attribute are established. The distributed evaluation grades and DoBs for the "Cost" criterion are presented in Fig. 4.5. The same process has been applied to obtain the values of the other decision criteria at this level and the results are contained in Appendix 6. The assessment values for the top level event (Ballast Water Management Option) were obtained through a similar process that combined the output values of the upper level assessment with the weights of the five criteria. This is illustrated in Fig. 4.6.

Fig. 4.5 Distributed Assessments for the Cost Criterion

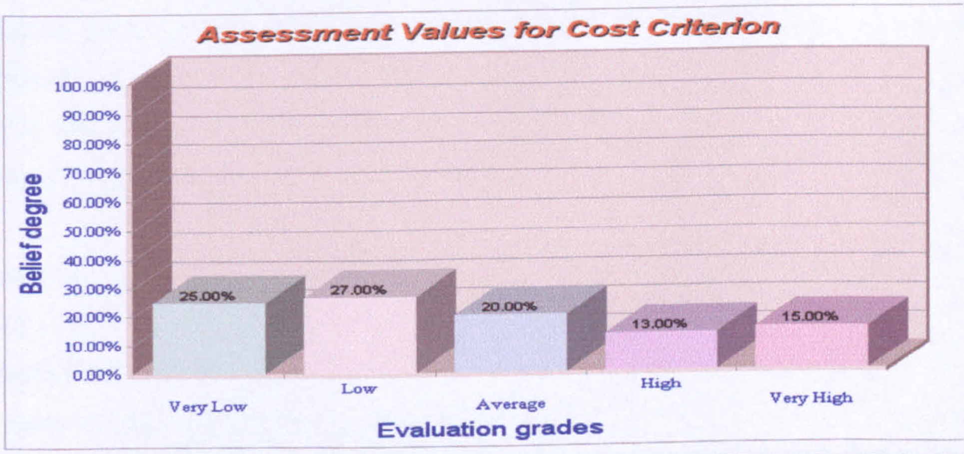
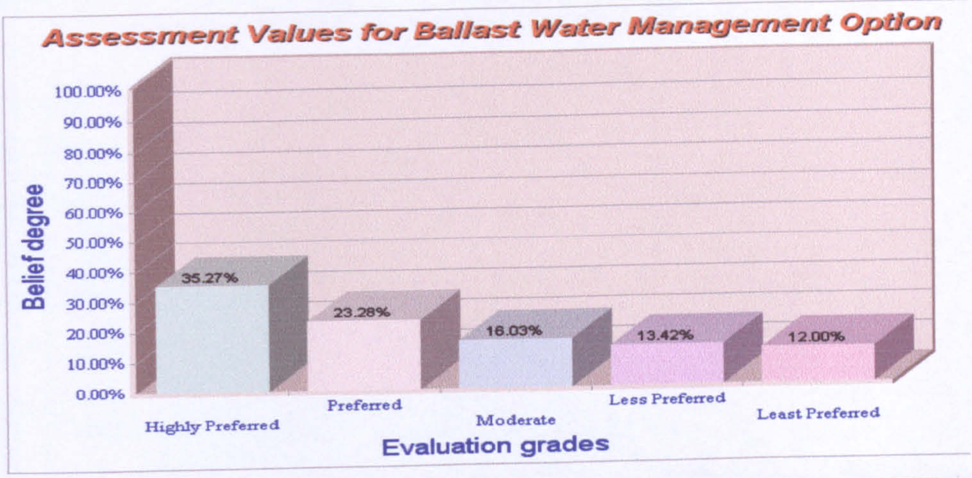


Fig. 4.6 Distributed Assessments for Identification of Best Ballast Water Management Option



4.5 Results and Partial Validation of Model

The result of the synthesisation process for the main decision criteria shows that the evaluation grade "Highly Preferred" returned the highest value (35.27%). The grade "Preferred" is associated with the value 23.28%. The values, 16.03%, 13.42% and 12.00% are associated with the grades, "Moderate", "Less Preferred" and "Least Preferred", respectively.

A sensitivity analysis was conducted to partially validate the developed model. The objective of a sensitivity analysis when applied in a model verification process is to ascertain if the model output responds appropriately to changes in the model input. In this study the aim was to demonstrate the sensitivity of an assessment grade when the input values of the decision attribute changed. The process involved reducing the value of the highest preferred grade by percentages and increasing the value of the least preferred grade by the same amount. In this regard, 20 Conditions were generated for the conduct of the sensitivity analysis. The Conditions are described in Table 4.19.

Table 4.19 Sensitivity Analysis (by Reducing Values by Percentages)

Conditions		Results				
		Highly Preferred	Preferred	Moderate	Less Preferred	Least Preferred
	Main	35.27%	23.28%	16.03%	13.42%	12.00%
1	Reduce Cost by 20%	34.93%	23.30%	16.05%	13.43%	12.29%
2	Reduce Cost by 40%	34.61%	23.32%	16.06%	13.44%	12.58%
3	Reduce Cost by 60%	34.28%	23.34%	16.07%	13.45%	12.86%
4	Reduce Cost by 80%	33.95%	23.35%	16.08%	13.46%	13.15%
5	Reduce Practicability by 20%	33.85%	23.34%	16.08%	13.46%	13.27%
6	Reduce Practicability by 40%	32.24%	23.42%	16.13%	13.50%	14.71%
7	Reduce Practicability by 60%	30.80%	23.49%	16.18%	13.54%	16.00%
8	Reduce Practicability by 80%	29.17%	23.56%	16.23%	13.58%	17.46%
9	Reduce Safety by 20%	31.72%	23.38%	16.10%	13.48%	15.32%
10	Reduce Safety by 40%	28.15%	23.48%	16.10%	13.54%	18.66%
11	Reduce Safety by 60%	24.55%	23.58%	16.24%	13.59%	21.03%
12	Reduce Safety by 80%	20.91%	23.69%	16.31%	13.65%	25.43%
13	Reduce Environmental Acceptability by 20%	33.67%	23.36%	16.09%	13.47%	13.41%
14	Reduce Environmental Acceptability by 40%	32.07%	23.44%	16.14%	13.51%	14.83%
15	Reduce Environmental Acceptability by 60%	30.73%	23.51%	16.19%	13.55%	16.02%
16	Reduce Environmental Acceptability by 80%	29.10%	23.59%	16.25%	13.60%	17.46%
17	Reduce Biological Effectiveness by 20%	34.46%	23.32%	16.06%	13.45%	12.71%
18	Reduce Biological Effectiveness by 40%	33.65%	23.37%	16.09%	13.47%	13.41%
19	Reduce Biological Effectiveness by 60%	32.84%	23.41%	16.13%	13.50%	14.13%
20	Reduce Biological Effectiveness by 80%	32.02%	23.46%	16.16%	13.52%	14.84%

The first Condition involved reducing the value of the highest preferred evaluation grade of the “Cost” attribute by 20% and increasing the value of the lowest preferred grade of the same criterion by the same amount. The second Condition involved reducing the value of the highest preferred grade of the "Cost" criterion by 40% and increasing the value of the lowest preferred grade of the same criterion by the same amount. The third Condition involved reducing the value of the highest preferred grade of the "Cost" attribute by 60% and increasing the value of the lowest preferred grade of the same criterion by the same amount. The fourth Condition involved reducing the value of the highest preferred grade by 80% and increasing the value of the lowest preferred grade of the same criterion by the same amount. The same process was utilised for the remaining four decision criteria. The results of the sensitivity analysis are also summarised in Table 4.19.

From the results obtained it can be seen that when every attribute changes, the output changes. For example, when the value of the highly preferred evaluation grade of the "Cost" criteria was reduced by 20% in Condition 1, the main values of the evaluation grades (Highly Preferred, Preferred, Moderate, Less Preferred and Least Preferred) changed from 35.27%, 23.28%, 16.03%, 13.42% and 12.00% to 34.93%, 23.30%, 16.05%, 13.43% and 12.29, respectively. The values of the lowest evaluation grades of the overall assessment maintained a consistent increment when the values of the highly preferred evaluation grades were increasingly reduced. The values associated with the grades "Preferred", "Moderate" and "Less Preferred" in overall assessment recorded very slight changes. These changes are to be anticipated. However, the "Safety" attribute recorded a significant change in the assessment of the top level criterion when the value of the highest preferred belief degree was reduced by 20%, 40%, 60% and 80% in Conditions 9 to 12. For example, the value (31.72%) associated with the highly preferred grade in Condition 9 represents a more significant change compared to the values (34.93%, 33.85%, 33.67% and 33.46%) in Conditions 1, 5, 13 and 17, respectively. This is related to the fact that the belief degree associated with the highest preferred grade of this criterion is large compared to the belief degree associated with the same evaluation grade of the other decision criteria. Furthermore, the safety criterion also has the highest weight among the five criteria at the upper level. The model is more sensitive to "Safety" than the other decision criteria. The above sensitivity study shows that reasonable results can be produced through the model.

4.6 Conclusion

The plurality of decision making criteria for the selection of an appropriate ballast water management option presents an enormous challenge for port states administrations and stake-holders in the maritime industry. Similarly, the development of an acceptable ballast water management option would require an evaluation and prioritisation of these uncertain variables. This study has demonstrated that by applying powerful classical engineering decision analysis theories such as AHP and ER, the problems of uncertainty, inadequacy and/or unavailability of historical data on ballast water safety management can be addressed. The model developed in this study is indicative of its potential in addressing multi-criteria decision making problems associated with discharged ships' ballast water and other related maritime environmental pollution problems. It has also justified the need for the introduction of artificial intelligence methodologies into the evaluation of safety related issues associated with ballast water prototype treatment technologies. The model is capable of absorbing new data and subsequent modification without necessarily distorting its methodology and applicability.

This model is by no means exhaustive as it is subject to further development and applicability. A prominent constraint during the development of this model was the inadequacy of quantitative data (particularly the production costs of individual prototype ballast water treatment technologies). Financial estimates for most of these technologies were often not disclosed by manufacturers as a business strategy. A sensitivity analysis was conducted to partially validate the developed model and establish their ability to respond to changes in the model input.

Chapter Five

Application of Fuzzy Multi-Criteria Decision Making Models to Group Decision-Making Analysis of Ship-Based Ballast Water Treatment Technologies

5.1 Introduction

Regulations D2 and D4 of the IMO International Convention for the Control and Management of Ships' Ballast Water and Sediments Ballast Water (2004) stipulate that all ships under construction in or after 2009 and having a ballast capacity between 1500 and 5000 cubic metres must have ballast water treatment systems fitted to and used on-board with effect from January 1, 2009 (Lloyds Register, 2007).

Compliance to such IMO Regulations has propelled the development of numerous ballast water treatment technologies. Some of these technologies are currently in their final stages of approval by the IMO and/or Flag State Administrations (Lloyds Register, 2007). However, the selection of a particular treatment system for a designated vessel or voyage route will have to be pre-determined by technical (safety of crew, ship and cargo), cost (production and running) and environmental (sustainability of the marine eco-systems) variables. Evaluating these variables may not be straight-forward due to inherent uncertainties and inadequacy of historical data. The choice of an appropriate ballast water treatment system can therefore be a daunting task for both ship-owners and managers. Port states and/or regional regulatory authorities are also subjected to decision-making problems as they are expected to strike a balance between the sustenance of a pollution-free maritime environment and the promotion of maritime trade of their countries/regions.

A novel methodology is developed in this paper to deal with multi-criteria decision making (MCDM) problems associated with the analysis and selection of ballast water treatment systems under a subjective group decision framework. A group decision-making problem arises when there are two or more individuals who, characterized by their perceptions, attitudes, motivations, and personalities, recognize the existence of a common problem and attempt to reach a collective decision (Cheng & Lin, 2002). The methodology utilises fuzzy sets theory (FST) and two MCDM models (AHP and TOPSIS) for the analysis of decision-making variables. The AHP methodology is incorporated into the model to determine the importance weights of the decision alternatives, while the TOPSIS technique is incorporated into the model to obtain the performance ratings of decision alternatives using linguistic terms parameterised with triangular fuzzy numbers.

The rest of the chapter is structured as follows. Section 5.2 is a literature review of the methodologies that constitute the background to the proposed model. The methodologies reviewed include fuzzy sets theory, the AHP and Fuzzy-TOPSIS. The framework and hierarchical structure of the model is presented in Section 5.3. The proposed model is demonstrated using a test case involving selected proto-type ballast water treatment technologies in Section 5.4. The results of the Fuzzy-TOPSIS analysis are contained in Section 5.5. A sensitivity analysis to validate the proposed model is provided in Section 5.6.

5.2 Background to Research Methodology

This section reviews the different techniques that have been applied in the development of the proposed model in this Chapter.

5.2.1 Fuzzy Sets Theory and Fuzzy Membership Functions

FST has been described in Sections 2.6.2.1 and 3.2.1.

5.2.2 Fuzzy Multi-Criteria Decision-Making (FMCDM) Methodology

Bellman & Zadeh (1970) surveyed decision-making problems using fuzzy sets and initiated the FMCDM methodology to resolve the lack of precision in assigning importance weights of criteria and the ratings of alternatives regarding evaluation criteria (Chen & Klein, 1997; Wang & Chang, 2007). FMCDM has subsequently helped decision makers to solve complex decision-making problems with multiple criteria and alternatives by assigning importance weights and ratings of evaluation criteria (Chen & Klein, 1997; Carlsson & Fuller, 1996).

A FMCDM problem can be defined as follows.

Let $A = \{ A_i$, for $i = 1,2,3,\ldots, m\}$ be a (finite) set of decision alternatives and $G = \{ g_j$, for $j = 1,2,3,\ldots, n\}$ be a (finite) set of goals according to which the desirability of an action is judged. Determine the optimal alternative A^+ with the highest degree of desirability with respect to all relevant goals g_j (Zimmermann, 1991).

A decision problem is said to be complex and difficult where the following conditions apply (Hipel *et al.*, 1993):

1. Multiple criteria exist, which can be both quantitative and qualitative in nature.
2. There may be multiple decision makers.
3. Uncertainty and risk is involved.
4. Decision (input) data may be vague, incomplete or imprecise.

Linguistic term sets used for describing each fundamental parameter are decided according to the situation of the case of interest (Liu *et al.*, 2004). However, some literature (Karwowski & Mital, 1986; Bowles & Pelaez, 1995; Wang, 1997; An *et al.*, 2000) shows that the number of linguistic terms ranging between four and seven labels is commonly acceptable to represent risk factors in engineering risk analysis. In this study five linguistic terms have been used to describe the evaluation criteria.

The methodology has been applied in broad fields that include: the selection of strategic alliances partners for liner shipping (Ding & Liang, 2005); safety assessment (Schinas, 2007); tool steel material selection (Chen, 1997); assessment of climate change (Bell *et al.*, 2003); sustainable fishing development strategies evaluation (Chiou *et al.*, 2005); distribution centre location selection (Chen, 2001) and airline service quality evaluation (Tsaur *et al.*, 2002).

The FMCDM has been applied in this model due to the fact that decision-making process for the selection of ballast water treatment technologies involves a subjective analysis of uncertain and/or incomplete data.

5.2.3 Analytic Hierarchy Process

The AHP has already been described in Sections 2.6.2.2 and 4.2.3.

5.2.4 Fuzzy-TOPSIS

TOPSIS has been described in Section 2.6.2.3. Fuzzy-TOPSIS is a fuzzy extension of TOPSIS to efficiently handle the fuzziness of the data to be applied in the decision-making process. A fuzzy approach to TOPSIS is advantageous because it assigns the relative importance of attributes using fuzzy numbers instead of precise numbers. Linguistic preferences can easily be converted to fuzzy numbers and TOPSIS allows the use of these fuzzy numbers in the calculation. In order to apply fuzzy TOPSIS to a MCDM problem, selection criteria have to be monotonic. Monotonic criteria could be classified either as benefits (B) or costs (C). A criterion can be classified as a benefit if the more desirable the candidate, the higher its score versus this criterion. On the contrary, cost criteria see the most desirable candidate scoring at the lowest. In fuzzy TOPSIS, the cost criteria are defined as the most desirable candidates scoring at the lowest, while the benefit criteria are described as the most desirable candidate scoring at the highest. Other advantages of the Fuzzy-TOPSIS technique include the fact that (Deng *et al*, 2000; Olson, 2004; Bottani & Rizzi, 2006):

1. The logic is rational and understandable.
2. Computation processes are straightforward.
3. The concept permits the pursuit of best alternatives for each criterion depicted in a simple mathematical form.
4. It allows the straight linguistic definition of weights and ratings under each criterion, without the need of cumbersome pairwise comparisons and the risk of inconsistencies.

5. The obtained weights of evaluation criteria are incorporated into the comparison procedures.

Given the stochastic nature of species assemblages, current inadequacy of historical data on non-indigenous invasive species (NIS) origin and dispersal mechanism within the bio-geographical regions of the world, the fuzzy TOPSIS model has been proposed as an alternative technique for use in the analysis of ballast water treatment decision options. While the uncertainty issue is tackled by means of fuzzy logic, the application of TOPSIS makes it possible to appraise the distances of each decision option from the positive ideal solution and the negative ideal solution. Moreover, the way linguistic ratings and weights are given is very straightforward. A Fuzzy-TOPSIS approach has been applied in this study in order to support the evaluation of decision-making criteria and attributes.

The triangular fuzzy numbers are applied in the fuzzy-TOPSIS used in this study. This is because it is intuitively easy for the decision-makers to use and calculate (Dagdeviren *et al.*, 2009). Secondly, modelling using triangular fuzzy numbers has proven to be an effective way for the formulation of the decision problem where the information is subjective and imprecise (Dagdeviren *et al.*, 2009; Chang *et al.*, 2007).

Let $\tilde{A}$ and $\tilde{B}$ be two positive triangular fuzzy numbers denoted by the triplets (a_1, a_2, a_3) and (b_1, b_2, b_3) respectively (Fig. 3). Then the basic fuzzy arithmetical operations on these two fuzzy numbers are defined as (Dubios & Prade, 1980; Kauffman & Gupta, 1991).

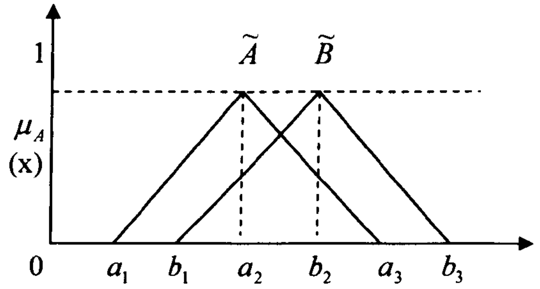
$$\tilde{A}(+)\tilde{B} = (a_1, a_2, a_3)(+)(b_1, b_2, b_3) = (a_1+b_1, a_2+b_2, a_3+b_3) \quad (5.1)$$

$$\tilde{A}(-)\tilde{B} = (a_1, a_2, a_3)(-)(b_1, b_2, b_3) = (a_1-b_3, a_2-b_2, a_3-b_1) \quad (5.2)$$

$$\tilde{A}(\times)\tilde{B} = (a_1, a_2, a_3)(\times)(b_1, b_2, b_3) = (a_1 b_1, a_2 b_2, a_3 b_3) \quad (5.3)$$

$$\tilde{A}(\div)\tilde{B} = (a_1, a_2, a_3)(\div)(b_1, b_2, b_3) = \left(\frac{a_1}{b_3}, \frac{a_2}{b_2}, \frac{a_3}{b_1}\right) \quad (5.4)$$

Fig. 5.1 Membership Function of Two Triangular Fuzzy Numbers



The distance between fuzzy numbers $\tilde{A}$ and $\tilde{B}$ (Fig. 5.1) can be measured using the vertex method (Chen, 2000) and calculated using the following equation.

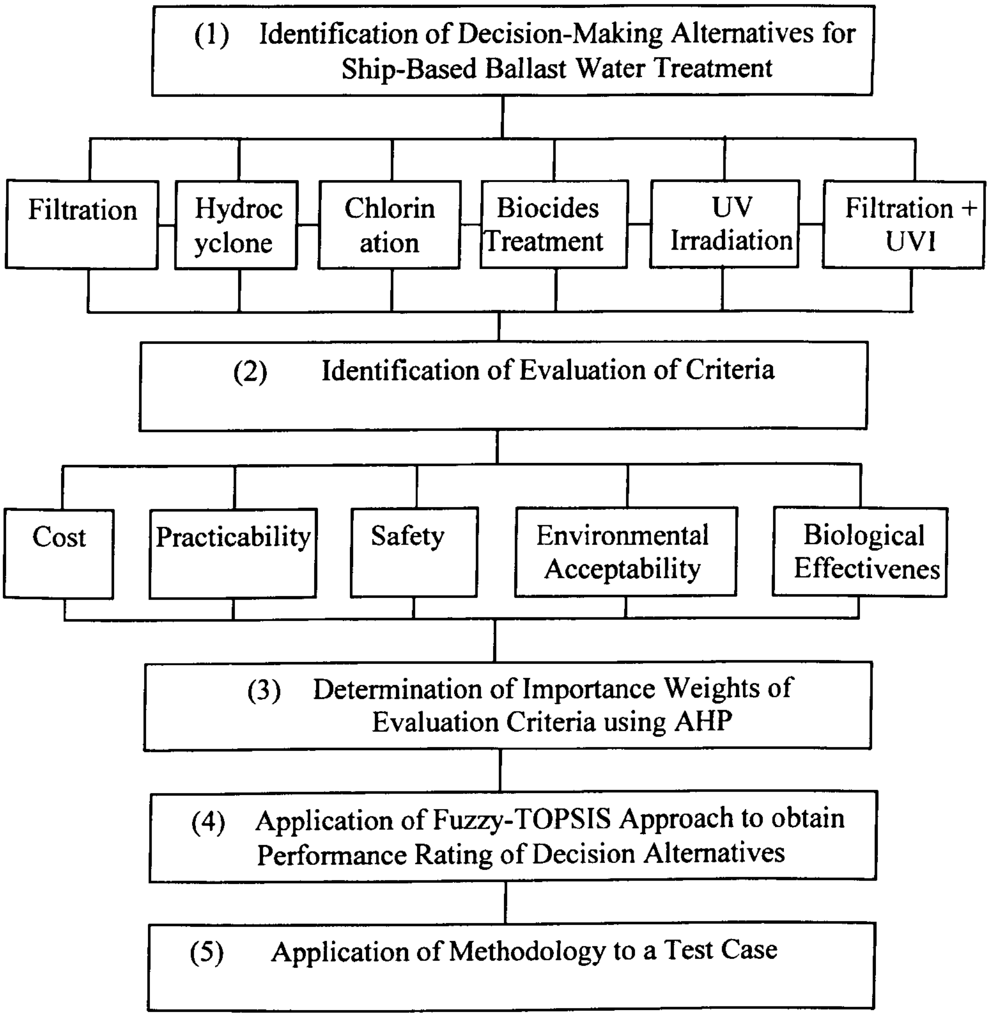
$$d(\tilde{A},\tilde{B}) = \sqrt{\frac{1}{3}\left[(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2\right]} \tag{5.5}$$

While the problem of uncertainty is tackled by means of fuzzy logic, the application of TOPSIS makes it possible to appraise the distances of each decision option from the positive ideal solution and the negative ideal solution. The framework of TOPSIS is incorporated and presented in the following section.

5.3 Methodology

The proposed methodology and hierarchical structure describing the decision-making process of selecting the best ballast water treatment system is graphically illustrated in Fig. 5.2. The first stage is the identification of decision-making alternatives for ship-based ballast water treatment. The decision alternatives and evaluation criteria are literature-based and have been derived from the IMO Ballast Water Convention 2004 and the Lloyds Report 2007 (IMO, 2004; Lloyd's Register, 2007). The evaluation process is conducted by decision analysts based on their subjective knowledge and judgment.

Fig. 5.2 Hierarchical Model of Decision Making Analysis



The second stage in the methodology is the identification of the evaluation criteria for the identified proto-type treatment technologies. In the third stage, the AHP methodology is applied to obtain the importance weights of the evaluation criteria. In the fourth stage fuzzy-TOPSIS is applied to obtain performance ratings of the various decision alternatives. The importance weights obtained through the AHP are incorporated into the fuzzy-TOPSIS analysis to obtain performance ratings of the decision alternatives.

A Microsoft Windows Application (Excel) is used to compute the performance ratings of these alternatives. Results of the decision analysis are ranked in their order of preference by the analysts for a final selection and adaptation by the decision-makers (e.g. Port State Authorities, Ship-Owners, Ship-Managers and Classification Societies) or end-users within the maritime industry.

5.3.1 Identification of Decision-Making Alternatives

Six decision-making alternatives (surface filtration, hydro-cyclones, chlorination, biocides treatment, ultra-violet irradiation, and filtration + ultra-violet irradiation) have been identified and applied in this model. The treatment systems have been selected from the three generic ballast water treatment technologies (physical solid-liquid separation (primary treatment), disinfection (secondary treatment) and hurdle technologies) recommended by the IMO for the global maritime industry (Lloyd's Register, 2007).

5.3.2 Identification of Evaluation Criteria

Five evaluation criteria have been identified for the evaluation of the decision alternatives. The criteria are based on the IMO guidelines for the development of proto-type treatment technologies for on-board ballast water treatment (Globallast, 2001; IMO, 2004). They include:

1. Cost (expense of treatment equipment and operations).
2. Practicability (eases of operating treatment equipment and interference with normal ship operations, as well as impact on the structural integrity of the ship).
3. Safety (of crew, ship and cargo).
4. Environmental Acceptability (not causing more or greater environmental impact than it solves).

5. Biological Effectiveness (efficacy or effectiveness of removing or otherwise rendering inactive harmful non-indigenous invasive species (NIS) in ballast water).

5.3.3 Determination of Importance Weight of Decision Alternatives Using AHP

The next step in the methodology is the determination of importance weights of these alternatives using the AHP approach. The AHP algorithm has already been defined and described in Sections 2.6.2.2 and 4.2.3.

5.3.4 Application of Fuzzy-TOPSIS Approach to Obtain Performance Rating of Decision Alternatives

In this assessment process, all the variables are assumed to be fuzzy variables and represented by triangular fuzzy numbers. The fuzzy sets and membership functions of the Fuzzy-TOPSIS analysis are developed using subjective judgement and experience of the decision analysts. The process is conducted as follows.

5.3.4.1 Construction of Fuzzy Decision Matrix

A decision matrix A is an (m × n) matrix in which element p_{ij} indicates the performance of alternative A_i when it is evaluated in terms of decision criterion C_j, (for i = 1,2,3, ..., m, and j = 1,2,3, ..., n) (Schinas, 2007). From this definition it implies that an MCDM problem with a given decision matrix is in essence a problem for a set of known alternatives and a set of known criteria (Schinas, 2007). The algorithm of this methodology is described as follows:

Given m alternatives, n criteria and s decision analysts, a typical FMCDM problem can be represented using the following matrix (Wang & Chang, 2007; Bottani & Rizzi, 2006).

$$\tilde{R}_k = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{bmatrix} \tilde{r}_{11} & \tilde{r}_{12} & \cdots & \tilde{r}_{1n} \\ \tilde{r}_{21} & \tilde{r}_{22} & \cdots & \tilde{r}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{r}_{m1} & \tilde{r}_{m2} & \cdots & \tilde{r}_{mn} \end{bmatrix} \end{array} \quad i = 1, 2, ..., m; \; j = 1, 2, ..., n \tag{5.6}$$

where, $A_1, A_2, ..., A_m$ represent the decision alternatives; C_1, C_2, ..., C_j represent the evaluation criteria, and $\tilde{r}_{ij}$ is a fuzzy number that represents the rating of the alternative A_i when examined in terms of criterion C_j evaluated by the s^{th} analyst.

In the proposed model the process for the estimation of the values of the ballast water treatment systems will depend on expert knowledge and judgement of the decision analysts, the method of average value is applied to integrate the fuzzy performance score $\tilde{r}_{ij}$ for s decision analysts with regard to the same evaluation criteria, that is:

$$\tilde{r}_{ij} = \frac{1}{s}\left(\tilde{r}_{ij}^{1} + \tilde{r}_{ij}^{2} + \cdots + \tilde{r}_{ij}^{s}\right) \tag{5.7}$$

where $\tilde{r}_{ij}^{s}$ is the rating of alternative A_i with respect to the criterion C_j evaluated by the s^{th} analyst, and $\tilde{r}_{ij}^{s} = \left(a^{s}_{ij}, b^{s}_{ij}, c^{s}_{ij}\right)$.

5.3.4.2 Normalisation of Fuzzy Decision Matrix

The fuzzy data obtained in the decision matrix are normalised in order to eliminate the units of criteria scores, so that numerical comparisons often associated with MCDM problems can be brought to the same universe of discourse. The process involves dividing the score within each criterion by the root-sum-of-squares for all the decision-making criteria. Normalisation has two main aims; for the comparison of heterogeneous criteria and to ensure that all triangular fuzzy numbers range within the interval, 0 and 1 (Wang & Chang, 2007). The normalised fuzzy-decision matrix is conducted using Equations 5.8 – 5.10 as follows:

If $\tilde{R}$ denotes the normalised fuzzy decision matrix, then

$$\tilde{R} = \left[\tilde{r}_{ij}\right]_{m \times n} \; i = 1, 2, \ldots, m; \; j = 1, 2, \ldots, n \tag{5.8}$$

where

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^{+}}, \frac{b_{ij}}{c_j^{+}}, \frac{c_{ij}}{c_j^{+}}\right), j \in B, \tag{5.9}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^{-}}{c_{ij}}, \frac{a_j^{-}}{b_{ij}}, \frac{a_j^{-}}{a_{ij}}\right), \; j \in C, \tag{5.10}$$

$$c_j^{+} = \max_i c_{ij} \qquad j \in B,$$

$$a_j^{-} = \min_i a_{ij} \qquad j \in C.$$

5.3.4.3 Construction of Weighted Normalised Fuzzy Decision Matrix

The weighting factors are a set of percentages that add up to 100%, with the most important alternative receiving the highest weighting factor. The process involves multiplying the importance weights of the alternative by the values in the normalised fuzzy decision matrix. Considering the different importance of each criterion, the weighted normalized fuzzy-decision matrix $\tilde{V}$ is constructed using Equations 5.17 and 5.18 and defined as:

$$\tilde{V} = \left[\tilde{v}_{ij}\right]_{m \times n}, \quad i = 1, 2, \ldots., m; \quad j = 1, 2, \ldots., n \tag{5.11}$$

$$\tilde{v}_{ij} = \tilde{r}_{ij} \times \tilde{w}_j \tag{5.12}$$

where $\tilde{w}_j$ denotes the importance weight of the criterion C_j.

5.3.4.4 Determination of the Fuzzy Positive Ideal Reference Point (FPIRP) and Fuzzy Negative Ideal Reference Point (FNIRP)

The FPIRP is obtained by identifying the best score in a criterion. Similarly, the worst score of a criterion is identified and recorded as the FNIRP. Against the background that all the triangular fuzzy numbers in $\widetilde{V}$ are in the interval (0, 1), the FPIRP (A^+) (the benefit criterion) and FNIRP (A^-) (the cost criterion) are defined as follows:

$$A^+ = \left(v_1^+, v_2^+, \ldots, v_n^+\right), \tag{5.13}$$

$$A^- = \left(v_1^-, v_2^-, \ldots, v_n^-\right) \tag{5.14}$$

where

$$\widetilde{v}_j^+ = (1,1,1) \text{ and} \tag{5.15}$$

$$\widetilde{v}_j^- = (0,0,0)\ ,\ j = 1, 2, \ldots, n \tag{5.16}$$

5.3.4.5 Calculation of Distances of Each Alternative to FPIRP and FNIRP

The distance of each alternative (treatment system) from the FPIRP and FNIRP with respect to each criterion is calculated using the vertex method (Equation 5.5) and calculated as follows.

$$d_i^+ = \sum_{j=1}^{n} d(\widetilde{v}_{ij}, \widetilde{v}_j^+) \quad i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n \tag{5.17}$$

$$d_i^- = \sum_{j=1}^{n} d(\widetilde{v}_{ij}, \widetilde{v}_j^-) \quad i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n \tag{5.18}$$

where $d(\widetilde{v}_{a.} \widetilde{v}_b)$ denotes the distance measurement between two fuzzy numbers, d_i^+ denotes the distance of alternative A_p from FPIRP and d_i^- denoting the distance of alternative A_p from FNIRP.

The calculated d_i^+ and d_i^- values are used to obtain the Closeness Coefficient (CC_i) of each alternative for ranking purposes.

5.3.4.6 Obtain the Closeness Coefficient and Ranking of Alternatives

The ranking of the alternatives is determined after the CC_i is obtained. This allows the decision analyst(s) to choose the most rational and appropriate alternative. The CC_i is calculated using Equation 5.19.

$$CC_i = \frac{d_i^-}{d_i^+ + d_i^-} \qquad i = 1, 2, \ldots., m \tag{5.19}$$

where CC_i is equal to 0 if and only if $d_i^- = 0$ or $A_p = A^-$. $CC_i = 1$ when $d_i^+ = 0$ or $A_p = A^+$. Consequently, the best alternative is the one with the value of CC_i closer to 1.

5.4 Application of Methodology to a Test Scenario

The proposed model will be demonstrated in a decision analysis of selected on-board ballast water treatment technologies. The decision-making alternatives and criteria have been discussed in Section 5.3, while the hierarchical model of this decision-making analysis process is illustrated in Fig. 5.3. For the purpose of this model five experts have been identified to conduct the analysis. The analysts are assigned equal ratings and the analysis will be conducted through brainstorming based on their knowledge and experience. Details on the analysts and their degrees of competency are contained in Table 5.1.

Table 5.1 Selected Experts and Assigned Degree of Competency

S/N	Expertise and Knowledge	Degree of Competency
1	Marine Biologist	0.20
2	Maritime Environmentalist	0.20
3	Shipmaster/Engineer	0.20
4	Port Manager/Harbour Master	0.20
5	Environmental Risk Assessor	0.20

The primary objective of the decision-making analysis is to identify the best, appropriate and acceptable ballast water treatment system to be adopted by an end user. Accordingly, the following process was applied.

5.4.1 Determination of Importance Weights of Decision Alternatives Using AHP

The weight values obtained for the evaluation criteria in Chapter 4 are applied as weight values of the decision alternatives in this chapter. This is to maintain consistency and continuity in the research.

Weight of Cost = 0.068
Weight of Practicability = 0.171
Weight of Safety = 0.392
Weight of Environmental Acceptability = 0.237
Weight of Biological Effectiveness = 0.132

The obtained weight values will be applied in the assessment process to establish the fuzzy performance ratings of the model's evaluation criteria.

5.4.2 Application of Fuzzy-TOPSIS Approach to Obtain Performance Rating of Decision Alternatives

The Fuzzy-TOPSIS process as applied in this model is conducted by the analysts involved in the AHP approach. Thus, the knowledge and judgement of these experts is to be considered. The six decision alternatives and five evaluation criteria (Table 5.2) utilized in the AHP will be used to develop the fuzzy decision matrix.

Table 5.2 Fuzzy-TOPSIS Decision Alternatives and Evaluation Criteria

	Decision Alternatives		Evaluation Criteria
A1	Surface Filtration	C1	Cost
A2	Hydrocyclones	C2	Practicability
A3	Chlorination	C3	Safety
A4	Biocides	C4	Environmental Acceptability
A5	UV Irradiation	C5	Biological Effectiveness
A6	Filtration + UV Irradiation		

5.4.2.1 Construction of a Fuzzy-TOPSIS Decision Matrix

A Fuzzy-TOPSIS decision matrix (Table 5.4) was constructed based on the six decision making alternatives (A1 – A6) and five evaluation criteria (C1 – C5) (Table 5.2). The figures obtained are based on the membership functions of the linguistic variables developed and the scale for the measurement of the evaluation criteria (Table 5.3). The method of average value is thereafter applied to integrate in all the fuzzy performance scores of the different analysts using Equation 5.7.

Table 5.3 Fuzzy-Linguistic Scale for Measuring Performance of Evaluation Criteria

Linguistic Variable	Corresponding Triangular Fuzzy Number
Very Poor	(0, 1, 3)
Poor	(1, 3, 5)
Average	(3, 5, 7)
Good	(5, 7, 9)
Very Good	(7, 9, 10)

Table 5.4 Fuzzy-TOPSIS Decision Matrix

	C1	C2	C3	C4	C5
A1	5,7,9	7,9,10	5,7,9	7,9,10	5,7,9
A2	5,7,9	5,7,9	5,7,9	7,9,10	5,7,9
A3	3,5,7	5,7,9	5,7,9	3,5,7	5,7,9
A4	3,5,7	5,7,9	3,5,7	1,3,5	5,7,9
A5	5,7,9	5,7,9	3,5,7	5,7,9	5,7,9
A6	5,7,9	7,9,10	7,9,10	7,9,10	7,9,10

5.4.2.2 Normalisation of Fuzzy Decision Matrix

The normalized fuzzy decision matrix is constructed using Equations 5.8 – 5.10. The results are described in Table 5.5.

Table 5.5 Fuzzy TOPSIS Normalised Decision Matrix

	C1	C2	C3	C4	C5
A1	0.555, 0.777, 1.000	0.700, 0.900, 1.000	0.500, 0.700, 0.900	0.700, 0.900, 1.000	0.500, 0.700, 0.900
A2	0.555, 0.777, 1.000	0.500, 0.700, 0.900	0.500, 0.700, 0.900	0.700, 0.900, 1.000	0.500, 0.700, 0.900
A3	0.333, 0.555, 0.777	0.500, 0.700, 0.900	0.500, 0.700, 0.900	0.300, 0.500, 0.700	0.500, 0.700, 0.900
A4	0.333, 0.555, 0.777	0.500, 0.700, 0.900	0.300, 0.500, 0.700	0.100, 0.300, 0.500	0.500, 0.700, 0.900
A5	0.555, 0.777, 1.000	0.500, 0.700, 0.900	0.300, 0.500, 0.700	0.500, 0.700, 0.900	0.500, 0.700, 0.900
A6	0.555, 0.777, 1.000	0.700, 0.900, 1.000	0.700, 0.900, 1.000	0.700, 0.900, 1.000	0.700, 0.900, 1.000

5.4.2.3 Construction of Weighted Normalised Fuzzy-Decision Matrix

The weighted normalized decision matrix was constructed by applying Equations 17 and 18. The normalized triangular fuzzy numbers obtained in Table 5.3 are multiplied by the importance weight values of the evaluation criteria. For example, the weighted normalized fuzzy numbers for A3 of C2 were obtained as follows.

$$(0.500, 0.700, 0.900) \times 0.171 = (0.086, 0.120, 0.154)$$

The weighted normalized fuzzy numbers for other decision alternatives were obtained in similar way and contained in Table 5.6.

Table 5.6 Weighted Normalised Decision Matrix of the Six Ballast Water Treatment Systems

	C1	C2	C3	C4	C5
A1	0.037, 0.052, 0.068	0.119, 0.153, 0.171	0.196, 0.274, 0.352	0.165, 0.213, 0.237	0.066, 0.092, 0.118
A2	0.038, 0.053, 0.068	0.120, 0.154, 0.171	0.196, 0.274, 0.353	0.166, 0.213, 0.237	0.066, 0.092, 0.119
A3	0.023, 0.038, 0.053	0.086, 0.120, 0.154	0.196, 0.274, 0.353	0.071, 0.119, 0.166	0.066, 0.092, 0.119
A4	0.023, 0.038, 0.053	0.086, 0.120, 0.154	0.118, 0.196, 0.274	0.024, 0.071, 0.119	0.066, 0.092, 0.119
A5	0.038, 0.053, 0.068	0.086, 0.120, 0.154	0.118, 0.196, 0.274	0.119, 0.166, 0.213	0.066, 0.092, 0.119
A6	0.038, 0.053, 0.068	0.120, 0.154, 0.171	0.274, 0.353, 0.392	0.166, 0.213, 0.237	0.092, 0.119, 0.132

5.4.2.4 Determination of the Fuzzy Positive Ideal Reference Point (FPIRP) and Fuzzy Negative Ideal Reference Point (FNIRP)

The Fuzzy Positive Ideal Reference Point (FPIRP) and Fuzzy Negative Ideal Reference Point (FNIRP) are defined using Equations 5.13 – 5.16 as follows.

$$A^+ = [\ (1,1,1), (1,1,1), (1,1,1), (1,1,1), (1,1,1), (1,1,1)\ ]$$

$$A^- = [\ (0,0,0), (0,0,0), (0,0,0), (0,0,0), (0,0,0), (0,0,0)\ ]$$

5.4.2.5 Calculation of the Distance of each Alternative to the FPIRP and FNIRP

The distance of Alternative A1 to A^+ was calculated using Equations 5.17 and 5.18 as follows.

$$d_1^+ = \sqrt{\frac{1}{3}\left[(0.0378-1)^2 + (0.0529-1)^2 + (0.0680-1)^2\right]}$$

$$+\sqrt{\frac{1}{3}\left[(0.1197-1)^2 + (0.1539-1)^2 + (0.1710-1)^2\right]}$$

$$+\sqrt{\frac{1}{3}\left[(0.1960-1)^2 + (0.2744-1)^2 + (0.3528-1)^2\right]}$$

$$+\sqrt{\frac{1}{3}\left[(0.1659-1)^2 + (0.2133-1)^2 + (0.2370-1)^2\right]}$$

$$+\sqrt{\frac{1}{3}\left[(0.0660-1)^2 + (0.0924-1)^2 + (0.1188-1)^2\right]}$$

$$= 4.231$$

The distance of Alternative A1 to A^- was calculated as follows:

$$d_1^- = \sqrt{\frac{1}{3}\left[(0.0378-0)^2 + (0.0529-0)^2 + (0.0680-0)^2\right]}$$

$$+\sqrt{\frac{1}{3}\left[(0.1197-0)^2 + (0.1539-0)^2 + (0.1710-0)^2\right]}$$

$$+\sqrt{\frac{1}{3}\left[(0.1960-0)^2 + (0.2744-0)^2 + (0.3528-0)^2\right]}$$

$$+\sqrt{\frac{1}{3}\left[(0.1659-0)^2 + (0.2133-0)^2 + (0.2370-0)^2\right]}$$

$$+\sqrt{\frac{1}{3}\left[(0.0660-0)^2 + (0.0924-0)^2 + (0.1188-0)^2\right]}$$

$$= 0.788$$

The distances of the other decision alternatives to the FRIRP and ENIRP were determined in the same way using the Microsoft Excel application and the results are described in Table 5.7.

5.4.2.6 Obtain Closeness Co-efficient and Ranking of Alternatives

The ballast water treatment system with a CC value closest to 1 has the shortest distance from the fuzzy positive ideal reference point and the largest distance from the fuzzy negative ideal reference point. In other words, the treatment system with a larger CC value is more desirable. Equation 5.19 was applied in this process. The calculation of the CC value has been described below using Alternative A1 as an example.

$$d_1^+ = 4.231$$

$$d_1^- = 0.788$$

$$CC_1 = \frac{0.788}{4.231 + 0.788} = 0.157$$

The CC values for Alternatives A2-A6 were calculated in the same way and the results are shown in Table 5.7.

Table 5.7 Results of Fuzzy TOPSIS Analysis

	Decision-Making Attributes	d^+	d^-	Closeness Coefficient Values	Ranking
A1	Surface Filtration	4.231	0.788	0.157	2
A2	Hydrocyclones	4.299	0.724	0.144	3
A3	Chlorination	4.362	0.663	0.132	4
A4	Biocides	4.487	0.545	0.108	6
A5	UV Irradiation	4.377	0.649	0.129	5
A6	Filtration + UV Irradiation	4.142	0.870	0.174	1

5.5 Results and Validation of Model

From the result of the Fuzzy-TOPSIS analysis (Table 5.7) it can be seen that the highest CC value (0.174) is associated with Alternative A6 (Filtration + UV Irradiation). The lowest CC value (0.108) is associated with Alternative A4 (Biocides). The result also shows that Alternative A2 is ranked third with a CC value of 0.144. Alternative A3 is ranked fourth having returned a CC value of 0.132, while Alternative A5 is placed fifth in the ranking with a CC value of 0.129. The result also shows that the CC values of the six decision alternatives are marginally separated. This suggests the degree of reasonableness and relative closeness of the systems for the treatment of ships' ballast water. Based on the output values obtained in this analysis, the ranking (in order of preference) of the six decision alternatives in descending order is: A6 > A1 > A2 > A3 > A5 > A4.

In order to validate and test the robustness of this model, a sensitivity analysis is conducted. The analysis is necessary in order to test the suitability and sensitivity of the model for decision analysis of prototype ballast water treatment technologies (as decision alternatives). The analysis will be conducted under eight conditions as tabulated in Table 5.8.

Table 5.8 Conditions for Changing Output Values by Percentages

Condition	Percentage
1	Increase d^+ by 5%
2	Increase d^- by 5%
3	Decrease d^+ by 5%
4	Decrease d^- by 5%
5	Increase d^+ by 20%
6	Increase d^- by 20%
7	Decrease d^+ by 20%
8	Decrease d^- by 20%

The first step in the sensitivity analysis process involves an increment of the main values of the positive and negative reference points (d^+ and d^-) of each decision alternative by 5% and 20%. The next step is to decrease the same values separately by 5% and 20%.

Table 5.9 Result of Sensitivity Analysis (by Changing Output Values by Percentages)

		A1			A2			A3		
Condition		d^+	d^-	CC_i	d^+	d^-	CC_i	d^+	d^-	CC_i
Main		4.231	0.788	0.157	4.299	0.724	0.144	4.362	0.663	0.132
1	Increase d^+ by 5%	4.442	0.788	0.151	4.514	0.724	0.138	4.580	0.663	0.126
2	Increase d^- by 5%	4.231	0.827	0.164	4.299	0.688	0.138	4.362	0.696	0.138
3	Decrease d^+ by 5%	4.019	0.788	0.164	4.084	0.724	0.151	4.144	0.663	0.138
4	Decrease d^- by 5%	4.231	0.749	0.150	4.299	0.688	0.138	4.362	0.630	0.126
5	Increase d^+ by 20%	5.077	0.788	0.134	4.444	0.724	0.140	5.234	0.663	0.112
6	Increase d^- by 20%	4.231	0.946	0.183	4.299	0.869	0.144	4.362	0.796	0.154
7	Decrease d^+ by 20%	3.385	0.788	0.189	3.439	0.724	0.174	3.490	0.663	0.160
8	Decrease d^- by 20%	4.231	0.630	0.130	4.299	0.579	0.119	4.362	0.530	0.108

		A4			A5			A6		
Main		4.487	0.545	0.108	4.377	0.649	129	4.142	0.870	0.174
1	Increase d^+ by 5%	4.711	0.545	0.104	4.596	0.649	0.124	4.349	0.870	0.167
2	Increase d^- by 5%	4.487	0.572	0.113	4.377	0.681	0.135	4.142	0.914	0.181
3	Decrease d^+ by 5%	4.263	0.545	113	4.158	0.649	0.135	3.935	0.870	0.181
4	Decrease d^- by 5%	4.487	0.518	0.103	4.377	0.617	0.124	4.142	0.827	0.166
5	Increase d^+ by 20%	5.384	0.545	0.092	5.252	0.649	0.110	4.970	0.870	0.149
6	Increase d^- by 20%	4.487	0.654	0.127	4.377	0.779	0.151	4.142	1.044	0.201
7	Decrease d^+ by 20%	3.599	0.545	0.132	3.502	0.649	0.156	3.314	0.870	0.208
8	Decrease d^- by 20%	4.487	0.436	0.089	4.377	0.519	0.106	4.142	0.696	0.140

From the results of the sensitivity analysis (Table 5.9), it can be seen that the ranking order of the six decision alternatives maintained a consistency when the d^+ and d^- of each alternative were increased by 5% and 20%. Such a ranking order also maintained a consistency when the d^+ and d^- of each alternative were decreased by 5% and 20%. The result also shows that the Closeness Coefficient values of Alternatives A1 – A6 consistently increased in Conditions 1, 2, 5 and 6. The Closeness Coefficient values of Alternatives A1 – A6 consistently decreased in Conditions 3, 4, 7 and 8. This pattern in the results is to be expected. It can therefore be deduced that the model is reasonable and capable of being applied in the analysis of ballast water decision-making alternatives.

5.6 Conclusion

This model was developed taking into consideration the legislative requirements of Regulation D2 – D4 of the IMO Ballast Water Convention 2007 as well as the positive contributions of the scientific and technological communities in developing prototype ballast water treatment systems. It is pertinent to state that the inadequacy of data and/or stochastic nature of species assemblages within the global bio-geographical regions pose a great threat to the attainment of the IMO Standards and the utilization of any developed treatment systems for the management of NIS. It therefore remains uncertain that a chosen treatment system would be safe, practicable, cost effective, environmentally acceptable or biologically effective in minimizing the survivability of ballast tank based NIS. This uncertainty can result in the selection of an inappropriate treatment system for the wrong ship type and/or wrong voyage route, thus resulting in severe environmental and/or financial consequences. Powerful MCDM methodologies (AHP and TOPSIS) were applied in this generic model to solve inherent decision-making problems that could be encountered during the selection process of a ballast water treatment technology under a fuzzy environment. These methodologies have been applied in different specialized fields as stated earlier and found to be effective. The model developed in this study is by no means conclusive. It is subject to further modification given the acquisition of new data or before its utilization by end-users in the industry. A sensitivity analysis was conducted to partially validate the developed model and establish its ability to respond to changes in input variables.

Chapter Six

Discussion

6.1 Integration and Verification of Research

The background to this research is the identification of bio-environmental pollution problems arising from the discharge of NIS through ships' ballast water and hulls into recipient port/coastal states. The impact of this pollution on human health, social lives of maritime communities, economy of recipient port states, marine installations and the marine environments of affected recipient ports has in some cases resulted in significant negative financial, social and environmental consequences in those countries. This situation is evident in the Great Lakes where Zebra Mussels (believed to have been tranlocated through ships' ballast water) have resulted in environmental, social and financial consequences. Tackling these problems at micro or macro levels has not been easy either. The inadequacy of data and uncertainties surrounding the stochastic nature of species assemblages within the global bio-geographical regions pose a great threat to achieving any meaningful success of minimizing the translocation of these unwanted guests. In this regard, the IMO Globallast programme initiated demonstration sites for the conduct of trial BWRA methodologies in Sepetiba (Brazil), Dalian (China), Mumbai (India), Kharg Island (Iran) Odessa (Ukraine) and Saldanha (South Africa). Similarly, 26 ballast water management treatment systems have currently been approved by the IMO for on-board ballast water treatment operations. Despite its limitations ballast water exchange at sea (either flow-through or sequential treatment) is the current recommended ballast water management option recommended by the IMO and INTERTANKO. The need for an acceptable international standard for available ballast water management plan continues. It is the continuous search for solutions to this maritime environmental problem that generated the interest in this research. Two fundamental questions were posed at the beginning of the research, namely:

i. Can the application of safety principles of the formal safety assessment (FSA) framework to ballast water safety management minimize and control the translocation of NIS through ships' ballast water and hulls to recipient ports/coastal states?

ii. Can the application of fuzzy logic and possibilistic theories in decision-making analysis of ballast water exchange options address the decision-making problems associated with the selection of appropriate ballast water treatment systems by an end-user?

These questions are intricately linked to the research aims and objectives, namely, to develop novel subjective risk management models (based on the safety principles of the FSA framework) capable of addressing the problems associated with discharged NIS in recipient ports/coastal states through ships' ballast water, and to address decision making problems that could arise during the evaluation of ballast water safety management decision attributes. The objective of this research was to minimise risks associated with discharged ballast water (either at the ballast upload stage or at different stages of the ballast water voyage and subsequent discharge in recipient ports/coastal states) to ALARP levels.

Although this research recognises the previously developed ballast water risk management methodologies as discussed in Sections 2.5.1, 3.2.5 and 3.2.6, it should be observed that relatively little was done in the aforementioned methodologies to address the problems of uncertainty and inadequacy of historical data in relation to ballast water management as a subject of research. This research also recognised previous BWRA methods that have applied FSA principles in their methodologies. However, it has to be emphasised that these methodologies were based either on assessment end-points or environmental matching similarities (within similar zoogeographical regions) tailor-made to address targeted species at either donor or recipient ports/regions. In most cases the methodologies applied quantitative risk management approaches.

In this theoretical treatise, three generic models were developed using a possibilistic approach and the safety principles of the FSA framework to address the problem of uncertainty and inadequacy of historical data in ballast water safety management. These methodologies are contained in Chapters Three, Four and Five. The developed models recognised inherent uncertainties and inadequacy of historical data required to undertake objective ballast water hazard assessment and decision-making analyses. Consequently, subjective/qualitative safety management approaches were applied in the models. The sensitivity analyses conducted on all the developed models proved that they are reasonable and sensitive to changes in input. This implied that the models are capable of absorbing new data at any stage of its application.

A review of relevant literature related to the subject of research was conducted in Chapter Two of this thesis. The chapter highlighted the need for the utilisation of rational and systematic processes (e.g. FSA) for proactive management of safety in maritime operations. The successful application of the FSA safety principles in maritime operations as well as the marine and offshore safety management processes precipitated the need for its application in ballast water management. In this regard, and to adequately appreciate the subject of research a review of ballast water operations and its resultant position as the primary vector for the translocation of NIS across zoogeographical regions of the world was conducted in this chapter. Current international legislative instruments for the development and implementation of ballast water exchange plans and treatment technologies in IMO member states were considered in this chapter. The different exchange plans and prototype treatment systems were also reviewed in the chapter. However, specific treatment systems were selected to represent evaluation criteria and decision alternatives in the developed decision-making models of this research. The contents of major research publications and international conference proceedings on ballast water management and legislations were relevant to the understanding of the impact of the problems as well as providing a preview for the development of three generic and novel models in this research. The three models (presented in Chapters Three, Four and Five of this thesis) reflect the hazard identification, risk estimation and decision-making stages of the safety principles of the FSA process.

A novel subjective hazard identification model, "Fuzzy-Infection Mode and Effect Analysis (*FUZIMEA*)" was developed and presented in Chapter Three. The model incorporates fuzzy sets theory, fuzzy rule-base and IMEA techniques to evaluate bio-environmental hazards associated with the infection modes of a generic ship. The model was developed to deal with the problems of uncertainty and inadequacy of data often associated with the identification of ballast water vector hazards and infection modes management. Information for the conduct of this analysis was gathered by experts and integrated in a formal way to reflect a subjective method of risk ranking. The experts involved in the process were carefully selected based on their knowledge and experience in order to eliminate any biases that may arise during the assessment process. The framework for modelling the technique was based on the identification of on-board infection components that outlined the necessary procedure required for safety evaluations. FST was applied because the risk factors inherent in ballast water pollution are often incomplete and sometimes ill-defined for which traditional quantitative risk assessment approaches do not give adequate answers/solutions. IMEA was utilised in order to identify hazards associated with the infection modes of the generic ship. The developed FRB (Appendix 4) was utilised in the hazard estimation process to determine the risk levels of the identified infection modes. A defuzzification process was thereafter conducted to obtain single crisp values and ranking for the priority for attention. The defuzzified values represent the risk levels of the infection components, and therefore determine the priority level of attention to be assigned to the infected components. Through this process the main risk contributors and their potential adverse impact (risk levels) on recipient ports/regions are identified and ranked. Consequently, the model did not require the use of a utility function to define the probability of occurrence, severity and detectability considered for similar analyses that would have otherwise applied traditional RPNs. The result of the risk ranking was presented in Section 3.4.6 and illustrated in Table 3.8. From the obtained results, it can be seen that Scenarios 1, 3, 9 and 10 returned the highest risk ranking (6.701) and therefore assigned the highest level of priority of attention, represented by the "High" membership function in Fig. 3.8. Table 3.8 also indicated that the least level of priority for attention was associated with Scenario 6. The outcome of the hazard identification process can be utilised as a standalone result or constitutes the first step in the ballast water risk assessment process. The result is also expected to provide information for decisions makers in terms of management strategy and resource allocation. However, the application of this model may not be limited to ballast water risk management alone, but capable of being applied in the hazard screening of components associated with bio-environmental pollution.

The assessment and selection of any ballast water management plan should be determined by the fact that such a plan should reduce the risk of NIS translocation and establishment in recipient ports/coastal states to the As-Low-As-Reasonably-Practicable (ALARP) level. The selection process is complex and intractable due to inherent trade-offs between socio-political, ecological and economic factors that prevail among port states and/or regional blocks. This is even made harder considering the uncertainty and inadequacy of historical data. Another constraint is the fact that the selection process would require compliance to stochastically related IMO guidelines that include safety, cost effectiveness, operational practicability, environmental acceptability and biological effectiveness while developing any ballast water treatment system (IMO, 2007). The guidelines were utilised as decision-making options/evaluation criteria in this research.

Chapter Four addressed the problems associated with the identification of an appropriate ballast water exchange plan from a holistic point of view. A novel model that incorporated powerful MCDM theories was developed to evaluate the identified variables in the analysis. The ER and AHP methodologies were applied in this model due to the prevalence of multi-criteria problems which had to be evaluated using subjective reasoning. These methodologies have been successfully applied (either singularly or as integrated approaches) in different fields to solve complex multi-criteria problems of qualitative and quantitative nature under uncertainty. In this model, the weight and relative importance of each evaluation criteria was acquired using the pairwise comparison method of the AHP theory. The results of the pairwise comparison showed that the highest priority level was associated with the "Safety" criterion having attained the highest weight value (0.392). The criterion with the lowest weight value (0.068) was "Cost". The details of the result are contained in Table 5.7. The obtained weights were subsequently used to propagate the lower level criteria assessment to their respective upper levels. Through the transformation (mapping) process, the lower level criteria (fuzzy inputs) were converted to their upper level criteria (fuzzy outputs) by aggregating the fuzzy inputs values and probability values. A two-level mapping process was applied in the model because it enabled the decision analysts to easily convert lower level criteria to upper level criteria as well as obtaining quantitative data to be applied for each level during the decision analysis. This process was discussed in Sections 4.3.3 to 4.3.4. The output values of the decision options were thereafter synthesised using powerful computer-based user-friendly Windows software (IDS) package that incorporates the ER algorithm (Section 4.4.3) and facilitates information collection, processing and display. Results obtained through the IDS assessment process usually provide unequivocal output at every stage of the assessment process. The weight values obtained in this chapter were applied as the values for the decision alternatives of the model developed and presented in Chapter Five.

A hybrid model capable of dealing with MCDM problems associated with the selection of a ballast water treatment technology under a group decision framework was developed in Chapter Five. Two powerful safety management methodologies (AHP and TOPSIS) and the fuzzy sets theory were utilised in the development of this model. While the AHP technique was utilised for the determination of the importance weights of evaluation criteria, the fuzzy-TOPSIS technique was utilised to obtain the performance ratings of the decision-making alternatives. For the purpose of consistency and continuity in this research, the evaluation criteria and their associated importance weight values obtained in Chapter Four were utilised in the decision-making analysis of the model developed in Chapter Five.

TOPSIS has successfully been applied as a decision-making analysis methodology in diverse fields of knowledge (Section 5.2.4). The technique is based on the premise that a chosen alternative should have the shortest distance from the positive ideal reference point (PIRP) and the farthest distance from the negative ideal reference point (NIRP). A fuzzy-TOPSIS approach is meant to efficiently handle the fuzziness of data utilised in the decision-making process. The fuzzy sets and membership functions for the fuzzy-TOPSIS analysis were developed based on the subjective judgment and expertise of the decision analysts. The process for this analysis is contained in Sections 5.3.4.1 to 5.3.4.6. The fuzzy-TOPSIS technique was applied as a subjective methodology to support the evaluation of numerous ballast water treatment technologies. Five principles laid down by the IMO for the development of any ballast water treatment technology were applied in this model as evaluation criteria for the analysis of the decision alternatives. The principles included: Cost, Practicability, Safety, Environmental Acceptability and Biological Effectiveness (Section 5.3.1). Similarly, six ballast water treatment technologies were selected from the three generic ballast water treatment options (physical solid liquid separation, disinfection and hurdle technology) to represent the decision making alternatives applied in the evaluation process of this hybrid model. They included: surface filtration; hydro-clones; chlorination; biocide treatment; ultra-violet irradiation (UVI) and a combined filtration + UVI treatment systems (Section 5.3.2).

6.2 Contribution of Research to Knowledge

This research has been inspired by obvious shortcomings in existing ballast water risk management methodologies. To be precise, these methodologies were unable to address uncertainty and inadequacy of historical data inherent in ballast water risk management. For example, to defensibly detect and enumerate viable or live organisms in an unknown assemblage across the taxonomic spectrum found in port waters globally is a herculean analytical undertaking that would require both quantitative and qualitative assessment process. Furthermore, there is inability to explore and apply subjective/qualitative decision-making methodologies for the evaluation of decision attributes and priority levels of attention. This research has been able to develop novel methodologies capable of addressing some of the problems mentioned above. The concept of ballast water safety management has also been introduced in this research as a way of identifying ballast water pollution as a maritime and ecological problem that requires a holistic risk management approach that can be addressed using powerful engineering safety analysis methodologies and possibilistic theories.

The subjective approach adopted in this research makes it suitable to be incorporated into a BWM plan of port states that lack sufficient scientific and quantitative data on which to develop a more robust BWM plan. Hence, this research is capable of being utilized by port states within developing economies in the absence of a robust arrangement.

6.3 Limitations of Research

In order to fully validate a research outcome, a benchmark based on previous research findings is often utilised and then a comparison between the two is conducted. However, the methodologies developed in Chapters Three, Four and Five are novel and devoid of this benchmark. As observed in Chapter Two (Section 2.5.1) the non-availability of relevant data from the industry on which to base empirical techniques posed a major difficulty in applying quantitative risk assessment methodologies to ballast water risk assessment. For example, the refusal by developers of prototype ballast water treatment technologies to disclose the product and running cost of developed treatment systems made any quantitative approach to the study difficult. Research in ballast water risk management has been very limited, and where it has been conducted the target is often defined – to address specific ecological problems arising from the discharge of ballast water and NIS into specific port state of region. There was therefore huge reliance on reports of international research groups and consultants in the sector. The implication of this approach is the likelihood of taking on board the biases of these researchers and consultants.

Against the background that the framework for the hazard estimation and decision management proposed in these models involved the use of expert judgement and knowledge to conduct the decision-making analyses, the knowledge and opinions of these experts are crucial in the development and application of the framework of these models in the industry. In this regard, care must be taken in the selection of these experts to limit the choice to personnel who are knowledgeable in these fields rather than occupants of offices who would have been there based on political expediency and linkages. In other words, if the experts engaged in the exercise do not have sufficient knowledge with regard to the subject matter under consideration, the value of the framework in this research will not be achieved.

6.4 Future work

Although sensitivity analyses were conducted for each of the three models developed in this thesis, it has to be observed here that there is need for future work on these models in order to achieve maximum validation or to facilitate their application by end-users in the industry.

Against the background that inadequacy of historical data affected the application of a quantitative approach to the evaluation of some evaluation criteria in this research (e.g. the cost of development and production of most prototype treatment technologies), it is expected that the availability of information in the future should pave the way for further work on the subject or a more robust approach to be applied to the field of research. Similarly, future work on this research would evaluate the impact of multiple experts in the assessment process and subsequent outcome of the research.

Finally, it should be observed that subject to further modifications, the developed models in this research are capable of being utilized as stand-alone hazard identification and decision analysis techniques, or applied as a ballast water safety management process in the industry. The models are particularly relevant for port states of oil producing countries within the global developing economies that lack historical data on resident species types as well as lacking in scientific, technological and human resources for the management of bio-environmental problems associated with discharged NIS. Examples of these countries in West Africa include Nigeria, Cameroon, Angola and Equatorial Guinea.

Chapter Seven

Conclusion

This research study has been able to establish that despite the scientifically-based quantitative approaches to ballast water risk management the methods are not capable of addressing uncertainty and inadequacy of historical data on species establishment and dispersal mechanism.

Arising from the above-mentioned, it is concluded in this thesis that:

- Subjective/qualitative assessment methods be utilised in the analysis and evaluation decision criteria and attributes in ballast water safety management. This is particularly necessary for port states and coastal regions in developing countries that lack historical database for species assemblages as well as the impact of NIS establishment within their Exclusive Economic Zones (EEZ). Oil producing countries in the developing economies like Nigeria and Angola are host to millions of gallons of ballast water and myriad of invasive species and pathogens without adequate manpower and technological resources to monitor the entire process. It should also be observed that not much is being done in these states to conduct scoping studies of their port waters to identify either host or invasive species.

- The qualitative models developed in this research be modified and utilised in the industry (especially within the developing countries) either individually or holistically for ballast water risk assessment processes and addressing decision-making problems while efforts are being made to develop and incorporate qualitative approaches into robust scientifically established ballast water risk management methodologies.

- Given the extent of the bio-environmental damage caused by established invasive species in maritime communities and the likely impact on natural species located within the marine protected areas (MPAs), IMO ballast water management programme at global, regional and/or national levels be tied to sustainable development and accorded similar global attention as enjoyed by other programmes like global warming.

- Ballast water bio-environmental pollution be treated as a human induced problem which should be addressed using ecosystem approaches in order to achieve sustainable use of "ecosystem goods and services" and the maintenance of ecosystem integrity. The aim of the ecosystem approach would be to ensure that fisheries and environmental protection, conservation and management measures are consistent with maintaining the characteristics, structure and functioning, productivity and biological diversity of ecosystems, and a higher level of protection of species and their habitat.

- Developing countries be assisted and encouraged to domesticate IMO and other internationally acceptable ballast water management regulations and legislations to minimise and control the establishment of NIS in their seaports and marine environments.

- Activities of the IMO Globallast Programme be packaged and taught in Schools (at different levels) for grassroots education on the dangers of bio-environmental pollution from discharged ships' ballast water.

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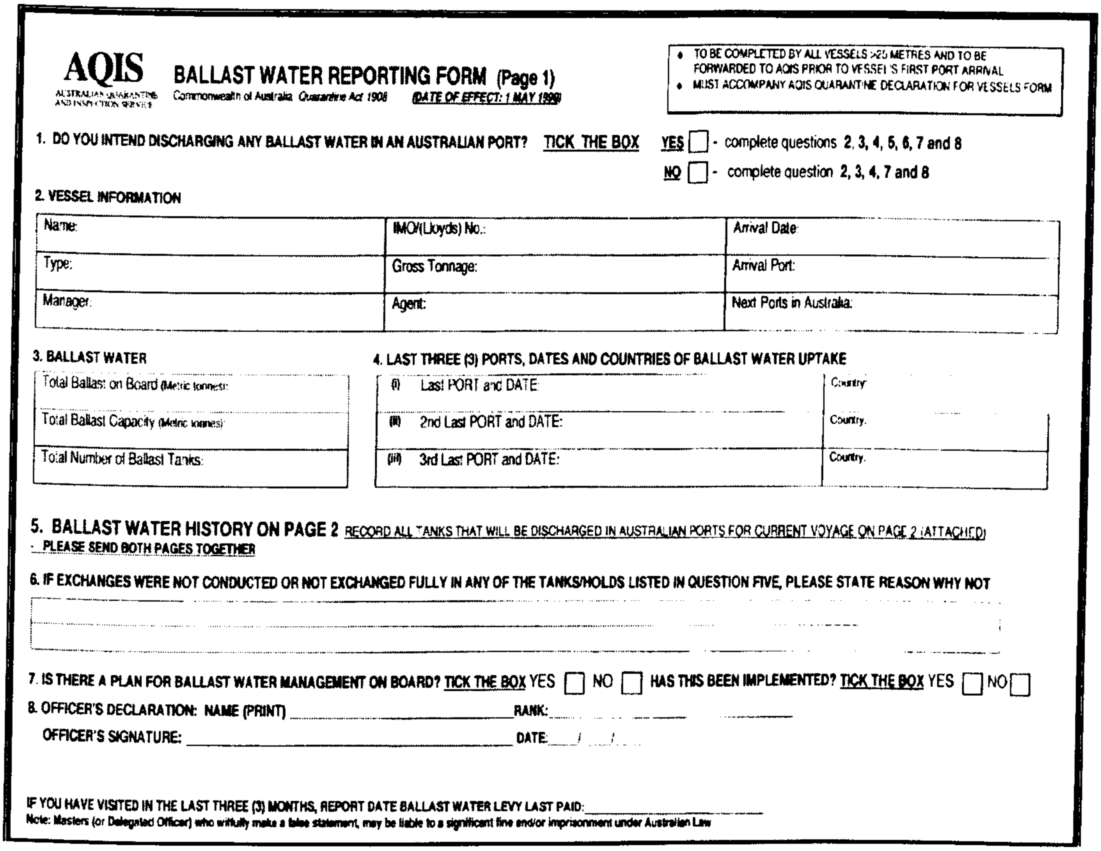
Appendices

Appendix 1(a)

Sample of IMO Ballast Water Reporting Form

(Source: Model Ballast Water Management Plan, ICS & INTERTANKO, 1997)



AQIS
AUSTRALIAN QUARANTINE AND INSPECTION SERVICE

BALLAST WATER REPORTING FORM (Page 1)
Commonwealth of Australia *Quarantine Act 1908* ***DATE OF EFFECT: 1 MAY 1999***

- TO BE COMPLETED BY ALL VESSELS >25 METRES AND TO BE FORWARDED TO AQIS PRIOR TO VESSEL'S FIRST PORT ARRIVAL
- MUST ACCOMPANY AQIS QUARANTINE DECLARATION FOR VESSELS FORM

1. DO YOU INTEND DISCHARGING ANY BALLAST WATER IN AN AUSTRALIAN PORT? TICK THE BOX **YES** ☐ - complete questions **2, 3, 4, 5, 6, 7 and 8**
NO ☐ - complete question **2, 3, 4, 7 and 8**

2. VESSEL INFORMATION

Name:	IMO/(Lloyds) No.:	Arrival Date:
Type:	Gross Tonnage:	Arrival Port:
Manager:	Agent:	Next Ports in Australia:

3. BALLAST WATER

Total Ballast on Board (Metric tonnes):
Total Ballast Capacity (Metric tonnes):
Total Number of Ballast Tanks:

4. LAST THREE (3) PORTS, DATES AND COUNTRIES OF BALLAST WATER UPTAKE

(i)	Last PORT and DATE:	Country:
(ii)	2nd Last PORT and DATE:	Country:
(iii)	3rd Last PORT and DATE:	Country:

5. BALLAST WATER HISTORY ON PAGE 2 RECORD ALL TANKS THAT WILL BE DISCHARGED IN AUSTRALIAN PORTS FOR CURRENT VOYAGE ON PAGE 2 (ATTACHED) - **PLEASE SEND BOTH PAGES TOGETHER**

6. IF EXCHANGES WERE NOT CONDUCTED OR NOT EXCHANGED FULLY IN ANY OF THE TANKS/HOLDS LISTED IN QUESTION FIVE, PLEASE STATE REASON WHY NOT

7. IS THERE A PLAN FOR BALLAST WATER MANAGEMENT ON BOARD? TICK THE BOX YES ☐ NO ☐ **HAS THIS BEEN IMPLEMENTED? TICK THE BOX** YES ☐ NO ☐

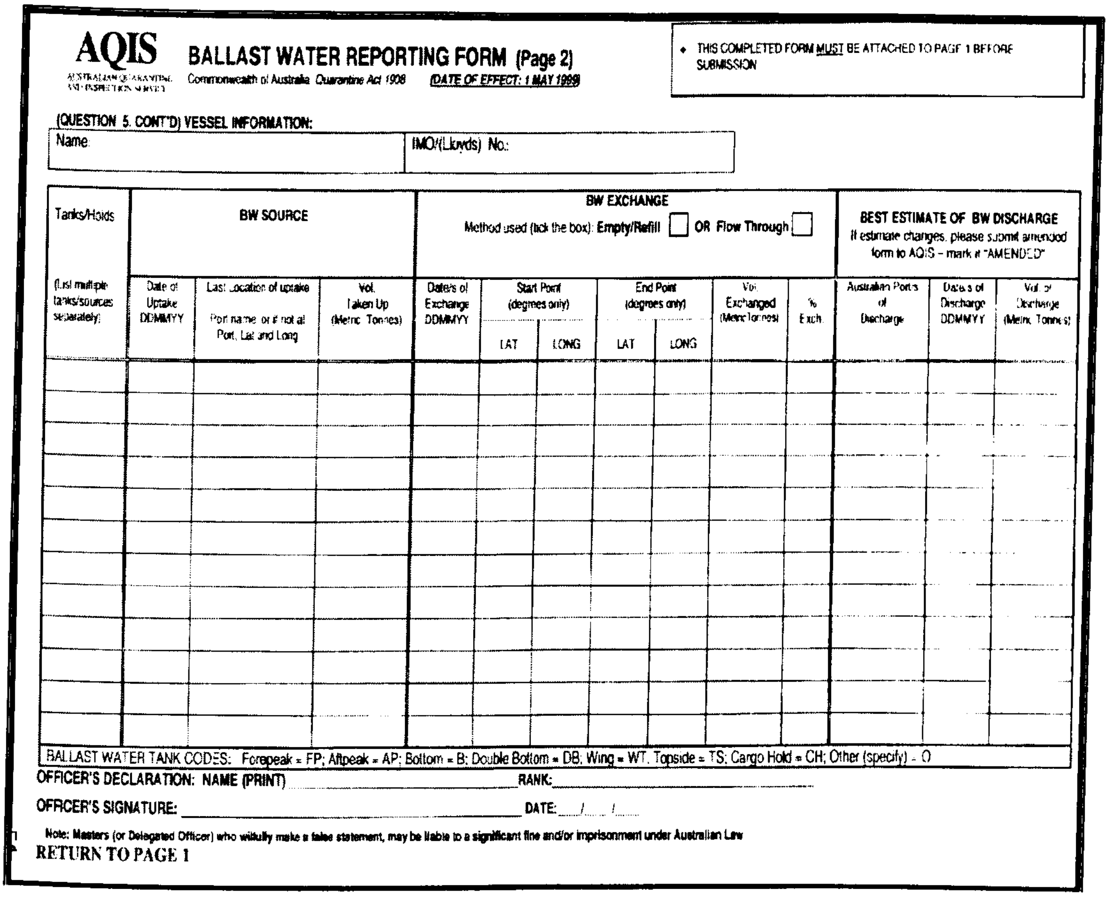
8. OFFICER'S DECLARATION: NAME (PRINT) ____________ **RANK:** ____________

OFFICER'S SIGNATURE: ____________ **DATE:** ___/___/___

IF YOU HAVE VISITED IN THE LAST THREE (3) MONTHS, REPORT DATE BALLAST WATER LEVY LAST PAID: ____________

Note: Masters (or Delegated Officer) who wilfully make a false statement, may be liable to a significant fine and/or imprisonment under Australian Law

Appendix 1(b)



AQIS AUSTRALIAN QUARANTINE AND INSPECTION SERVICE

BALLAST WATER REPORTING FORM (Page 2)

Commonwealth of Australia *Quarantine Act 1908* ***DATE OF EFFECT: 1 MAY 1999***

- THIS COMPLETED FORM MUST BE ATTACHED TO PAGE 1 BEFORE SUBMISSION

(QUESTION 5. CONT'D) VESSEL INFORMATION:

Name:

IMO/(Lloyds) No.:

Tanks/Holds	BW SOURCE			BW EXCHANGE Method used (tick the box): **Empty/Refill** ☐ OR **Flow Through** ☐							BEST ESTIMATE OF BW DISCHARGE If estimate changes, please submit amended form to AQIS – mark it "AMENDED"		
(List multiple tanks/sources separately)	Date of Uptake DDMMYY	Last Location of uptake Port name or if not at Port, Lat and Long	Vol. Taken Up (Metric Tonnes)	Date/s of Exchange DDMMYY	Start Point (degrees only)		End Point (degrees only)		Vol. Exchanged (Metric Tonnes)	% Exch.	Australian Ports of Discharge	Dates of Discharge DDMMYY	Vol. of Discharge (Metric Tonnes)
					LAT	LONG	LAT	LONG					

BALLAST WATER TANK CODES: Forepeak = FP; Aftpeak = AP; Bottom = B; Double Bottom = DB; Wing = WT; Topside = TS; Cargo Hold = CH; Other (specify) = O

OFFICER'S DECLARATION: NAME (PRINT) ______________ **RANK:** ______________

OFFICER'S SIGNATURE: ______________ **DATE:** ___/___/___

Note: Masters (or Delegated Officer) who wilfully make a false statement, may be liable to a significant fine and/or imprisonment under Australian Law

RETURN TO PAGE 1

Appendix 2

Table Showing Some Examples of Aquatic Bio-invasions that have been Recorded Causing Major Impact around the World (Source: IMO Website, 2006).

Name	Native to	Introduced to	Impact
Cholera *Vibrio cholerae* (various strains)	Various strains with broad ranges	South America, Gulf of Mexico and other areas	Some cholera epidemics appear to be directly associated with ballast water
Cladoceran Water Flea *Cercopagis pengoi*	Black and Caspian Seas	Baltic Sea	Reproduces to form very large populations that dominate the zooplankton community and clog fishing nets and trawls, with associated economic impacts
Mitten Crab *Eiocheir sinensis*	Northern Asia	Western Europe, Baltic Sea and West Coast North America	Undergoes mass migrations for reproductive purposes. Burrows into river banks and dykes causing erosion and siltation. Preys on native fish and invertebrate species, causing local extinctions during population outbreaks. Interferes with fishing activities
Toxic Algae(Red/Brown/ Green Tides) Various species	Various species with broad ranges	Several species have been transferred to new areas in ships' ballast water	May form Harmful Algae Blooms. Depending on the species, can cause massive kills of marine life through oxygen depletion, release of toxins and/or mucus. Can foul beaches and impact on tourism and recreation. Some species may contaminate filter-feeding shellfish and cause fisheries to be closed. Consumption of contaminated shellfish by humans may cause severe illness and death
Round Goby *Neogobius melanostomus*	Black, Asov and Caspian Seas	Baltic Sea and North America	Highly adaptable and invasive. Increases in numbers and spreads quickly. Competes for food and habitat with native fishes including commercially important species, and preys on their

			eggs and young. Spawns multiple times per season and survives in poor water quality
North American Comb Jelly *Mnemiopsis leidyi*	Eastern Seaboard of the Americas	Black, Azov and Caspian Seas	Reproduces rapidly (self fertilising hermaphrodite) under favourable conditions. Feeds excessively on zooplankton. Depletes zooplankton stocks; altering food web and ecosystem function. Contributed significantly to collapse of Black and Asov Sea fisheries in 1990s, with massive economic and social impact. Now threatens similar impact in Caspian Sea.
North Pacific Seastar *Asterias amurensis*	Northern Pacific	Southern Australia	Reproduces in large numbers, reaching 'plague' proportions rapidly in invaded environments. Feeds on shellfish, including commercially valuable scallop, oyster and clam species
Zebra Mussel *Dreissena polymorpha*	Eastern Europe (Black Sea)	Introduced to: Western and northern Europe, including Ireland and Baltic Sea; eastern half of North America	Fouls all available hard surfaces in mass numbers. Displaces native aquatic life. Alters habitat, ecosystem and food web. Causes severe fouling problems on infrastructure and vessels. Blocks water intake pipes, sluices and irrigation ditches. Economic costs to USA alone of around US$750 million to $1 billion between 1989 and 2000
Asian Kelp *Undaria pinnatifida*	Northern Asia	Southern Australia, New Zealand, West Coast of the United States, Europe and Argentina	Grows and spreads rapidly, both vegetatively and through dispersal of spores. Displaces native algae and marine life. Alters habitat, ecosystem and food web. May affect commercial shellfish stocks

			through space competition and alteration of habitat
European Green Crab *Carcinus maenus*	European Atlantic Coast	Southern Australia, South Africa, the United States and Japan	Highly adaptable and invasive. Resistant to predation due to hard shell. Competes with and displaces native crabs and becomes a dominant species in invaded areas. Consumes and depletes wide range of prey species. Alters inter-tidal rocky shore ecosystem

Appendix 3

List of IMO Approved Ballast Water Management Systems

(Source: www.imo.org/html)

ANNEX 1

LIST OF BALLAST WATER MANAGEMENT SYSTEMS THAT MAKE USE OF ACTIVE SUBSTANCES WHICH RECEIVED BASIC APPROVAL IN ACCORDANCE WITH PROCEDURE (G9)

Name of the system and MEPC document related to the proposal for Basic Approval	Name of manufacturer	Relevant GESAMP-Ballast Water Working Group report	Date of Basic Approval	Specifications
1. Peraclean® Ocean MEPC 53/2/12 (Germany)	Degussa Gmbh, Germany	MEPC 54/2/12, annex 5	24 March 2006 (MEPC 54)	Flag State Administration was invited to authorize onboard testing only when the concerns identified in annex 5 of the Report of the first meeting of the GESAMP-Ballast Water Working Group (MEPC 54/2/12) had been addressed to its complete satisfaction.
2. Electro-Clean (electrolytic disinfection) system (subsequently changed to Electro-Cleen™) MEPC 54/2/3 (The Republic of Korea)	Techcross Ltd. and Korea Ocean Research and Development Institute (KORDI)	MEPC 54/2/12, annex 6	24 March 2006 (MEPC 54)	Flag State Administration was invited to authorize onboard testing only when the concerns identified in annex 6 of the Report of the first meeting of the GESAMP-Ballast Water Working Group (MEPC 54/2/12) had been addressed to its complete satisfaction.
3. Special Pipe Ballast Water Management System (combined with Ozone treatment) MEPC 55/2 (Japan)	Japan Association of Marine Safety (JAMS)	MEPC 55/2/16, annex 5	13 October 2006 (MEPC 55)	Flag State Administration was invited to take into account all the recommendations indicated in annex 5 of the Report of the second meeting of the GESAMP-Ballast Water Working Group (MEPC 55/2/16) during further development of the system.
4. EctoSys™ electrochemical system MEPC 55/2/4 (Sweden)	Permascand AB, Sweden, subsequently acquired by RWO GmbH, Germany	MEPC 55/2/16, annex 7	13 October 2006 (MEPC 55)	Flag State Administration was invited to take into account all the recommendations indicated in annex 7 of the Report of the second meeting of the GESAMP-Ballast Water Working Group (MEPC 55/2/16) during further development of the system.

Name of the system and MEPC document related to the proposal for Basic Approval	Name of manufacturer	Relevant GESAMP-Ballast Water Working Group report	Date of Basic Approval	Specifications
5. PureBallast System MEPC 55/2/5 (Sweden)	Alfa Laval/Wallenius Water AB	MEPC 56/2/2, annex 5	13 July 2007 (MEPC 56)	
6. NK Ballast Water Treatment System (subsequently changed to NK-O3 BlueBallast System (Ozone)) MEPC 55/2/3 and MEPC 55/2/27 (The Republic of Korea)	NK Company Ltd., the Republic of Korea	MEPC 56/2/2, annex 6	13 July 2007 (MEPC 56)	Flag State Administration was invited to take into account all the recommendations indicated in annex 6 of the Report of the third meeting of the GESAMP-Ballast Water Working Group (MEPC 56/2/2) during further development of the system.
7. Hitachi Ballast Water Purification System (ClearBallast) MEPC 57/2/2 (Japan)	Hitachi, Ltd. /Hitachi Plant technologies, Ltd.	MEPC 57/2, annex 5	4 April 2008 (MEPC 57)	Flag State Administration was invited to take into account all the recommendations indicated in annex 5 of the Report of the fourth meeting of the GESAMP-Ballast Water Working Group (MEPC 57/2) during further development of the system.
8. Resource Ballast Technologies System MEPC 56/2/3 (South Africa)	Resource Ballast Technologies (Pty) Ltd.	MEPC 57/2/10, annex 5	4 April 2008 (MEPC 57)	Flag State Administration was invited to take into account all the recommendations indicated in annex 5 of the Report of the fifth meeting of the GESAMP-Ballast Water Working Group (MEPC 57/2/10) during further development of the system.

Name of the system and MEPC document related to the proposal for Basic Approval	Name of manufacturer	Relevant GESAMP-Ballast Water Working Group report	Date of Basic Approval	Specifications
9. GloEn-PatrolTM Ballast Water Management System MEPC 57/2/4 (The Republic of Korea)	Panasia Co., Ltd.	MEPC 57/2/10, annex 6	4 April 2008 (MEPC 57)	Flag State Administration was invited to take into account all the recommendations indicated in annex 6 of the Report of the fifth meeting of the GESAMP-Ballast Water Working Group (MEPC 57/2/10) during further development of the system.
10. OceanSaver® Ballast Water Management System (OS BWMS) MEPC 57/2/6 (Norway)	MetaFil AS	MEPC 57/2/10, annex 8	4 April 2008 (MEPC 57)	Flag State Administration was invited to take into account all the recommendations indicated in annex 8 of the Report of the fifth meeting of the GESAMP-Ballast Water Working Group (MEPC 57/2/10) during further development of the system.
11. TG Ballastcleaner and TG Environmentalguard System MEPC 57/2/8 (Japan)	The Toagosei Group (TG Corporation, Toagosei Co. Ltd. and Tsurumi Soda Co. Ltd.)	MEPC 58/2/7, annex 5	10 October 2008 (MEPC 58)	Flag State Administration was invited to take into account all the recommendations indicated in annex 5 of the Report of the sixth meeting of the GESAMP-Ballast Water Working Group (MEPC 58/2/7) during further development of the system.
12. Greenship Sedinox Ballast Water Management System MEPC 57/2/7 (The Netherlands)	Greenship Ltd	MEPC 58/2/7, annex 6	10 October 2008 (MEPC 58)	Flag State Administration was invited to take into account all the recommendations indicated in annex 6 of the Report of the sixth meeting of the GESAMP-Ballast Water Working Group (MEPC 58/2/7) during further development of the system.

Name of the system and MEPC document related to the proposal for Basic Approval	Name of manufacturer	Relevant GESAMP-Ballast Water Working Group report	Date of Basic Approval	Specifications
13. Ecochlor® Ballast Water Treatment System MEPC 58/2/2 (Germany)	Ecochlor, INC, Acton (USA)	MEPC 58/2/8, annex 5	10 October 2008 (MEPC 58)	Flag State Administration was invited to take into account all the recommendations indicated in annex 5 of the Report of the seventh meeting of the GESAMP-Ballast Water Working Group (MEPC 58/2/8) during further development of the system.
14. Blue Ocean Shield Ballast Water Management System MEPC 59/2/2 (China)	China Ocean Shipping (Group) Company (COSCO)	MEPC 59/2/16, annex 7	17 July 2009 (MEPC 59)	Flag State Administration was invited to take into account all the recommendations indicated in annex 7 of the Report of the eighth meeting of the GESAMP-Ballast Water Working Group (MEPC 59/2/16) during further development of the system
15. Hyundai Heavy Industries Co., Ltd (HHI) Ballast Water Management System (EcoBallast) MEPC 59/2/4 (The Republic of Korea)	Hyundai Heavy Industries Co., Ltd. the Republic of Korea	MEPC 59/2/16, annex 8	17 July 2009 (MEPC 59)	Flag State Administration was invited to take into account all the recommendations indicated in annex 8 of the Report of the eighth meeting of the GESAMP-Ballast Water Working Group (MEPC 59/2/16) during further development of the system
16. AquaTriComb™ Ballast Water Treatment System MEPC 59/2/8 (Germany)	Aquaworx ATC GmbH	MEPC 59/2/19, annex 6	17 July 2009 (MEPC 59)	Flag State Administration was invited to take into account all the recommendations indicated in annex 6 of the Report of the ninth meeting of the GESAMP-Ballast Water Working Group (MEPC 59/2/19) during further development of the system

ANNEX 2

LIST OF BALLAST WATER MANAGEMENT SYSTEMS THAT MAKE USE OF ACTIVE SUBSTANCES WHICH RECEIVED FINAL APPROVAL IN ACCORDANCE WITH PROCEDURE (G9)

Name of the system and MEPC document related to the proposal for Final Approval	Name of manufacturer	Relevant GESAMP-Ballast Water Working Group report	Date of Final Approval	Specifications
1. PureBallast System MEPC 56/2/1 (Norway)	Alfa Laval/Wallenius Water AB	MEPC 56/2/2, annex 5	13 July 2007 (MEPC 56)	Flag State Administration was invited to verify that the concerns raised in annex 5 of the Report of the third meeting of the GESAMP-Ballast Water Working Group (MEPC 56/2/2) with regard to ship and crew safety have been fully addressed prior to the issuance of Type Approval certificate.
2. SEDNA® Ballast Water Management System (Using Peraclean® Ocean) MEPC 57/2/5 (Germany)	Degussa Gmbh, Germany	MEPC 57/2/10, annex 7	4 April 2008 (MEPC 57)	Flag State Administration was invited to take into account all the recommendations contained in annex 7 of the Report of the fifth meeting of the GESAMP-Ballast Water Working Group (MEPC 57/2/10) prior to the issuance of Type Approval Certificate.
3. Electro-Cleen™ System MEPC 58/2 (The Republic of Korea)	Techcross Ltd. and Korea Ocean Research and Development Institute (KORDI)	MEPC 58/2/7, annex 7	10 October 2008 (MEPC 58)	n/a
4. OceanSaver® Ballast Water Management System (OS BWMS) MEPC 58/2/1 (Norway)	MetaFil AS	MEPC 58/2/8, annex 4	10 October 2008 (MEPC 58)	Flag State Administration was invited to verify that all the recommendations contained in annex 4 of the Report of the seventh meeting of the GESAMP-BWWG (MEPC 58/2/8) have been fully addressed prior to the issuance of a Type Approval Certificate.

Name of the system and MEPC document related to the proposal for Final Approval	Name of manufacturer	Relevant GESAMP-Ballast Water Working Group report	Date of Final Approval	Specifications
5. RWC Ballast Water Management System (CleanBallast) MEPC 59/2 (Germany)	RWO GmbH Marine Water Technology, Germany	MEPC 59/2/16, annex 5	17 July 2009 (MEPC 59)	Flag State Administration was invited to verify that all the recommendations contained in annex 5 of the Report of the eighth meeting of the GESAMP-BWWG (MEPC 59/2/16) have been fully addressed prior to the issuance of a Type Approval Certificate.
6. NK-O3 BlueBallast System (Ozone) MEPC 59/2/3 (the Republic of Korea)	NK Company Ltd., the Republic of Korea	MEPC 59/2/16, annex 6	17 July 2009 (MEPC 59)	Flag State Administration was invited to verify that all the recommendations contained in annex 6 of the Report of the eighth meeting of the GESAMP-BWWG (MEPC 59/2/16) have been fully addressed prior to the issuance of a Type Approval Certificate.
7. Hitachi Ballast Water Purification System (ClearBallast) MEPC 59/2/5 (Japan)	Hitachi, Ltd. /Hitachi Plant technologies, Ltd.	MEPC 59/2/19, annex 4	17 July 2009 (MEPC 59)	Flag State Administration was invited to verify that all the recommendations contained in annex 4 of the Report of the ninth meeting of the GESAMP-BWWG (MEPC 59/2/19) have been fully addressed prior to the issuance of a Type Approval Certificate.
8. Greenship Sedinox Ballast Water Management System. MEPC 59/2/6 (the Netherlands)	Greenship Ltd	MEPC 59/2/19, annex 5	17 July 2009 (MEPC 59)	Flag State Administration was invited to verify that all the recommendations contained in annex 5 of the Report of the ninth meeting of the GESAMP-BWWG (MEPC 59/2/19) have been fully addressed prior to the issuance of a Type Approval Certificate.

Appendix 4

Fuzzy Rule-Base for Hazard Screening of Infection Components

Rule No.	Infection Probability Rate	Infection Severity Rate	Infection Detection Rate	Priority Level of Attention with Belief Degrees
1	Very Low	Negligible	Highly unlikely	Low (1)
2	Very Low	Negligible	Unlikely	Low (0.9) Fairly Low (0.1)
3	Very Low	Negligible	Likely	Low (0.8) Fairly Low (0.2)
4	Very Low	Negligible	Highly likely	Low (0.7) Fairly Low (0.3)
5	Very Low	Negligible	Definite	Low (0.6) Fairly Low (0.4)
6	Very Low	Marginal	Highly unlikely	Low (0.9) Fairly Low (0.1)
7	Very Low	Marginal	Unlikely	Low (0.8) Fairly Low (0.2)
8	Very Low	Marginal	Likely	Low (0.7) Fairly Low (0.3)
9	Very Low	Marginal	Highly likely	Low (0.6) Fairly Low (0.4)
10	Very Low	Marginal	Definite	Low (0.5) Fairly Low (0.5)
11	Very Low	Moderate	Highly unlikely	Low (0.8) Fairly Low (0.2)
12	Very Low	Moderate	Unlikely	Low (0.7) Fairly Low (0.3)
13	Very Low	Moderate	Likely	Low (0.6) Fairly Low (0.4)
14	Very Low	Moderate	Highly likely	Low (0.5) Fairly Low (0.5)
15	Very Low	Moderate	Definite	Low (0.4) Fairly Low (0.6)
16	Very Low	Critical	Highly unlikely	Low (0.7) Fairly Low (0.3)
17	Very Low	Critical	Unlikely	Low (0.6) Fairly Low (0.4)
18	Very Low	Critical	Likely	Low (0.5) Fairly Low (0.5)
19	Very Low	Critical	Highly likely	Low (0.4) Fairly Low (0.6)
20	Very Low	Critical	Definite	Low (0.3) Fairly Low (0.7)
21	Very Low	Catastrophic	Highly unlikely	Low (0.6) Fairly Low (0.4)
22	Very Low	Catastrophic	Unlikely	Low (0.5) Fairly Low (0.5)
23	Very Low	Catastrophic	Likely	Low (0.4) Fairly Low (0.6)
24	Very Low	Catastrophic	Highly likely	Low (0.3) Fairly Low (0.7)
25	Very Low	Catastrophic	Definite	Low (0.2) Fairly Low (0.8)
26	Low	Negligible	Highly unlikely	Low (0.9) Fairly Low (0.1)
27	Low	Negligible	Unlikely	Low (0.8) Fairly Low (0.2)
28	Low	Negligible	Likely	Low (0.7) Fairly Low (0.3)
29	Low	Negligible	Highly likely	Low (0.6) Fairly Low (0.4)
30	Low	Negligible	Definite	Low (0.5) Fairly Low (0.5)
31	Low	Marginal	Highly unlikely	Low (0.8) Fairly Low (0.2)
32	Low	Marginal	Unlikely	Low (0.7) Fairly Low (0.3)
33	Low	Marginal	Likely	Low (0.6) Fairly Low (0.4)
34	Low	Marginal	Highly likely	Low (0.5) Fairly Low (0.5)
35	Low	Marginal	Definite	Low (0.4) Fairly Low (0.6)
36	Low	Moderate	Highly unlikely	Low (0.7) Fairly Low (0.3)
37	Low	Moderate	Unlikely	Low (0.6) Fairly Low (0.4)
38	Low	Moderate	Likely	Low (0.5) Fairly Low (0.5)

39	Low	Moderate	Highly likely	Low (0.4) Fairly Low (0.6)
40	Low	Moderate	Definite	Low (0.3) Fairly Low (0.7)
41	Low	Critical	Highly unlikely	Low (0.6) Fairly Low (0.4)
42	Low	Critical	Unlikely	Low (0.5) Fairly Low (0.5)
43	Low	Critical	Likely	Low (0.4) Fairly Low (0.6)
44	Low	Critical	Highly Likely	Low (0.3) Fairly Low (0.7)
45	Low	Critical	Definite	Low (0.2) Fairly Low (0.8)
46	Low	Catastrophic	Highly Unlikely	Low (0.5) Fairly Low (0.5)
47	Low	Catastrophic	Unlikely	Low (0.4) Fairly Low (0.6)
48	Low	Catastrophic	Likely	Low (0.3) Fairly Low (0.7)
49	Low	Catastrophic	Highly Likely	Low (0.2) Fairly Low (0.8
50	Low	Catastrophic	Definite	Low (0.1) Fairly Low (0.9)
51	Moderate	Negligible	Highly unlikely	Fairly Low (1)
52	Moderate	Negligible	Unlikely	Fairly Low (0.9) Moderate (0.1)
53	Moderate	Negligible	Likely	Fairly Low (0.8) Moderate (0.2)
54	Moderate	Negligible	Highly likely	Fairly Low (0.7) Moderate (0.3)
55	Moderate	Negligible	Definite	Fairly Low (0.6) Moderate (0.4)
56	Moderate	Marginal	Highly unlikely	Fairly Low (0.9) Moderate (0.1)
57	Moderate	Marginal	Unlikely	Fairly Low (0.8) Moderate (0.2)
58	Moderate	Marginal	Likely	Fairly Low (0.7) Moderate (0.3)
59	Moderate	Marginal	Highly likely	Fairly Low (0.6) Moderate (0.4)
60	Moderate	Marginal	Definite	Fairly Low (0.5) Moderate (0.5)
61	Moderate	Moderate	Highly unlikely	Fairly Low (0.8) Moderate (0.2)
62	Moderate	Moderate	Unlikely	Fairly Low (0.7) Moderate (0.3)
63	Moderate	Moderate	Likely	Fairly Low (0.6) Moderate (0.4)
64	Moderate	Moderate	Highly likely	Fairly Low (0.5) Moderate (0.5)
65	Moderate	Moderate	Definite	Fairly Low (0.4) Moderate (0.6)
66	Moderate	Critical	Highly unlikely	Fairly Low (0.7) Moderate (0.3)
67	Moderate	Critical	Unlikely	Fairly Low (0.6) Moderate (0.4)
68	Moderate	Critical	Likely	Fairly Low (0.5) Moderate (0.5)
69	Moderate	Critical	Highly likely	Fairly Low (0.4) Moderate (0.6)
70	Moderate	Critical	Definite	Fairly Low (0.3) Moderate (0.7)
71	Moderate	Catastrophic	Highly unlikely	Fairly Low (0.6) Moderate (0.4)
72	Moderate	Catastrophic	Unlikely	Fairly Low (0.5) Moderate (0.5)
73	Moderate	Catastrophic	Likely	Fairly Low (0.4) Moderate (0.6)
74	Moderate	Catastrophic	Highly likely	Fairly low (0.3) Moderate (0.7)
75	Moderate	Catastrophic	Definite	Fairly Low (0.2) Moderate (0.8)
76	High	Negligible	Highly unlikely	Moderate (1)
77	High	Negligible	Unlikely	Moderate (0.9) Fairly High (0.1)
78	High	Negligible	Likely	Moderate (0.8)Fairly High (0.2)
79	High	Negligible	Highly likely	Moderate (0.7) Fairly High (0.3)
80	High	Negligible	Definite	Moderate (0.6) Fairly High (0.4)
81	High	Marginal	Highly unlikely	Moderate (0.9) Fairly High (0.1)
82	High	Marginal	Unlikely	Moderate (0.8) Fairly High (0.2)
83	High	Marginal	Likely	Moderate (0.7) Fairly High (0.3)
84	High	Marginal	Highly likely	Moderate (0.6) Fairly High (0.4)

85	High	Marginal	Definite	Moderate (0.5) Fairly High (0.5)
86	High	Moderate	Highly unlikely	Moderate (0.8) Fairly High (0.2)
87	High	Moderate	Unlikely	Moderate (0.7) Fairly High (0.3)
88	High	Moderate	Likely	Moderate (0.6) Fairly High (0.4)
89	High	Moderate	Highly likely	Moderate (0.5) Fairly High (0.5)
90	High	Moderate	Definite	Moderate (0.4) Fairly High (0.6)
91	High	Critical	Highly unlikely	Moderate (0.7) Fairly High (0.3)
92	High	Critical	Unlikely	Moderate (0.6) Fairly High (0.4)
93	High	Critical	Likely	Moderate (0.5) Fairly High (0.5)
94	High	Critical	Highly likely	Moderate (0.4) Fairly High (0.6)
95	High	Critical	Definite	Moderate (0.3) Fairly High (0.7)
96	High	Catastrophic	Highly unlikely	Moderate (0.6) Fairly High (0.4)
97	High	Catastrophic	Unlikely	Moderate (0.5) Fairly High (0.5)
98	High	Catastrophic	Likely	Moderate (0.4) Fairly High (0.6)
99	High	Catastrophic	Highly likely	Moderate (0.3) Fairly High (0.7)
100	High	Catastrophic	Definite	Fairly High (0.2) High (0.8)
101	Very High	Negligible	Highly unlikely	Fairly High (1)
102	Very High	Negligible	Unlikely	Fairly High (0.9) High (0.1)
103	Very High	Negligible	Likely	Fairly High (0.8) High (0.2)
104	Very High	Negligible	Highly likely	Fairly High (0.7) High (0.3)
105	Very High	Negligible	Definite	Fairly High (0.6) High (0.4)
106	Very High	Marginal	Highly unlikely	Fairly High(0.9) High (0.1)
107	Very High	Marginal	Unlikely	Fairly High (0.8) High (0.2)
108	Very High	Marginal	Likely	Fairly High (0.7) High (0.3)
109	Very High	Marginal	Highly likely	Fairly High (0.6) High (0.4)
110	Very High	Marginal	Definite	Fairly High (0.5) High (0.5)
111	Very High	Moderate	Highly unlikely	Fairly High (0.8) High (0.2)
112	Very High	Moderate	Unlikely	Fairly High (0.7) High (0.3)
113	Very High	Moderate	Likely	Fairly High (0.6) High (0.4)
114	Very High	Moderate	Highly likely	Fairly High (0.5) High (0.5)
115	Very High	Moderate	Definite	Fairly High (0.4) High (0.6)
116	Very High	Critical	Highly unlikely	Fairly High (0.6) High (0.4)
117	Very High	Critical	Unlikely	Fairly High (0.5) High (0.5)
118	Very High	Critical	Likely	Fairly High (0.4) High (0.6)
119	Very High	Critical	Highly likely	Fairly High (0.3) High (0.7)
120	Very High	Critical	Definite	Fairly High (0.2) High (0.8)
121	Very High	Catastrophic	Highly unlikely	Fairly High (0.4) High (0.6)
122	Very High	Catastrophic	Unlikely	Fairly High (0.3) High (0.7)
123	Very High	Catastrophic	Likely	Fairly High (0.2) High (0.8)
124	Very High	Catastrophic	Highly likely	Fairly High (0.1) High (0.9)
125	Very High	Catastrophic	Definite	High (1)

Appendix 5

Determination of Weights of Evaluation Criteria Using AHP

AHP Pairwise Comparisons for (2^{nd} Level) Sub-Criteria

The AHP equations and steps utilised for the determination of the weights of the evaluation criteria of the first level hierarchy of this study are also applied in the second level. In view of the fact that Biological Effectiveness and Cost have less than three evaluation criteria, the AHP theory cannot be applied to them. Consequently, their values will be based on knowledge and judgements of the experts involved in the decision making process. The numerical ratings of the verbal judgement of the pairwise comparisons were based on the following.

Verbal Judgement	Numerical Rating
Extremely More Practical	9 8
Very Strongly More Practical	7 6
Strongly More Practical	5 4
Moderately More Practical	3 2
Equally Practical	1

I. Practicability

This evaluation criterion has the sub-criteria of: exchange at Sea, shipboard treatment and discharge to reception facilities.

A. Conducting Pairwise Comparison

The pairwise comparison for this sub-criterion was conducted as follows.

Pairwise Comparison		More Practicable Criterion	How Much More Practical	Numerical Rating
Exchange at Sea -	Shipboard Treatment	Exchange at Sea	Strongly more practical	4
Exchange At Sea -	Discharge to Reception Facilities	Exchange at Sea	Moderately more practical	3
Shipboard Treatment -	Discharge to Reception Facilities	Shipboard Treatment	Moderately more practical	2

From the numerical ratings obtained above, a pairwise comparison matrix was developed for this level as follows.

Criterion	Exchange at Sea	Shipboard Treatment	Discharge to Reception Facilities
Exchange at Sea	1	4	3
Shipboard Treatment	¼	1	2
Discharge to Reception Facilities	⅓	½	1
Sum	1.583	5.500	6

B. Conducting AHP Synthesization Process

The weight of each criterion was calculated in terms of its contribution to the overall goal and using the following process:

i. Dividing each element of the matrix by its column total as follows:

$1 \div 1.583 = 0.632$ $4 \div 5.500 = 0.727$ $3 \div 6 = 0.50$

$\frac{1}{4} \div 1.583 = 0.158$ $1 \div 5.500 = 0.182$ $2 \div 6 = 0.333$

$\frac{1}{3} \div 1.583 = 0.210$ $\frac{1}{2} \div 5.500 = 0.091$ $1 \div 6 = 0.167$

ii. Determining the weight of each criterion by averaging the elements in each row as follows:

Weight Value

$(0.632 + 0.727 + 0.500) \div 3 =$ 0.620

$$(0.158 + 0.182 + 0.333) \div 3 = \qquad 0.224$$

$$(0.210 + 0.091 + 0.167) \div 3 = \qquad 0.156$$

C. Calculating the Consistency of the Pairwise Judgement

Step I: Multiply each value in the first column of the pairwise comparison matrix by the priority of the first item as follows:

$$0.620\begin{bmatrix}1\\1/4\\1/3\end{bmatrix} + 0.224\begin{bmatrix}4\\1\\1/2\end{bmatrix} + 0.156\begin{bmatrix}3\\2\\1\end{bmatrix} = \begin{bmatrix}0.620\\0.155\\0.206\end{bmatrix} + \begin{bmatrix}0.896\\0.224\\0.112\end{bmatrix} + \begin{bmatrix}0.468\\0.312\\0.156\end{bmatrix} = \begin{bmatrix}1.984\\0.691\\0.474\end{bmatrix}$$

Step II: Divide the elements of the weighted sum vector obtained in step I by the corresponding weight for each criterion:

$$w_{31} = \frac{1.984}{0.620} = 3.20 \qquad w_{32} = \frac{0.691}{0.224} = 3.085 \qquad w_{33} = \frac{0.474}{0.155} = 3.038$$

Step III: Compute the average of the values found in step II:

$$\lambda_{\max} = \frac{3.200 + 3.085 = 3.038}{3} = 3.108$$

Step IV: Compute the Consistency Index (CI)

$$\frac{3.108 - 3}{3 - 1} = 0.054$$

Step V: Compute the Consistency Ratio (CR)

Since there are 3 items in the first level of hierarchy and a corresponding RI of 0.58 the CR is calculated as follows:

$$\mathrm{CR} = \frac{0.054}{0.58} = 0.093$$

The pairwise comparison for the weights of the evaluation criteria shows a CR of 0.093. The degree of consistency in the pair-wise comparisons will be acceptable because the CR is less than 0.10. Consequently, the weight distribution for the evaluation sub-criteria of the criterion, "Practicability" will be:

Exchange at Sea = 0.620
Shipboard Treatment = 0.22
Discharge to Reception Facilities = 0.156

II. Safety

A. Conducting Pairwise Comparison

The pairwise comparison for the safety sub-criterion was conducted as follows:

Pairwise Comparison	More Important Criterion	How Much More Important	Numerical Rating
Crew - Vessel	Crew	Moderately more important	2
Crew - Cargo	Crew	Moderately more important	2
Vessel - Cargo	Vessel	Moderately more important	3

From the numerical ratings obtained above, a pairwise comparison matrix was developed for this level as follows:

Criterion	Crew	Vessel	Cargo
Crew	1	6	5
Vessel	1/6	1	2
Cargo	1/5	½	1
Sum	1.366	7.500	8

B. Conducting AHP Synthesization Process

The weight of each criterion was calculated in terms of its contribution to the overall goal and using the following process:

i. Each element of the matrix is divided by its column as follows:

$1 \div 1.366 = 0.732 \qquad 6 \div 7.500 = 0.800 \qquad 5 \div 8 = 0.625$

$1/6 \div 1.366 = 0.122 \qquad 1 \div 7.500 = 0.133 \qquad 2 \div 8 = 0.250$

$1/5 \div 1.366 = 0.146 \qquad ½ \div 7.500 = 0.067 \qquad 1 \div 8 = 0.125$

ii. In order to determine the weight of each criterion the average of the elements in each row is established as follows:

	Weight Value
$(0.732 + 0.800 + 0.625) \div 3 =$	0.719
$(0.122 + 0.133 + 0.250) \div 3 =$	0.168
$(0.146 + 0.067 + 0.125) \div 3 =$	0.113

C. Calculating the Consistency of the Pairwise Judgement

Step I: Multiply each value in the first column of the pairwise comparison matrix by the priority of the first item as follows:

$$0.719\begin{bmatrix}1\\1/6\\1/5\end{bmatrix}+0.168\begin{bmatrix}6\\1\\1/2\end{bmatrix}+0.113\begin{bmatrix}5\\2\\1\end{bmatrix}=\begin{bmatrix}0.719\\0.119\\0.144\end{bmatrix}+\begin{bmatrix}1.008\\0.168\\0.084\end{bmatrix}+\begin{bmatrix}0.565\\0.226\\0.113\end{bmatrix}=\begin{bmatrix}2.292\\0.513\\0.341\end{bmatrix}$$

Step II: Divide the elements of the weighted sum vector obtained in step I by the corresponding weight for each criterion:

$$w_{11} = \frac{2.292}{0.719} = 3.188 \qquad w_{12} = \frac{0.513}{0.168} = 3.054 \qquad w_{13} = \frac{0.341}{0.113} = 3.081$$

Step III: Compute the average of the values found in step II.

$$\frac{3.088 + 3.054 + 3.018}{3} = 3.087$$

Step IV: Obtain the Consistency Index (CI):

$$\frac{3.087 - 3}{3 - 1} = \frac{0.087}{2} = 0.044$$

Step V: Computation of the Consistency Ratio (CR).

Since there are 3 items in the first level of hierarchy resulting in a corresponding RI of 0.58 the CR is calculated as follows:

$$CR = \frac{0.044}{0.58} = 0.076$$

The pairwise comparison for the weights of the evaluation criteria shows a CR of 0.076. Consequently, the degree of consistency in the pairwise comparisons is acceptable because the CR is less than 0.10.

The weight distribution for the evaluation sub-criteria of the criterion, "Safety" will be as follows:

Crew = 0.719

Vessel = 0.168

Cargo = 0.113

III. Environmental Acceptability

A. Pairwise Comparison

The pairwise comparisons for the environmental acceptability criterion were conducted as follows:

Pairwise Comparison	More Acceptable Criterion	How Much More Acceptable	Numerical Rating
Human Habitat - Marine Environment	Human Habitat	Moderately more acceptable	3
Human Habitat - Marine Installations	Human Habitat	Strongly more acceptable	5
Marine Environment - Marine Installations	Marine Environment	Moderately more acceptable	2

From the numerical ratings obtained above, a pairwise comparison matrix was developed for this level as follows:

B. Conducting AHP Synthesization Process

The weight of each criterion was calculated in terms of its contribution to the overall goal using the following process:

Criterion	Human Habitat	Marine Environment	Marine Installations
Human Habitat	1	3	5
Marine Environment	⅓	1	2
Marine Installations	1/5	½	1

i. Summation of the values in each column of the pairwise comparison matrix. The following are the sums of the values in each column;

1.533 4.500 8

ii. Each element of the matrix is divided by its column as follows:

1 ÷ 1.533 = 0.652 3 ÷ 4.500 = 0.667 5 ÷ 8 = 0.625

⅓÷ 1.533 = 0.217 1 ÷ 4.500 = 0.222 2 ÷ 8 = 0.250

1/5 ÷ 1.533 = 0.130 ½ ÷ 4.500 = 0.111 1 ÷ 8 = 0.125

iii. In order to determine the weight of each criterion the average of the elements in each row is established as follows:

	Weight Value
(0.652 + 0.667 + 0.625) ÷ 3 =	0.648
(0.217 + 0.222 + 0.250) ÷ 3 =	0.230
(0.130 + 0.111 + 0.125) ÷ 3 =	0.122

B. Calculating the Consistency of the Pairwise Judgement

Step I: Multiply each value in the first column of the pair-wise comparison matrix by the priority of the first item as follows:

$$0.648\begin{bmatrix}1\\1/3\\1/5\end{bmatrix}+0.230\begin{bmatrix}3\\1\\1/2\end{bmatrix}+0.122\begin{bmatrix}5\\2\\1\end{bmatrix}=\begin{bmatrix}0.648\\0.216\\0.130\end{bmatrix}+\begin{bmatrix}0.690\\0.230\\0.115\end{bmatrix}+\begin{bmatrix}0.610\\0.244\\0.122\end{bmatrix}=\begin{bmatrix}1.948\\0.690\\0.367\end{bmatrix}$$

Step II: Divide the elements of the weighted sum vector obtained in step I by the corresponding weight for each criterion using the equation:

$$\frac{1.948}{0.648}=3.006 \qquad \frac{0.690}{0.230}=3.000 \qquad \frac{0.367}{0.122}=3.008$$

Step III: Compute the average of the values found in step II.

$$\frac{3.006+3.000+3.008}{3}=3.005$$

Step IV: Obtain the Consistency Index:

$$\frac{3.005-3}{3-1} = \frac{0.005}{2} = 0.025$$

Step V: Compute the Consistency Ratio:

Since there are 3 items in the first level of hierarchy resulting in a corresponding RI of 0.58 the CR is calculated as follows:

$$\mathrm{CR}=\frac{0.025}{0.58} = 0.043$$

The pairwise comparison for the weights of the evaluation criteria shows a CR of - 0.043. Consequently, the degree of consistency in the pairwise comparisons is acceptable because the CR is less than 0.10.

The weight distribution for the evaluation sub-criteria of the criterion, "Environmental Acceptability" is obtained as follows:

Human Habitat = 0.648

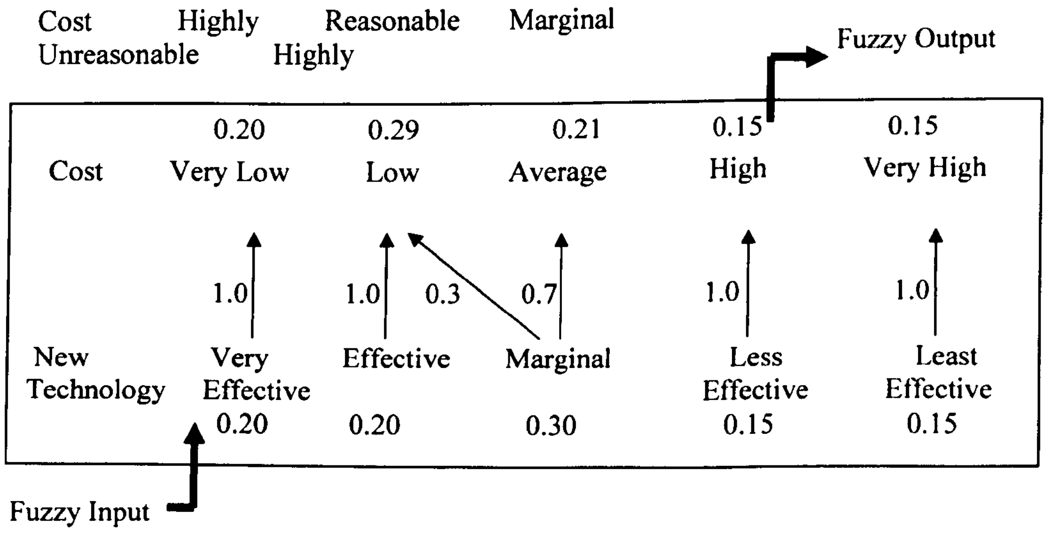
Marine Environment = 0.230

Marine Installations = 0.122

Appendix 6

Evidential Reasoning Assessment Transformation Process

Transformation of New Technology to Cost



1. If new technology is very effective, and the cost is very low, then the treatment system is highly acceptable (1.0).
2. If new technology is effective and the cost is low, then the treatment system is acceptable (1.0).
3. If new technology is marginal, and the cost is average, then the treatment system is fairly acceptable (0.7) and acceptable (0.3).
4. If new technology is less effective, and the cost is high, then the treatment system is unacceptable (1.0).
5. If new technology is least effective, and the cost is very high, then the treatment system is highly unacceptable (1.0).

Very Reasonable = $0.20 \times 1.0 = 0.20$

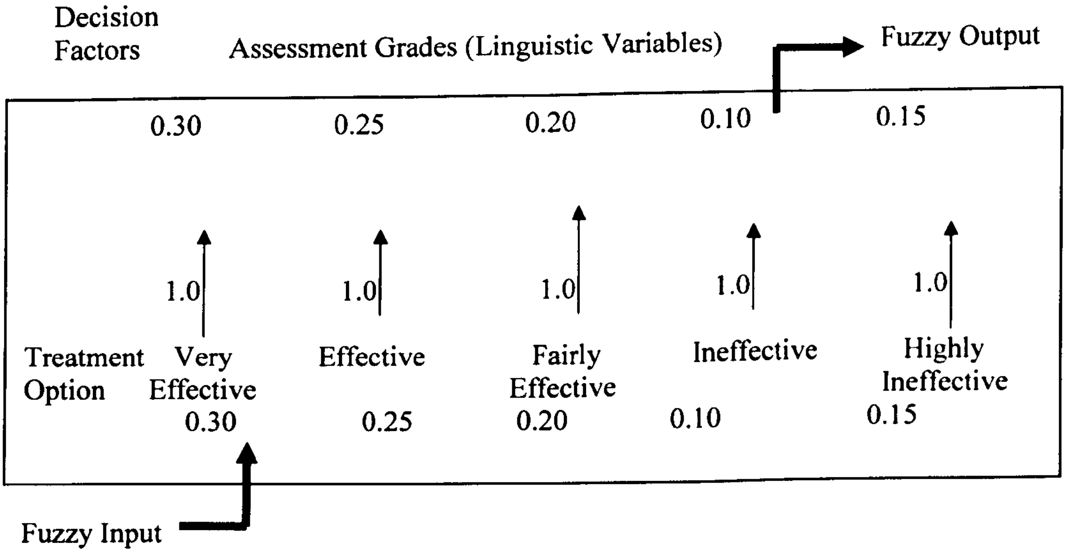
Reasonable = $(0.20 \times 1.0) + (0.30 \times .3) = 0.2 + 0.09 = 0.29$

Marginal = $0.30 \times 0.7 = 0.21$

Unacceptable = $0.15 \times 1.0 = 0.15$

Very Unacceptable = $0.15 \times 1.0 = 0.15$

Transformation of Treatment Option to Cost



1. If the treatment option is very effective, and the cost is highly reasonable, then the system is highly acceptable (1.0).
2. If the treatment option is effective, and the cost is reasonable, then the system is acceptable (1.0).
3. If the treatment option is fairly effective, and the cost is marginal, then the system is fairly acceptable (1.0).
4. If the treatment option is ineffective, and the cost is unreasonable, then the system is unreasonable (1.0).
5. If the treatment option is very ineffective, and the cost is highly unreasonable, then the system is highly unacceptable (1.0).

Highly Reasonable = $0.30 \times 1.0 = 0.30$

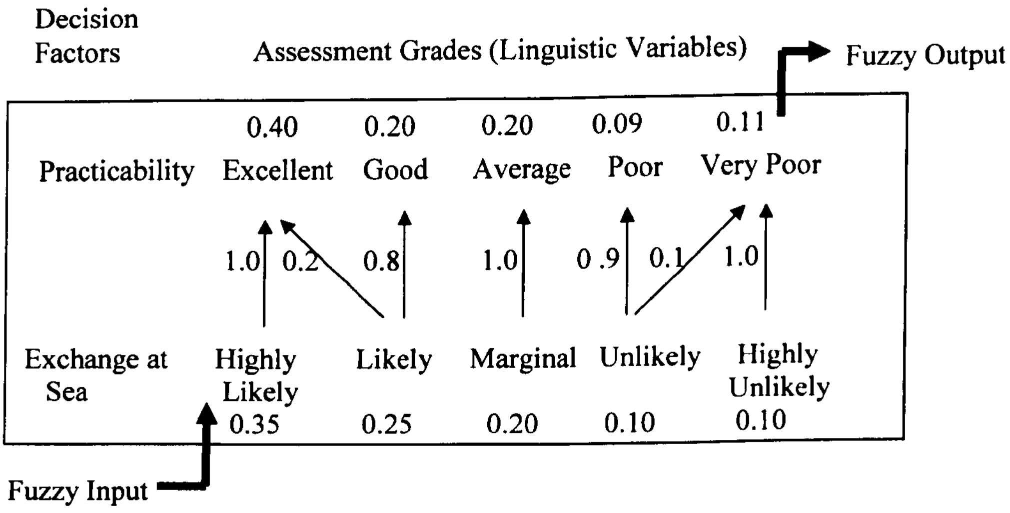
Reasonable = $0.25 \times 1.0 = 0.25$

Average = $0.20 \times 1.0 = 0.20$

Unreasonable = $0.10 \times 1.0 = 0.10$

Highly Unreasonable = $0.15 \times 1.0 = 0.15$

Transformation of Exchange at Sea to Practicability



1. If exchange at sea is highly likely, then practicability is excellent (1.0)
2. If exchange at sea is likely, then practicability is good (0.8), and very good (0.2).
3. If exchange at sea is marginal, then practicability is average (1.0).
4. If exchange at sea is unlikely, then practicability is poor (0.9) and poor (0.1).
5. If exchange at sea is highly unlikely, then practicability is very poor (1.0)

Excellent = $(0.35 \times 1.0) + (0.25 \times 0.2) = 0.35 + 0.05 = 0.40$

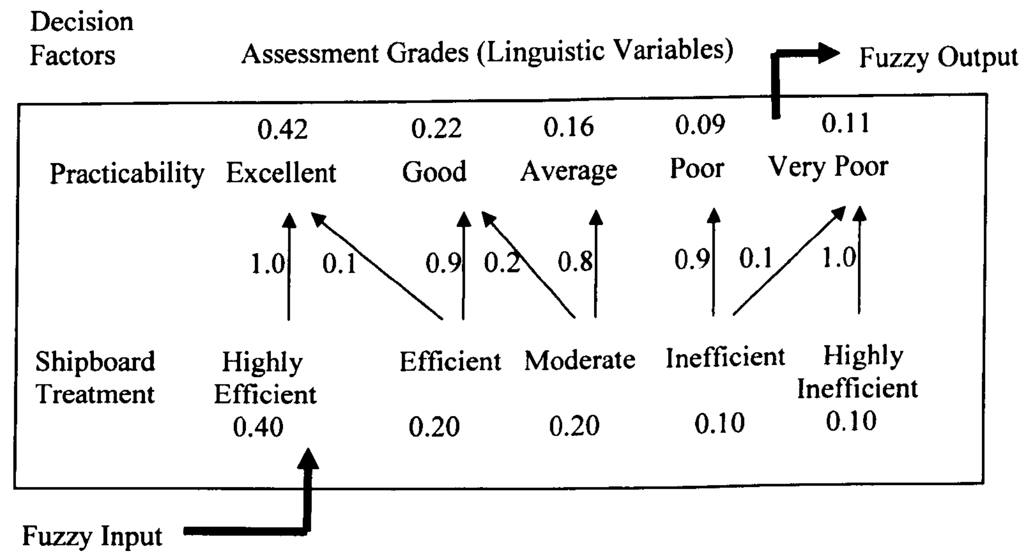
Good = $0.25 \times 0.8 = 0.20$

Average = $0.20 \times 1.0 = 0.20$

Poor = $0.10 \times 0.9 = 0.09$

Very Poor = $(0.10 \times 1.0) + (0.10 \times 0.1) = 0.1 + 0.01 = 0.11$

Transformation of Shipboard Treatment to Practicability



1. If shipboard treatment is highly efficient, then practicability is excellent (1.0).
2. If shipboard treatment is efficient, then practicability is good (0.9) and excellent (0.1).
3. If shipboard treatment is moderate, then practicability is average (0.9) and good (0.1).
4. If shipboard treatment is inefficient, then practicability is poor (0.9).
5. If shipboard treatment is highly inefficient, then practicability is very poor (1.0) and poor (0.1).

Excellent = (0.40 × 1.0) = (0.20 × 0.1) = 0.4 + 0.02 = 0.42

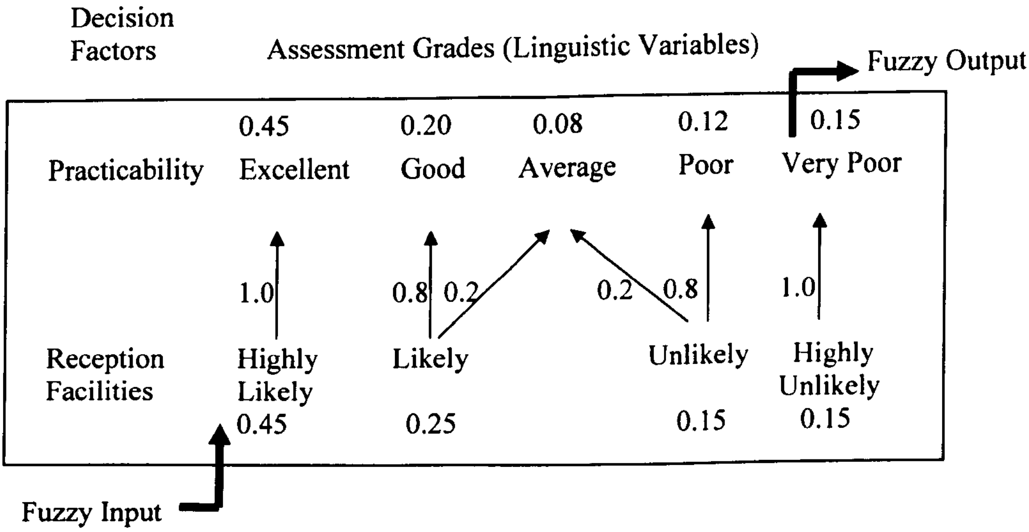
Good = (0.20 × 0.9) = (0.2 × 0.2) = 0.18 + 0.04 = 0.22

Average = 0.20 × 0.8 = 0.16

Poor = 0.10 × 0.9 = 0.09

Very Poor = (0.10 × 1.0) + (0.10 × 0.10) = 0.1 + 0.01 = 0.11

Transformation from Discharge to Reception Facilities to Practicability



1. If discharge to reception facilities is highly likely, then practicability of treatment system is excellent (1.0).
2. If discharge to reception facilities is likely, then practicability of treatment system is good (0.8) and average (0.2).
3. If discharge to reception facilities is unlikely, then practicability of treatment system is poor (0.8) and average (0.2).
4. If discharge to reception facilities is highly unlikely, then practicability of treatment system is very poor (1.0).

Excellent = $0.45 \times 1.0 = 0.45$

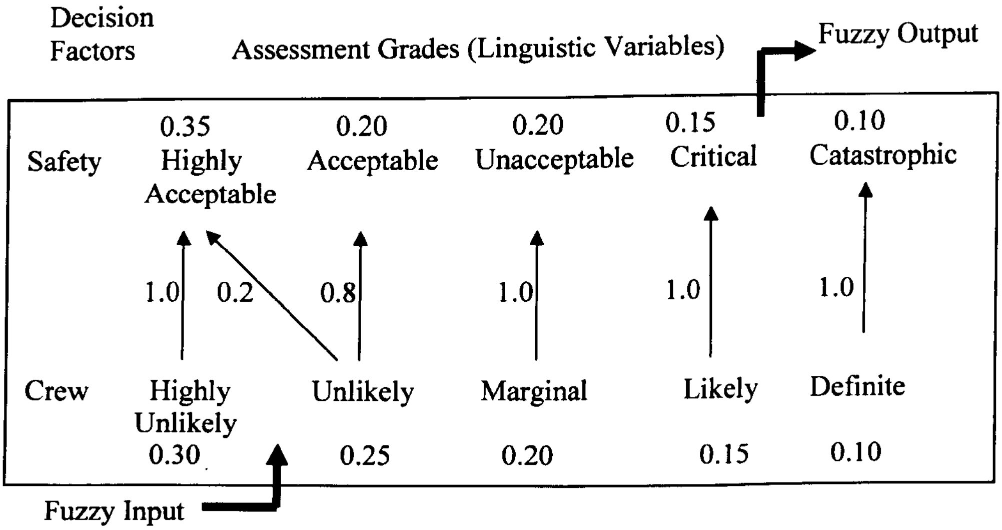
Good = $0.25 \times 0.8 = 0.20$

Average = $(0.25 \times 0.2) + (0.15 \times 0.2) = 0.05 + 0.03 = 0.08$

Poor = $0.15 \times 0.8 = 0.12$

Very Poor = $0.15 \times 1.0 = 0.15$

Transformation of Crew to Safety



1. If injury to ship crew is highly unlikely, then safety rate of treatment option is highly acceptable (1.0) and acceptable (0.2).
2. If injury to ship crew is unlikely, then safety rate of treatment option is acceptable (0.8).
3. If injury to ship crew is marginal, then safety rate of treatment option is unacceptable (1.0).
4. If injury to ship crew is likely, then safety rate of treatment option is critical (1.0).
5. If injury to ship crew is definite, then safety rate of treatment option is catastrophic (1.0).

Highly Acceptable = $(0.30 \times 1.0) + (0.25 \times 0.2) = 0.3 + 0.05 = 0.35$

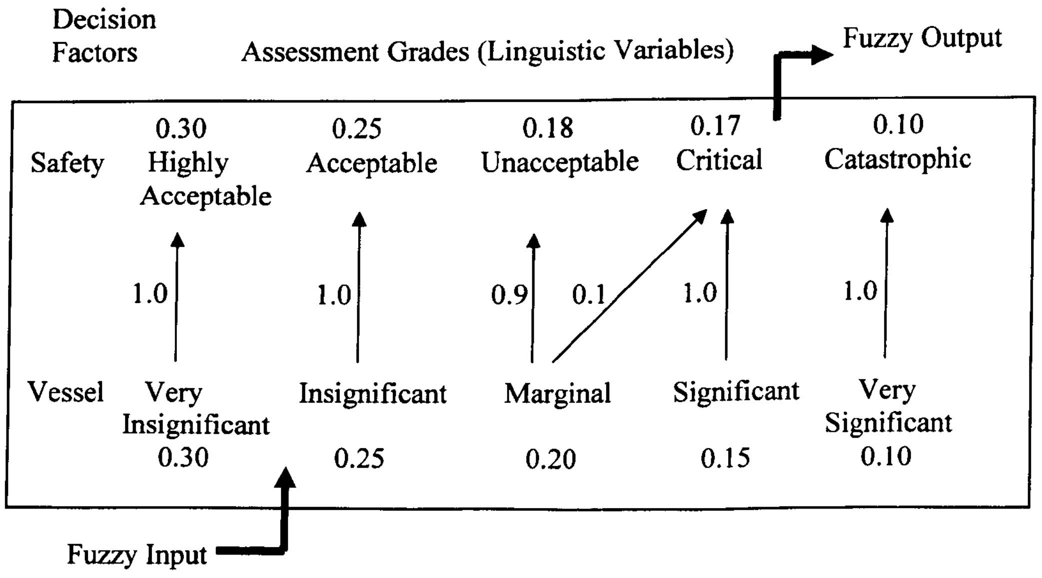
Acceptable = $0.25 \times 0.8 = 0.20$

Unacceptable = $0.20 \times 1.0 = 0.20$

Critical = $0.15 \times 1.0 = 0.15$

Catastrophic = $0.10 \times 1.0 = 0.10$

Transformation of Vessel to Safety



1. If impact on vessel is very insignificant, then safety rate of treatment option is highly acceptable (1.0).
2. If impact on vessel is insignificant, then safety rate of treatment option is acceptable (1.0).
3. If impact on vessel is marginal, then safety rate of treatment option is unacceptable (0.9).
4. If impact on vessel is significant, then safety rate of treatment option is critical (1.0) and (0.1) unacceptable.
5. If impact on vessel is very significant, then safety rate of treatment option is catastrophic (1.0).

Highly Acceptable = $0.30 \times 1.0 = 0.30$

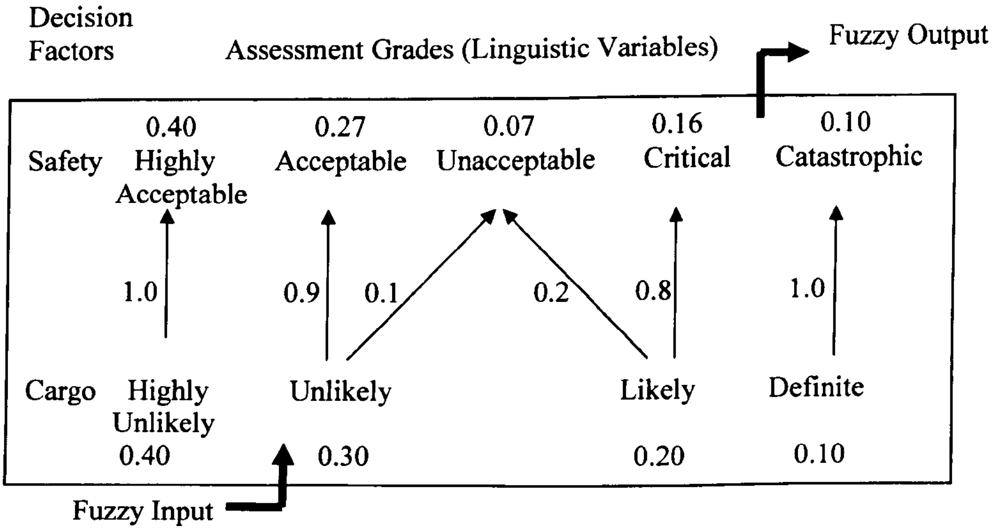
Acceptable = $0.25 \times 1.0 = 0.25$

Unacceptable = $0.20 \times 0.9 = 0.18$

Critical = $(0.15 \times 1.0) + (0.20 \times 0.1) = 0.15 + 0.02 = 0.17$

Catastrophic = $0.10 \times 1.0 = 0.10$

Transformation of Cargo to Safety



1. If the loss of cargo is highly unlikely, then safety rate of treatment option is highly acceptable (1.0).
2. If the loss of cargo is unlikely, then safety rate of treatment option is acceptable (0.9) and unacceptable (0.1).
3. If loss of cargo is likely, then safety rate of treatment option is critical (0.8) unacceptable (0.2).
4. If loss of cargo is definite, then safety is catastrophic (1.0).

Highly Acceptable = $0.40 \times 1.0 = 0.40$

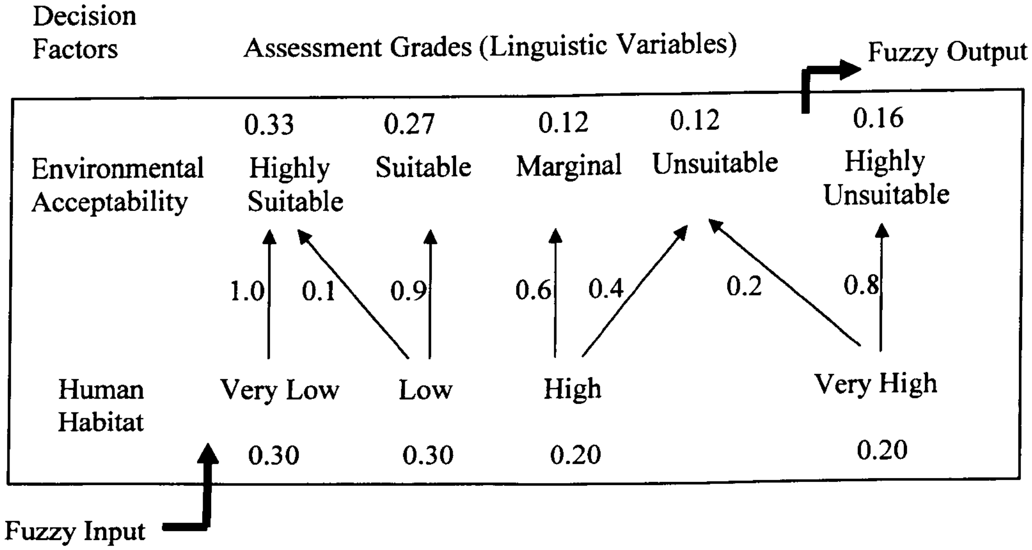
Acceptable = $0.30 \times 0.9 = 0.27$

Unacceptable = $(0.30 \times 0.1) + (0.20 \times 0.2) = 0.03 + 0.04 = 0.07$

Critical = $0.20 \times 0.8 = 0.16$

Catastrophic = $0.10 \times 1.0 = 0.10$

Transformation from Human Habitat to Environmental Acceptability



1. If threat to human habitat is very low, then environmental acceptability is highly suitable (1.0).
2. If threat to human habitat is low, then environmental acceptability is suitable (0.9) and highly suitable (0.1).
3. If threat to human habitat is high, then environmental acceptability is marginal (0.6) and unsuitable (0.4).
4. If threat to human habitat is very high, then environmental acceptability is highly unsuitable (0.8) and unsuitable (0.2).

Highly Suitable = $(0.30 \times 1.0) + (0.30 \times 0.1) = 0.30 + 0.03 = 0.33$

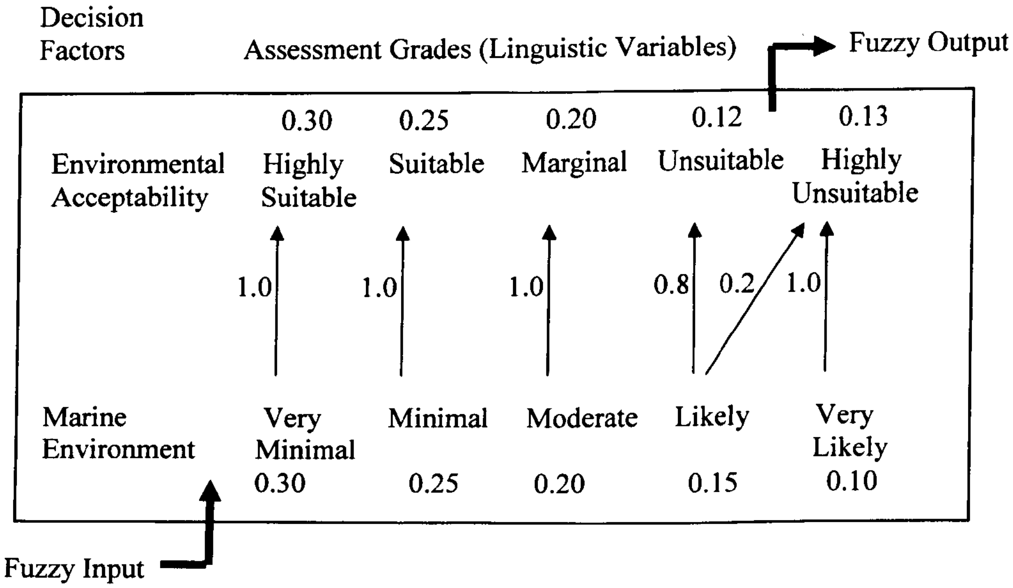
Suitable = $0.30 \times 0.9 = 0.27$

Marginal = $(0.20 \times 0.6) + (0.20 \times 0.2) = 0.12 + 0.04 = 0.16$

Unsuitable = $(0.20 \times 0.4) + (0.2 \times 0.2) = 0.08 + 0.4 = 0.12$

Highly Unsuitable = $0.20 \times 0.8 = 0.16$

Transformation of Marine Environment to Environmental Acceptability



1. If threat to marine environment is highly minimal, then environmental acceptability is highly suitable (1.0).
2. If threat to marine environment is minimal, then environmental acceptability is suitable (1.0).
3. If threat to marine environment is moderate, then environmental acceptability is marginal (1.0).
4. If threat to marine environment is likely, then environmental acceptability is unsuitable (0.8) and highly unsuitable (0.2).
5. If threat to marine environment is very likely, then environmental acceptability is highly unsuitable (1.0).

Highly Suitable = $0.30 \times 1.0 = 0.30$

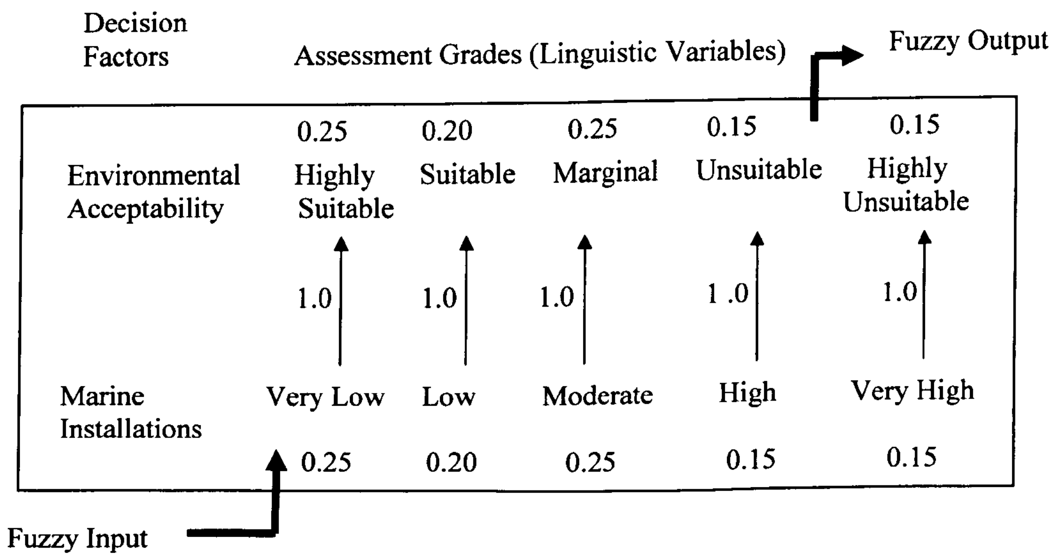
Suitable = $0.25 \times 1.0 = 0.25$

Marginal = $0.20 \times 1.0 = 0.20$

Unsuitable = $0.15 \times 0.8 = 0.12$

Highly Unsuitable = $(0.10 \times 1.0) + (0.15 \times 0.2) = 0.10 + 0.03 = 0.13$

Transformation from Marine Installations to Environmental Acceptability



1. If threat to marine installations is very low, then environmental acceptability is highly suitable (1.0).
2. If threat to marine installations is low, then environmental acceptability is suitable (1.0).
3. If threat to marine installations is moderate, then environmental acceptability is marginal (1.0).
4. If threat to marine installations is high, then environmental acceptability is unsuitable (1.0).
5. If threat to marine installations is very high, then environmental acceptability is highly unsuitable (1.0).

Highly Suitable = $0.25 \times 1.0 = 0.25$

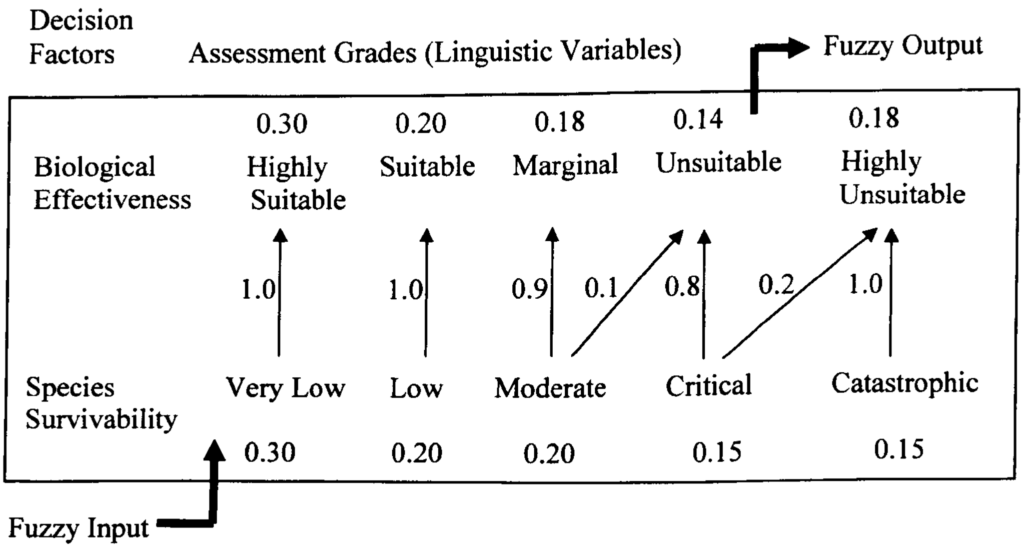
Suitable = $0.20 \times 1.0 = 0.20$

Marginal = $0.25 \times 1.0 = 0.25$

Unsuitable = $0.15 \times 1.0 = 0.15$

Highly Unsuitable = $0.15 \times 1.0 = 0.15$

Transformation of Species Survivability to Biological Effectiveness



1. If threat to indigenous marine species survivability is very low, then biological effectiveness of the treatment option is highly acceptable (1.0).
2. If threat to indigenous marine species survivability is low, then biological effectiveness of the treatment option is acceptable (1.0).
3. If threat to indigenous marine species survivability is moderate, then biological effectiveness of the treatment option is marginal (0.9) and critical (0.1).
4. If threat to indigenous marine species survivability is critical, then biological effectiveness of the treatment option is unsuitable (0.8).
5. If threat to indigenous marine species survivability is catastrophic, then biological effectiveness of the treatment option is highly unsuitable (1.0) and unsuitable (0.2).

Highly Suitable = $0.30 \times 1.0 = 0.30$

Suitable = $0.20 \times 1.0 = 0.20$

Marginal = $0.20 \times 0.9 = 0.18$

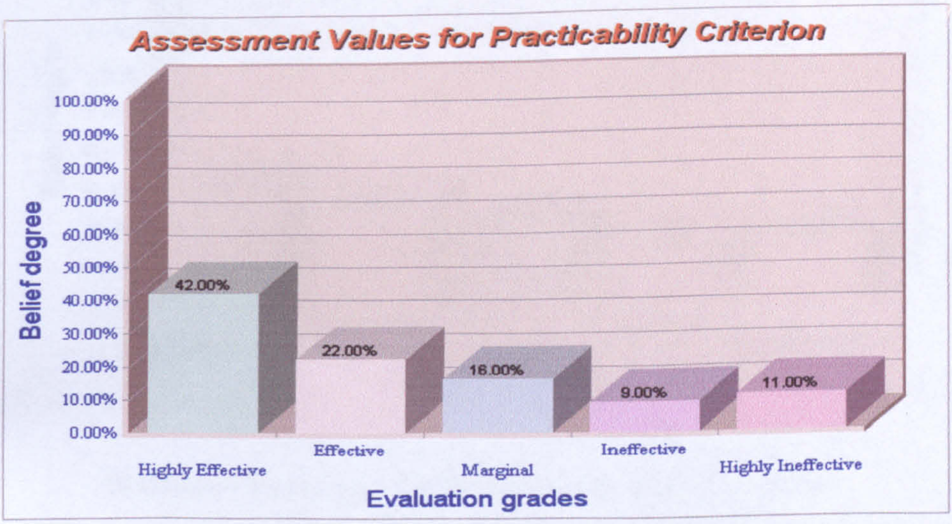
Unsuitable = $(0.15 \times 0.8) + (0.20 \times 0.1) = 0.12 + 0.02 = 0.14$

Highly Unsuitable = $(0.15 \times 1.0) + (0.15 \times 0.2) = 0.15 + 0.03 = 0.18$

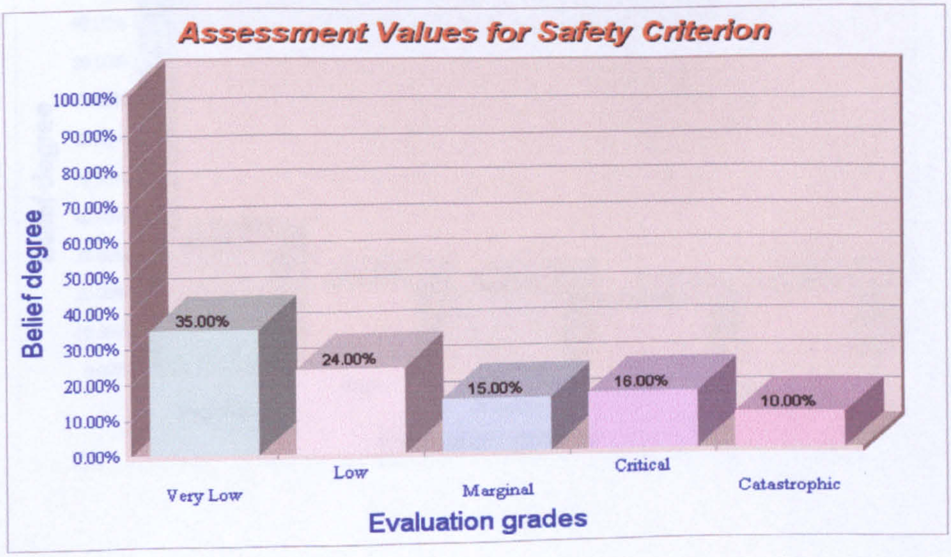
Appendix 7

Results of Distributed Assessments of Evaluation Criteria Using IDS Software Package

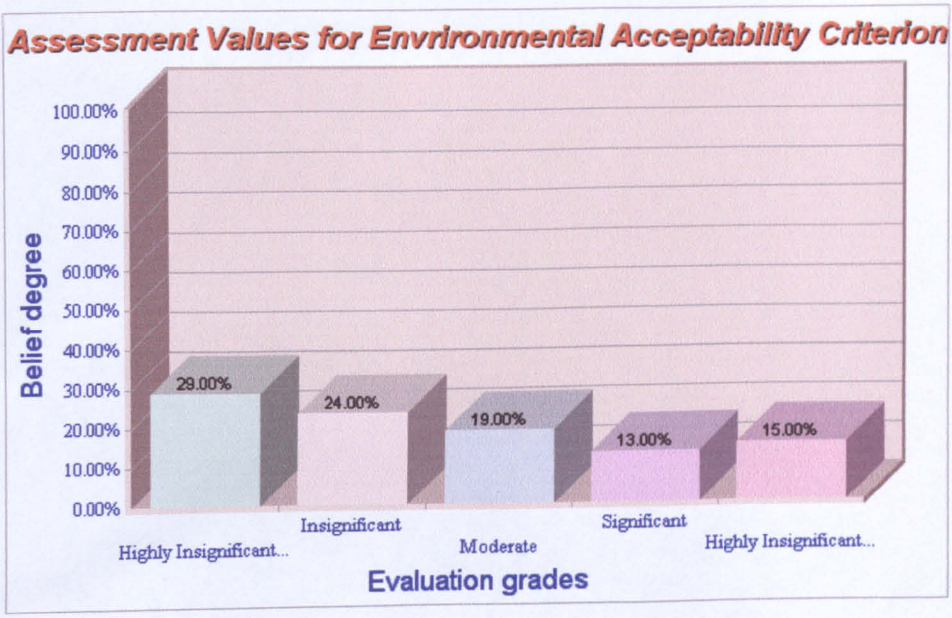
Distributed Assessments Values for Practicability Criterion



Distributed Assessments Values for Safety Criterion



Distributed Assessments Values for Environmental Acceptability Criterion



Distributed Assessment for Biological Effectiveness Criterion