HUMAN RELIABILITY ASSESSMENT IN OIL TANKER OPERATIONS

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Abstract

This research is carried out to improve Human Reliability Analysis (HRA) in oil tanker operations in general, to extend and enhance in specific Cognitive Reliability and Error Analysis Method (CREAM), with the aim of reducing human error and thus subsequently preventing oil tanker spills. It is concentrated on oil tanker operations to address the limitation of availability of human reliability data in the maritime domain. The continual occurrence of oil tanker spills, which was substantiated with analysis of historical data of oil tanker incidents/accidents from 1970 to 2008, provides a judicious reason to conduct this research. The critical review of Formal Safety Assessment (FSA) and HRA results in the development of a conceptual framework of HRA facilitating FSA and incorporating Human Organisational Factors (HOF), which addresses the shortcomings of the generic HRA and FSA methodologies that exist independently in the management of oil tankers to prevent oil spills.

The CREAM is reviewed due to its prominent use in identifying the root causes of human error. However, its inability of providing solutions to an incident/accident investigation and robust quantification of human reliability features stimulates the development of an advanced CREAM and a human reliability quantification model using a combined Analytic Hierarchical Process (AHP) and fuzzy logic approach in this research. In addition to facilitating identification of the root causes of human error, the advanced CREAM also provides the solutions to a quantification model, which enables the development of HRA data in the maritime domain.

Furthermore, lack of CREAM studies on relationships among Common Performance Conditions (CPCs) is addressed by proposing a Decision Making Trial and Evaluation Laboratory (DEMATEL) model, which allows for a comprehensive understanding of relationships and interdependencies among the CPCs. The model could also be used to appreciate and assimilate the relationships and interdependencies among human factor variables involved in other transportation systems and industrial fields. Finally, the research is concluded with an integrated AHP and fuzzy Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) model for determining the selection of an appropriate risk control option (RCO) while performing an incident/accident investigation by taking subjective judgments of decision makers into consideration.

This research as a pioneer work in developing and applying advanced techniques to improve the generic CREAM in oil tanker operations establishes a foundation for future effort to improve the use of CREAM in other industries. The techniques developed can also be tailored to investigate and deal with an incident/accident effectively, resulting in the reduction of human error within the system management of any organisation.

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The author would also like to dedicate this work to his family and thank them for their continuous encouragement and moral support throughout the ordeal of completing this research.

Finally, the author would like to pay tribute to all seafarers who spend their life at sea, ensuring that thousands of oil tanker voyages are completed without a barrel of oil being spilt and making the maritime adventure unique.

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Abbreviations

ABS	American Bureau of Shipping
AHP	Analytic Hierarchical Process
ALARP	As Low As Reasonably Practicable
APP	Availability of Plans/Procedures
ASO	Adequacy of Shipboard Organisation
ASP	Adequacy of Shipboard Training and Preparation
ATHEANA	A Technique for Human Event Analysis
BREAM	Bridge Reliability and Error Analysis Method
BV	Bureau Veritas
CBA	Cost Benefit Assessment
CES	Cognitive Environment Simulator
CI	Consistency Index
CICA	Consistent Configurations/Orientations
CO_2	Carbon Dioxide
COCOM	Contextual Control Model
COW	Crude Oil Washing
CPCs	Common Performance Conditions
CR	Consistency Ratio
CREAM	Cognitive Reliability and Error Analysis Method
CRT	Time of day (Circadian Rhythm)
DEA	Data Envelopment Analysis
DEMATEL	Decision Making Trial and Evaluation Laboratory
DMS	Decision Making Software
DMUs	Decision Making Units
DNV	Det Norske Veritas
DREAM	Driver Reliability and Error Analysis Method

EFCs	Error Forcing Contexts
ELECTRE	Elimination and Choice Expressing Reality
EOC	Errors of Commission
EPCs	Error Producing Conditions
FLIM	Failure Likelihood Index Methodology
FMEA	Failure Mode and Effects Analysis
FNIS	Fuzzy Negative Ideal Solution
FPIS	Fuzzy Positive Ideal Solution
FSA	Formal Safety Assessment
FTA	Fault Tree Analysis
GL	Germanischer Lloyds
HAZID	Identification of Hazards
HAZOP	Hazard and Operability Studies
HCR	Human Cognitive Reliability
HEA	Human Error Analysis
HEART	Human Error Assessment and Reduction Technique
HEI	Human Error Identification
HEP	Human Error Probability
HEPI	Human Error Probability Index
HEQ	Human Error Quantification
HLAs	Helicopter Landing Areas
HOF	Human Organisational Factors
HPFP	Human Performance Failure Probability
HRA	Human Reliability Analysis
HRMS	Human Reliability Management System
HRQ	Human Reliability Quantification
HTA	Hierarchical Task Analysis
IACS	International Association of Classification Societies

ICCL	International Council of Cruise Lines
IGS	Inert Gas System
IMO	International Maritime Organization
ISM	International Safety Management Code
ISPS	International Ship and Port Facility Security Code
ITOPF	International Tanker Owners Pollution Federation Ltd
KR	Korean Register of Shipping
LR	Lloyds Register
MACBETH	Measuring Attractiveness by a Categorical Based Evaluation Technique
MADM	Multi-attribute Decision Making
MARPOL	International Convention for the Prevention of Pollution from Ships, 1973 as amended by the Protocol of 1978
MARSAN	Méthode d'Analyse, de Recherche, et de Sélection d' Activités Nouvelles
MAUD	Multi-attribute Utility Decomposition
MCA	Maritime and Coastguard Agency (UK)
MCDM	Multiple Criteria Decision Making
MERMOS	Méthode d'Evaluation de la Réalisation des Missions Opérateur pour la Sûreté
MMD	Malaysian Marine Department
MMI	Adequacy of Man Machine Interface and Shipboard Operational Support
MODM	Multi-objective Decision Making
MPA	Maritime and Port Authority of Singapore
MTO	Man-Technology-Organisation
NASA	National Aeronautics and Space Administration
NIS	Negative Ideal Solution

NKK	Nippon Kaiji Kyokai
NMD	Norwegian Maritime Directorate
NSG	Number of Simultaneous Goals
OATS	Operator Action Tree System
OCIMF	Oil Companies International Marine Forum
OPA 90	Oil Pollution Act 1990
P & I	Protection and Indemnity Associations
PHRA	Probabilistic Human Reliability Assessment
PIS	Positive Ideal Solution
PRA	Probabilistic Risk Assessment
PSA	Probabilistic Safety Assessment
PROMETHEE	Preference Ranking Organisation Method for Enrichment of Evaluations
PSC	Port State Control
PSFs	Performance Shaping Factors
QAT	Available Time
RA	Risk Assessment
RCOs	Risk Control Options
RI	Random Index
RINA	Registro Italiano Navale
SARAH	Systematic Approach to the Reliability Assessment of Humans
SAW	Simple Additive Weighting
SCQ	Shipboard Crew Collaboration Quality
SHERPA	Systematic Human Error Reduction and Prediction Approach
SLI	Success Likelihood Index
SLIM	Success Likelihood Index Methodology

SMART	Simple Multi-attribute Rating
SMS	Safety Management System
SOLAS	Safety of Life at Sea 1974
STCW 1995	International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
STS	Ship to Ship Operations
SWC	Shipboard Working Condition
THERP	Technique for Human Error Rate Prediction
TOPSIS	Technique for Order Preference by Similarity to the Ideal Solution
TS	Total Sum
UKMSA	United Kingdom Marine Safety Agency

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Chapter 1
Introduction

Summary

This chapter presents an introduction to the research theme, including a brief review of the history and development of Human Reliability Analysis (HRA), an outline of the objectives and a statement of problems that this thesis will aim to solve. These are followed by an overview of the research methodology, elicitation of expert judgment and utilisation of case studies. Subsequently, the layout, scope and structure of the thesis are outlined and described. Finally, the chapter is concluded with remarks on the integration of chapters within the thesis.

1.1 Introduction

Human reliability refers to the probability that a person correctly carries out an action required by a system in a requisite time without performing any redundant activity, which can reduce the system performance (Pyy, 2000). Human Reliability Analysis (HRA) is defined as the utilisation of system engineering and human factor methods to describe the human contribution to risk, which includes a series of methods to identify sources of human errors and to predict the likelihood of their occurrence (Boring, 2008). The purpose of HRA is to provide a complete representation of the human contribution to risk and to establish ways to reduce that risk (Gertman and Blackman, 1994). The assessment of human reliability could represent the human contribution to the total risk in any system leading to a reduction in and prevention of human errors within that system (Kariuki and Lowe, 2006). The HRA can be employed as a tool to reduce human error probabilities (HEPs) to some acceptable minimum standards as determined by the maritime stakeholders. It is composed of quantitative and qualitative features, where quantitatively it facilitates to obtain HEPs, and qualitatively it identifies potential human errors in an incident/accident investigation. The growing need for the employment of HRA in the management of oil tankers to prevent oil spills is substantiated by the occurrences of oil tanker incidents/accidents, which are analysed in detail in Chapter 2.

The advancement and modernisation of the shipping industry has resulted in equipment becoming more reliable however, contribution of human errors towards the cause of an incident/accident tends to surface due to organisational system problems. Hence, it is of paramount importance that the aspect of human errors is incorporated in any effort of quantification of risk within a system. The HRA could provide a realistic assessment of the risks involved in the management of oil tankers, thus assisting stakeholders to reduce spills from oil tankers.

1.2 Aim and Objectives of the Research

The principal aim of this thesis is to improve HRA in oil tanker operations in general, to extend and enhance in specific Cognitive Reliability and Error Analysis Method (CREAM), with the aim of reducing human error and thus subsequently preventing oil tanker spills. The research concentrates on maritime operations due to lack of human reliability data in the maritime domain. The secondary aim of this research is to examine and critically evaluate the applicability of HRA to Formal Safety Assessment (FSA) incorporating Human Organisational Factors (HOF) in the management of oil tankers to prevent oil spills. To achieve these aims, the measurable objectives are outlined as follows:

a). To carry out a critical review of FSA and HRA.

b). To analyse and present a generic oil tanker to provide means of risk factors that need to be considered while carrying out risk assessment for an oil tanker.

c). To develop a conceptual framework of HRA facilitating FSA incorporating HOF in the management of oil tankers to prevent oil spills.

d). To improve the generic CREAM by constructing a novel advanced CREAM framework addressing the human errors and reliability associated with maritime operations taking into account risk control options (RCOs) and cost benefit assessment (CBA) elements while performing an incident/accident investigation.

e). To develop an innovative approach using a Decision Making Trial and Evaluation Laboratory (DEMATEL) technique to reprioritise Common Performance Conditions (CPCs) in CREAM.

f). To establish an innovative human reliability quantification model using a combined Analytic Hierarchical Process (AHP) and fuzzy logic approach, capable of quantitatively evaluating human reliability probabilities in CREAM in maritime operations.

g). To generate an integrated AHP and fuzzy Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) model to determine the selection of an appropriate RCO by taking subjective judgments of decision makers into consideration.

1.3 The Statement of Problems

The problems that this research tries to solve can be identified and described as follows:

a). The HRA element has not been assimilated well into FSA, even though the importance of including human factors in FSA has been reiterated for some time. The thesis attempts to develop a better framework that is capable of incorporating the element of human factors more effectively into FSA concentrating on oil tanker operations.

b). The existing generic CREAM mainly target on the root causes of an incident/accident, in its qualitative analysis. An enhanced novel advanced CREAM framework would be developed to address the human errors and reliability associated with maritime operations, which provides, in addition to the root causes of the incident/accident, corresponding solutions in order to overcome the root causes effectively.

c). Qualitative analysis is used to describe linguistic terms of CPCs in CREAM. Each linguistic term of CPCs is related to a particular contextual effect on the performance reliability. The resultant number of effects of CPCs will provide the state of the Contextual Control Model (COCOM) of CREAM. The interdependencies of CPCs are taken into consideration when the effects of principal CPCs in designated CPC groups fall into neutral. Currently the generic CREAM utilises CPC groupings to determine the outcome of the linguistic term of each CPC in the qualitative analysis of CREAM. Hence, CPCs, being a core component of CREAM, play an important role in CREAM analysis however, there is no systematic method available to illustrate the relationships between the CPCs. An attempt to develop a technique that allows better illustration of CPCs' relationships and interdependencies will be carried out.

d). One of the problems of the generic CREAM is the fallacy of making an assumption that all the CPCs had an equal influence in causing an incident/accident. In real life, the CPCs are not all of equal influence and importance but are interrelated with reference to the incident/accident that may occur. An attempt to quantify human performance failure probabilities in CREAM is carried out to overcome the above fallacy in performing quantification in CREAM.

e). Currently, the selection of RCO deduced from an assessment of an incident/accident to prevent a similar situation from its reoccurrence is often conducted by the expert judgment. An alternative method is developed to perform the RCO selection systematically and effectively to facilitate the establishment of an appropriate RCO for stakeholders with different perspectives.

1.4 Research Methodology

Quantitative and qualitative assessment approaches are utilised to conduct this research. The research will begin by analysing and synthesising historical oil tanker incident/accident statistics from reliable organisations to establish the need of carrying out HRA research in the management of oil tankers to prevent oil spills. The quantitative assessment would be employed in examining historical oil tanker incident/accident statistics to construct bar and pie charts to illustrate the trends of the past oil tanker incidents/accidents. This is followed by scrutinising the present FSA framework and HRA methods. Various technical models are developed using well-established Multiple Criteria Decision Making (MCDM) techniques to address the problems raised in Section 1.3. All the proposed technical models are substantiated with case studies and validated using sensitivity analyses.

1.4.1 Elicitation of Expert Judgment in Research

Experts from classification societies and flag state administrations, including personnel specialising in human reliability and a master mariner with more than ten years of oil tanker sailing experience, were used to evaluate data required for various technical models. Members of the International Association of Classification Societies (IACS) including the American Bureau of Shipping (ABS), Bureau Veritas (BV), Det Norske

Veritas (DNV), Germanischer Lloyds (GL), Korean Register of Shipping (KR), Lloyds Register (LR), Nippon Kaiji Kyokai (NKK) and Registro Italiano Navale (RINA) were requested to participate and share their expertise in evaluating data for technical models in the research. DNV and LR classification society officials responded promisingly to provide evaluation feedback within the permitted time period. Meanwhile, as for the flag state administration officials, the UK Maritime and Coastguard Agency (MCA), Norwegian Maritime Directorate (NMD), Malaysian Marine Department (MMD) and Maritime and Port Authority of Singapore (MPA) were approached. Finally, a DNV human reliability specialist and two anonymous flag state administration officials with accident investigation backgrounds provided the evaluated data for the technical models. The flag state administration officials are selected to provide expert judgments because flag states set, monitor and enforce standards of safety and pollution prevention on local vessels and, enforce international standards of safety and pollution prevention on foreign vessels calling ports under their jurisdictions. The classification societies, on the other hand, are involved in setting technical standards for ships and, provide inspection and assistance to enable the shipping industry to meet these standards, including quality system accreditation. Hence, these two types of organisations' perspectives carry considerable weight for maritime research. All the experts were provided with an Excel spreadsheet that contains the evaluation tables of various case studies presented throughout the thesis. A copy of the spreadsheet is provided in Appendix I and their responses are provided in the corresponding chapters. Lastly all the experts were provided with a final copy of the spreadsheet, which contains various evaluation tables that are used in the thesis, to have their concurrence in the data analysis of this research.

1.4.2 Utilisation of Case Studies

This research employs two types of case studies to cater for the two analysis methods in CREAM. CREAM consists of retrospective and prospective analyses. The retrospective analysis enables the past incident/accident to be reviewed and the root causes of the incident/accident to be determined. It also facilitates review of the likelihood of the incident/accident and ways to prevent reoccurrence. Meanwhile, the prospective analysis can be used to identify possible sources of human errors for an incident/accident that has not been encountered. A case study of the '*Prestige*' accident, which occurred while she was sailing off the West Coast of Galicia on November 13, 2002, is presented to illustrate the retrospective analysis use of CREAM, and a case study of the '*Carina*' incident is presented to illustrate the application of prospective analysis of CREAM. It is a simulation of an incident that occurred while an oil tanker was discharging crude oil at one of the US Gulf of Mexico ports. All the technical case studies are substantiated using sensitivity analyses.

1.5 Layout, Scope and Structure of the Thesis

The thesis is organised and presented in eight chapters. The general framework along with a graphical flowchart of the thesis is illustrated in Figure 1.1, which shows the layout and scope of the chapters. The contents of each chapter are detailed in the following subsections.

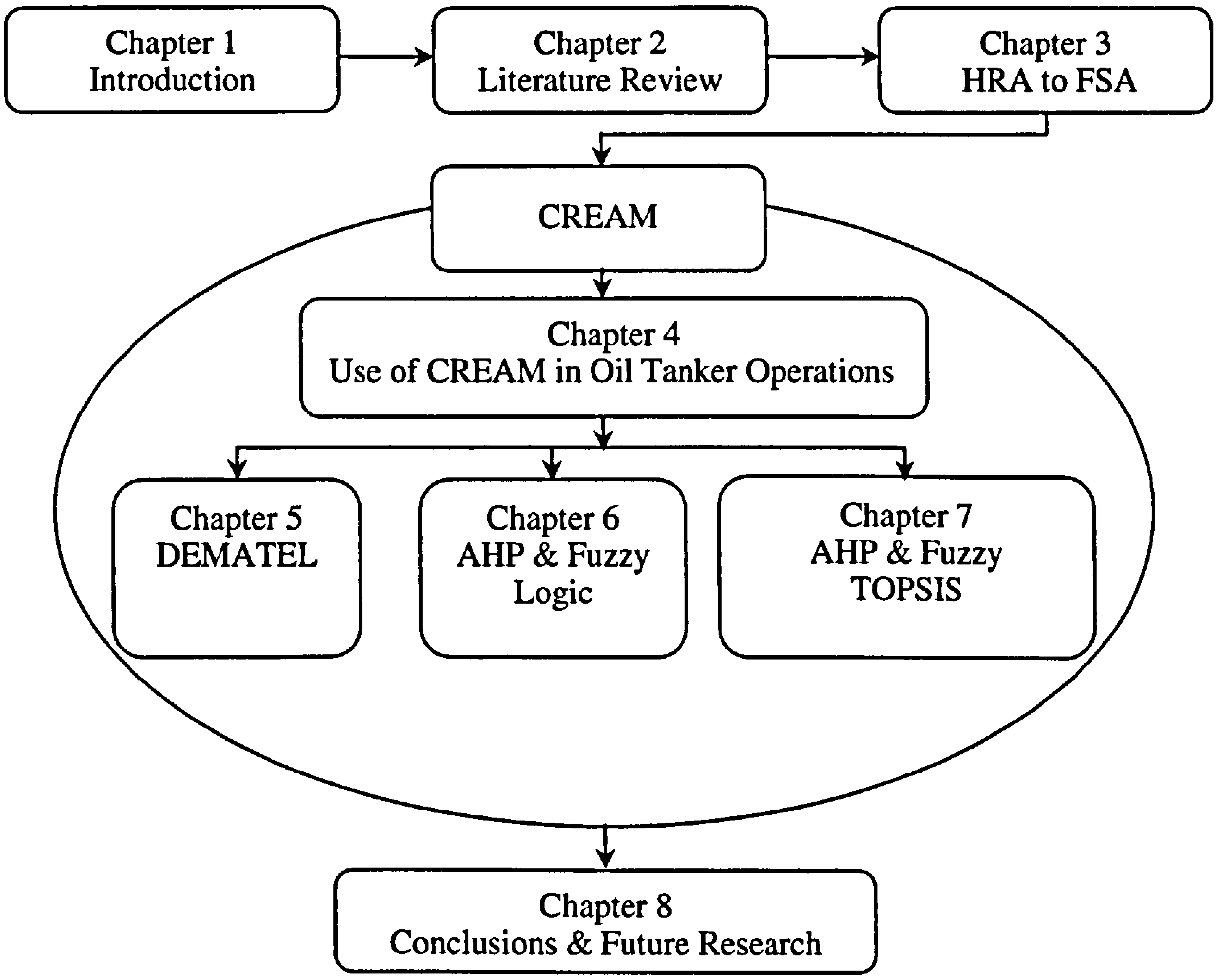

Figure 1.1 The Structure of the Thesis

1.5.1 Chapter 2 - Literature Review

This chapter examines the historical data relating to oil tanker incidents/accidents from 1970 to 2008. A bar chart and three pie charts are constructed and presented to illustrate the trends of the causes of oil tanker spills. Past oil tanker spill statistics are analysed to establish and substantiate the need of carrying out the research on HRA incorporating HOF in the management of oil tankers to prevent oil spills. This is followed by critical reviews of FSA. The chapter is concluded with review of first and second generations of HRA and MCDM methods.

1.5.2 Chapter 3 - Use of HRA to Facilitate FSA: An Oil Tanker Case

This chapter addresses the application of HRA to facilitate the FSA framework, which incorporates HOF in the management of oil tankers to prevent oil spills. The application of HRA to facilitate FSA onboard oil tankers is examined and critically evaluated. A new framework of an application of HRA to facilitate FSA, which has integrated human factor elements substantially into FSA, is developed. RCOs for HOF of various networks within the management of an oil tanker are analysed and presented to provide means of risk controls. The proposed framework is demonstrated with a case study. A hierarchical task analysis (HTA) on the status of cargo tanks' inert gas valves during discharging operations onboard an oil tanker is presented. Finally, a series of recommendations that should be adopted by tanker owners to reduce the risk of oil spills are presented.

1.5.3 Chapter 4 - Use of CREAM to Facilitate HRA in Oil Tanker Operations

This chapter presents a CREAM tailored for its application to a maritime context. A new advanced CREAM framework is developed and presented to address the human errors and reliability associated with maritime operations. The significance of addressing human cognitive functions and context in human error analysis (HEA) stimulates the creation and development of the advanced CREAM. The CREAM framework provides a practical approach in performing an incident/accident investigation through its prospective and retrospective analyses. The successful application of CREAM principles in the analysis of aviation and nuclear power plant incidents/accidents triggers its use in the maritime domain. In addition to applying the methodology, two new phases of RCOs and CBA are added to a novel advanced CREAM framework. Hence, the innovative advanced CREAM, besides finding the root causes of an incident/accident, also provides the corresponding solutions in order to overcome the root causes effectively. Furthermore, changes in the classification schemes, including the renaming of five CPCs, introduction of a CBA matrix and adding of new classification categories, have been made to allow CREAM to be more adaptable in the maritime domain. Case studies of the '*Carina*' and '*Prestige*' accidents are used to demonstrate that the new advanced CREAM could be applied to deal with human error analysis related to maritime incidents/accidents. Thus, this research could facilitate the development of HRA in the maritime field and enhance the HRA research in the maritime industry.

1.5.4 Chapter 5 - Reprioritisation of CPCs in CREAM Using a DEMATEL Technique

This chapter produces a novel approach using a DEMATEL technique to reprioritise CPCs in CREAM. Presently CPC groupings are used to determine the outcome of linguistic terms of CPCs in the qualitative analysis of CREAM. However no prioritisation of CPCs exists within the designated CPC groups. This results in the assumption that all the CPCs are of equal weights of importance however, this is not the case in reality. This innovative approach of using a DEMATEL model in CREAM could provide an alternative for decision makers to analyse scientifically an appropriate CPC that needs to be emphasised to reduce human errors and prevent a similar incident/accident to the one investigated from reoccurring. The model is developed to reprioritise CPCs by taking subjective judgments of decision makers into consideration. The proposed model has been demonstrated with a case study and substantiated using a sensitivity analysis. The model is a supplement to the new advanced CREAM framework that has been developed and can assist HRA analysts to perform better qualitative analysis. Finally, the newly developed approach using a DEMATEL model can be used in other HRA methods and can be adapted and utilised in other transportation systems and industrial fields, such as the chemical, gas and oil industries, resulting in the reduction of human errors.

1.5.5 Chapter 6 - Combined AHP and Fuzzy Approach to Facilitate the Quantification Analysis of CREAM in Oil Tanker Operations

In this part of research an innovative human reliability quantification model has been developed using a combined AHP and fuzzy logic approach, which is capable of quantitatively evaluating human reliability probabilities in CREAM in maritime operations. This methodology is found to be particularly useful in dealing with the limitation of availability of data in the maritime domain and, the uncertainty and complexity that exist in the quantitative analysis of human reliability. The proposed model is demonstrated with a case study and validated using a sensitivity analysis. Thus, this research can facilitate the development of HRA quantification in the maritime field and subsequently assist in reducing human errors in maritime operations.

1.5.6 Chapter 7 - RCO Selection in CREAM Using Integrated AHP and Fuzzy TOPSIS Model

This chapter presents an integrated AHP and fuzzy TOPSIS model to determine the selection of an appropriate RCO by taking subjective judgments of decision makers into consideration in CREAM. The AHP method is used to determine the relative importance of weights within the established criteria of CBA elements from the selected RCOs. This is followed by ranking of the RCOs determined by the fuzzy TOPSIS. The proposed model has been demonstrated with a case study and validated using a sensitivity analysis. Similar to the DEMATEL model, the integrated model is used as a supplement to the advanced CREAM that has been developed with a promising HRA model for identifying and providing solutions for the root causes of an incident/accident. Furthermore, the proposed integrated AHP and fuzzy TOPSIS model can be adapted and used in other transportation systems and industrial fields.

1.5.7 Chapter 8 – Conclusions and Further Research

Finally, conclusions and further research are presented in Chapter 8.

1.6 Integration of Chapters within the Research

The integration of the whole research begins with the construction of a framework for the application of HRA to facilitate FSA that leads to the review of one of the selected second generation HRA methods. Initially CREAM is reviewed due to its prominent use for identifying root causes of human errors. Its lack of providing solutions to an incident/accident investigation and a robust quantification of human reliability feature led to the development of a new advanced CREAM framework. The innovative advanced CREAM framework is developed to address the human errors and reliability in maritime applications with an emphasis on oil tanker operations. The lack of research studies on relationships and interdependencies of CPCs, which play a significant role in CREAM, resulted in this research introducing a novel approach using a DEMATEL model to allow decision makers to have better understanding of CPCs. To address CREAM's lack of quantification of human reliability feature, a new human reliability quantification model is proposed using a combined AHP and fuzzy logic approach dealing with the limitation of availability of data in the maritime domain and, the uncertainty and complexity that exist in the quantitative analysis of human reliabilities. The continuity of integration of the research ends with an integrated AHP and fuzzy TOPSIS model to determine the selection of an appropriate RCO by taking subjective judgments of decision makers into account, which enhances the applicability of the new advanced CREAM framework. Thereby all the chapters are effectively interwoven with a close relationship between chapters within this research.

1.7 Conclusion

This chapter outlines the principal aim and objectives of the research. The scope, research methodology and elicitation of expert judgement are briefly described followed by the layout of the thesis. Additionally, the integration of chapters within the thesis is provided. Most of the HRA previously studies have been carried out in the nuclear, chemical, oil, gas and aviation industries. This research has added to the frontier of knowledge in a way that has not been done before because of the limited nature of similar research in the maritime domain.

Chapter 2
Literature Review

Summary
This chapter presents a literature review on the significance of and need of carrying out research on HRA incorporating HOF in the management of oil tankers to prevent oil spills. Historical oil tanker accident data is analysed to emphasise and substantiate the need for this research. Other aspects relating to FSA, HRA and MCDM studies used in the research are also described.

2.1. Introduction
The majority of maritime accidents have been caused by human errors (DNV, 2002). Recent views on the development of human error studies indicated that human error is a symptom of deeper fault within a management system and is an instigating theme for an investigation of an accident (Dekker, 2006). The term ‘human error’ has many denotations including human error as a cause, human error as an event and human error as a consequence (Hollnagel and Amalberti, 2001). Reason (Reason, 1990) viewed human error as “a generic term to include all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency”. He also perceived that human error problems can be divided into person and system approaches. The person approach focused on individual errors, whereas the system approach concentrated on the environment in which an individual works (Reason, 2000). Human error can also be caused by failure of operation, poor management and lack of maintenance or faulty design within a system. It could even be the result of some latent failures left within a management system. Another tendency for the occurrence of human error is during human’s departure from routine procedures while performing a task (Rasmussen, 2003). Some research studies on HRA used the term ‘human failure event’ instead of ‘human error’ to avoid blame implication while performing an incident/accident investigation. Diversity in human error classification, including error of commission (EOC) and error of omission aggravates in determining which human error has occurred. Another expression used in human error terminology is human

factors. Human factors can be defined as "a discipline concerned with the design and operation of technological and organisational systems to achieve proper adaptation of human tasks" (IMO, 2002a). Additionally, human factors are dealt with through ergonomic principles that relate to the study of efficiency of persons in their working environment. For the purpose of this research, human error refers to larger terms that incorporate all of the above mentioned features. The introduction of automation and advancement in shipping management provide many defensive levels similar to Reason's Swiss Cheese Model of system accidents such as warning alarms, physical barriers and automatic shutdowns (Reason, 2000). Even though rules, regulations and procedures have been assimilated in the operation of shipboard management systems, oil tanker incidents/accidents still occur (Hollnagel, 2005). These have prompted the formulation of this research. The historical data of oil tanker incidents/accidents from 1970 to 2008 is analysed in the following section to establish and substantiate the need of carrying out research on HRA incorporating HOF in the management of oil tankers in order to prevent oil spills.

2.2 Historical Data of Oil Tanker Incidents/Accidents

Some of the organisations that maintain reliable data in the maritime industry include classification societies, which mainly operate from the viewpoint of compliance with various sets of rules and regulations being in force, and Protection and Indemnity Associations (P & I), which tend to collect data from the viewpoint of financial losses due to lack of safety. Meanwhile, the International Tanker Owners Pollution Federation Ltd. (ITOPF) concentrates on maintaining good failure data records on tanker incidents/accidents. Furthermore, the implementation of the International Safety Management Code (ISM), which demands the maintenance of proper systematic documentation as one of the required criteria in implementing the code, results in shipping companies keeping and maintaining well documented failure data on their fleets. The ITOPF statistics have been selected for this research because their failure data is more related to oil tankers.

2.2.1 ITOPF Statistics

The data collected by the ITOPF covers all incident/accident spillages except those resulting from acts of war. It is also noted that the figure for the amount of oil spilt in an incident/accident includes all oil lost to the environment, including that which is burnt or remains in a sunken vessel. Table 2.1 shows the annual quantity of oil spilt from 1970 to 2008. Similar annual quantity oil spilt is illustrated in Figure 2.1 for easier comprehension.

Table 2.1 The Annual Quantity of Oil Spilt from 1970 to 2008 (ITOPF, 2008)

Year	Quantity ('000 tonnes)	Year	Quantity ('000 tonnes)	Year	Quantity ('000 tonnes)
1970	330	1983	384	1996	80
1971	138	1984	28	1997	72
1972	297	1985	85	1998	13
1973	164	1986	19	1999	29
1974	175	1987	30	2000	14
1975	357	1988	190	2001	8
1976	364	1989	174	2002	67
1977	291	1990	61	2003	42
1978	386	1991	430	2004	15
1979	640	1992	172	2005	17
1980	206	1993	139	2006	13
1981	48	1994	130	2007	18
1982	12	1995	12	2008	2

Figure 2.1 The Annual Quantities of Oil Spilt from 1970 to 2008 (ITOPF, 2008)

A few very large spills are accountable for a high percentage of the oil spilt. The figure for a particular year is severely distorted by a single large incident/accident. It is clearly illustrated by those in 1979 (Atlantic Empress-287 000 tonnes), 1983 (Castillo de Bellver-252 000 tonnes), 1988 (Odyssey-132 000 tonnes), 1989 (Exxon Valdez-37 000 tonnes and Khark V-80 000 tonnes), 1991 (ABT Summer-260 000 tonnes), 1999 (Erika-20 000 tonnes) and 2002 (Prestige-63 000 tonnes). Furthermore, it is apparent that the quantity of oil spills has decreased significantly during the last thirty eight years. The average annual quantity of oil spills during the 1990's was about a third of that during the 1970's. One of the reasons could be due to the implementation of international and national regulations listed as follows:

a). International Convention for the Prevention of Pollution from ships, 1973 as amended by the protocol of 1978 (MARPOL 73 / 78).

b). Oil Pollution Act 1990 (OPA 90).

c). ISM Code which has been incorporated in International Convention for the Safety of Life at Sea, 1974 (SOLAS 1974).

However the average annual quantity of oil spilt during the 1990's is almost the same as that during the 1980's. The average annual quantity of oil spilt in the 2000's was about one sixth of that during the 1980's. Table 2.2 and Figures 2.2, 2.3 and 2.4 illustrate the causes of oil spills for incidents/accidents for the amount of less than 7 tonnes, 7 to 700 tonnes and more than 700 tonnes respectively for the period of 1974 to 2008.

Table 2.2 The Frequency of Incidents/Accidents of Oil Spills by Cause (ITOPF, 2008)

Figure 2.2 The Frequency of Incidents/Accidents Involving Oil Spills < 7 tonnes by Cause (ITOPF, 2008)

Figure 2.3 The Frequency of Incidents/Accidents Involving Oil Spills 7 – 700 tonnes by Cause (ITOPF, 2008)

Figure 2.4 The Frequency of Incidents/Accidents Involving
Oil Spills > 700 tonnes by Cause (ITOPF, 2008)

By analysing Figures 2.2, 2.3 and 2.4, the following conclusions can be made:

a). Most spills from oil tankers result from routine operations such as loading, discharging and bunkering operations, which normally occur in ports or at oil terminals. All these operations are associated with human interaction, thus substantiating the need for research into HRA incorporating HOF in the management of oil tankers in order to prevent oil spills. Detailed descriptions of oil tanker operations relating to loading, discharging and bunkering operations are provided in the ensuing section.

b). The majority of these operational spills are small, with 91% involving quantities of less than 7 tonnes.

c). Accidents involving collisions and groundings generally result in much larger spills, with almost half and a fifth involving accidents of oil spills of 7-700 tonnes and more than 700 tonnes respectively.

d). Oil spill incidents due to hull failures are less common for accidents involving less than 7 tonnes of spill and more prevalent for accidents involving spills of more than 700 tonnes. Similar trends are observed for the accident categories of fires and explosions.

2.3 Oil Tanker Operations

Some of the oil tanker routine operations that involve human interaction, including loading, discharging and bunkering operations, are illustrated in this section.

2.3.1 Loading Operations

Prior to a loading operation, the voyage order that includes loading orders will provide the quantity of cargo to be loaded. The designated person in charge onboard the vessel will plan the loading operation, such as the allocation of cargo tanks for various parcels of cargoes and the loading sequences, taking into consideration the vessel's stresses throughout the loading operation. The loading operation can be carried out via loading arms or flexible cargo hoses whilst the vessel is safely moored alongside a pier, while the vessel is moored to an offshore buoy, or by ship to ship transfer, when two vessels are moored to each other in open seas. Cargo can be loaded into cargo tanks via cargo valves, which are operated by designated crew members. Even for vessels equipped with highly automated valve operations, it is still necessary for a crew member to operate the valves. Some modern vessels are equipped with automated cargo tank gauging equipment. However, at the final stages of the loading operation, crew members are required to monitor the cargo levels in the cargo tanks by means of manual gauging (Huber and Marton 2001; Hayler and Keever, 2003; IMO, 2006b).

2.3.2 Discharging Operations

The discharging operation, like the loading operation, also has a designated person in charge onboard to monitor the overall discharging operation. Similar procedures to the loading operation take place, which involve the vessel's crew members. Additionally, cargo pumps are used to pump cargoes from the vessel, resulting in more manpower being required from the deck and engine department to monitor the operation of cargo pumps in the cargo pump room and in the engine room respectively. In the case of a crude oil tanker, an additional operation of crude oil washing will be carried out whilst the vessel is discharging the cargo (Huber and Marton 2001; IMO, 2006b).

2.3.3 Bunkering Operations

Human interactions involved in bunkering operations are similar to the loading operations of oil cargo. If the bunkering operations are performed by two vessels, the two designated persons in charge will be monitoring the bunkering operations on their respective vessels. On receiving a bunkering order, which states the quantity of bunkers to be loaded, the designated person in charge onboard the vessel will plan the bunkering operations. These include allocation of bunker tanks and the bunkering sequences, taking into account the vessel's stresses throughout the bunkering operations. Bunkering operations can be carried out via bunkering arms while the vessel is safely fast on the berth, by flexible cargo hoses whilst the vessel is safely moored alongside a pier, or by ship to ship transfer, when two vessels are moored to each other while the vessels are in open seas. Bunkers will be loaded into bunker tanks via bunker valves, which are operated by designated crew members. The bunker valves and bunker level in the bunker tanks will be monitored strictly by the crew members to prevent an oil spill. In addition to the automatic gauging system installed onboard, manual gauging is employed throughout the bunkering operations. Extra precautions are taken when bunkering operations are carried out at the same time as loading operations (Veentjer, 2009).

2.4 FSA

FSA is a formal, structured and systematic risk based methodology for assessing risk factors associated with an activity by evaluating the costs and benefits of different options for reducing those risks (IMO, 2002b). The FSA is proposed to enhance maritime safety in many aspects, including the marine environment and property. The FSA process can assist in determining when the worst consequences of human failure and relevant risks reach acceptable levels, or when certain operative or mitigation measures are to be adopted (IMO, 2002b). Hence, FSA can be used as a tool in the evaluation of new safety regulations or making a comparison between existing and possibly improved regulations, with a view of achieving a balance between the various technical and operational issues, including the human element, and between safety and costs (IMO, 1997b).

The FSA methodology was developed partly as a response to the disaster of a capsized ship, Herald of Free Enterprise, on March 06, 1987. The outcome of the investigation was the Carver Report, which recommended that FSA should be used to prepare safety cases for UK shipping. This led to the UK Maritime Coastguard Agency (MCA) to submit a proposal of a FSA approach in formulating rules and regulations for the maritime industry to the International Maritime Organization (IMO) in 1993. Consequently, an interim Guidelines for the Application of FSA to the IMO Rule-Making Process was adopted by the IMO in 1997 (Kuo, 1998). Some of the benefits that can be achieved by adopting FSA as a regulatory tool are as follows (Wang, 2001):

a). An integrated way of addressing all safety aspects using a consistent regulatory regime.

b). Safety investment is aimed at achieving the greatest benefit, resulting in cost effectiveness.

c). Using a proactive approach that allows hazards that have not yet given rise to accidents to be appropriately considered.

2.4.1 FSA and Its Current Status

Although the emphasis to include human factors in FSA has been echoing for some time, HRA has not been well incorporated into FSA. FSA can also be used as a tool to assist in the evaluation of new marine safety regulations whereby, it provides a consistent regulatory regime which deals with all aspects of safety incorporating cost effectiveness. Furthermore, it uses a proactive approach that addresses new risks posed in the future. Among the few efforts where FSA was applied in the maritime industry was its application to offshore support vessels (Sii, 2001), containerships (Wang and Foinikis, 2001), fishing vessels (Loughran et al., 2003), cruise ships (Lois, 2004; Lois et al., 2004), oil tankers (Subramaniam, 2003), ship navigation (Hu et al., 2007), a trial study on the safety of bulk carriers (IMO, 1998; 2002a), trial study on high-speed catamaran ferries (IMO, 1997a) and trial study on helicopter landing areas (HLAs) in passenger ships (Skjong et al., 1997). A generic vessel is required for the application of FSA. Many generic models describing vessels have been constructed, such as those for containerships (Wang and Foinikis, 2001), for fishing vessels (Loughran et al., 2003) and for oil tankers (Subramaniam, 2003). The use of FSA helps to identify the stakeholders to whom risks, costs and benefits may occur. A trial application of FSA of HLA on passenger ships as a safety measure carried out by DNV for Norway and the International Council of Cruise Lines (ICCL) showed that it could not be justified in terms of cost effectiveness and resulted in a decision to repeal the IMO's requirement of having HLAs on all passenger ships prior to the relevant regulations coming into effect

(Skjong et al., 1997). This was the initial sign of approval of FSA by the IMO. This was followed by the acceptance of FSA by the maritime community as an effective approach to having a safer shipping environment which was further proven by the fact that the IMO had approved the application of FSA for supporting the rule-making process in 2002 (IMO, 2002b; Wang, 2006).

Some of the recent critical reviews on FSA were carried out by Soares and Teixeira (2001), Wang (2001; 2006), Rosqvist and Tuominen (2004), Mennis et al. (2005) and, Kontovas and Psaraftis (2006; 2009). Soares and Teixeira (2001) reviewed a few applications of quantified risk assessment using reliability theories within the scope of maritime transportation. They agreed that the IMO had recognised the need for a formalised approach to safety assessment. Additionally, they drew attention to the slower phase of acceptance of risk-based decisions making. Wang (2001) emphasised the need for further development of FSA and suggested various safety assessment methods based on the situation to assess risks at different phases of a ship's life cycle. He (2006) also suggested the need of taking into account the problems of human errors in FSA. Furthermore, Wang added that application of FSA could facilitate collection of failure data thus leading to better credibility attained by the FSA. The call to incorporate human factor element into FSA has been in the research domain for some time however no framework has been developed to cater to its needs. This chapter will address the aspect of assimilating human error element in FSA by the proposal of application of HRA to FSA incorporating HOF in the management of oil tankers to prevent oil spills. Meanwhile Rosqvist and Tuominen (2004) proposed a new approach of FSA quantification criteria to be used as a safety test to guide the peer review process to establish the qualification of FSA to determine its acceptance. Mennis et al. (2005) used an application of Markov theory, which relates to the stochastic process, in second and third steps of FSA. The theory is used to identify probabilities for the different conditions a ship can be with the application of RCOs and proposed cost models and process modelling to examine the FSA methodology reliability. One of the important aspects raised by Kontovas and Psaraftis (2006; 2009) was suggestions to derive more than one RCO instead of the present FSA culture tendency of selecting one optimum RCO. In addition they have called for more transparency of the FSA process which could strengthen the FSA's position in the IMO's decision making process. The effectiveness of FSA was raised when the IMO decided not to implement mandatory double hulls and double side skins on bulk carrier regulations (IMO, 2004). In addition, utilisation of expert judgments in deriving and selecting RCOs taking into account the CBA raised more questions on the reliability of FSA. All these resulted in the IMO forming a FSA expert group to cater for the need of reviewing various FSA studies submitted judiciously, including those on cruise ships, Ro-Ro passenger ferries, liquefied natural gas carriers and containerships (IMO, 2009). Furthermore a new element of environment criteria was added to the generic FSA (IMO, 2008; LR, 2008). Hence, the FSA is going through a reasonable review continuously to ensure that it remains as one of the maritime safety policy decision making instruments in the maritime industry.

2.5 HRA

Human factors are the most important contributors to the causation and avoidance of accidents, leading to the identification of human elements, which is to be achieved through the HRA (IMO, 2002b). The HRA provides a good collection, interpretation and application approach to human failure data, resulting in improving human error and human factors within an organisation, including in the maritime industry, in a shipping company or onboard a ship (Cepin, 2008a). It can be used to estimate the quantitative and qualitative contributions of human performance to a system (Swain, 1990). Furthermore, prevention and reduction of human error is vital for the improvement of safety in shipboard management. The evidence from many incident/accident inquiries shows that events leading to an incident/accident are more often subject to error prone situations and error prone activities (Hollnagel, 2005). Hence, a second generation HRA method, CREAM was selected because it incorporates core elements of CPCs that take into account situations and activities relating to an incident/accident, to facilitate the finding of the root causes of the incident/accident. The assessment of CPCs can provide a better understanding of which aspects of human error caused an incident/accident. Some of the human error could be due to performance failure by crew, or the working situation in which the crew reacted, or could even be due to the lack of training provided to the crew.

2.5.1 HRA History

An independent discipline related to human factors concerned with the design of machines, operations and working environments to match human capabilities and limitations was established in the 1950s. The discipline is meant to reduce the frequency of unwanted consequences of human errors in the operation of a complex system, thus the research on human errors began in order to improve performance of the system. Researchers in this field came to recognise that the old approaches of designing a system primarily focused on hardware efficiency and effectiveness did not provide good system performance. Furthermore, they also realised the need for identification and quantification of human errors to verify various risks within a system. One of the ways to improve a system is by incorporating human elements, which can be achieved by carrying out HRA and mitigating potential human errors within the system. Once that has been achieved, the human errors element within the system can be reduced at the initial design stage itself by including new features to remove the human errors altogether within the system or by adding some new aspects within the existing system that reduce the human errors. The first attempt to estimate human error probabilities in a risk analysis of a complex system was carried out in 1952. One of the first HRA methods developed and used was the Technique for Human Error Rate Prediction (THERP), in 1961. The first symposium on HRA was held in 1964. The first large scale application of HRA was carried out in 1972, when THERP was used to assess the impact of estimated human errors in a probabilistic risk assessment (PRA) of two nuclear power plants, referred to as the WASH-1400 reactor safety study. A handbook of THERP HRA and companion workbook, which are most commonly used in commercial and military systems, were produced on the outcomes of the WASH-1400 reactor safety study (Swain, 1990).

2.5.2 Development of HRA

Development in HRA has experienced two generations. The first generation HRA methods use a simple error taxonomy and "fits/doesn't fit" dichotomy to correspond error state to error identification and quantification (Boring, 2005). There are two types of HRA which include retrospective HRA and prospective HRA. The retrospective HRA deals with review of past incidents/accidents and determines the root causes of the incident/accident , whereas the prospective HRA deals with identifying possible sources of human error in a system that has not been implemented or for an incident/accident that has not been encountered (Boring, 2008). These two types of HRA will be elaborated in detail from an improved advanced CREAM perspective in Chapters 4 and 5. Some classical first generation HRA methods are reviewed as follows.

2.5.2.1 Technique for Human Error Rate Prediction (THERP)

The THERP applies a schematic representation of human actions and relevant system events such as the HRA event tree. Its methodology includes defining the systems failures, listing and analysing the related human operations and identification of human errors that might occur, and relevant human error recovery modes. It also allows for estimation of relevant HEPs and the effects of human error in system failure events. Lastly the methodology provides recommendations for change to the system and recalculates the system failure probabilities. The prominent features of THERP are that it has been well validated by its use for the past five decade's in the various industries and its use of Performance Shaping Factors (PSF) to complement the task analysis. Furthermore its capability in modelling the recovery of errors of a system which allows for the use of checklists and subsequently, provides verifications that increase the system's reliability attracts the use of THERP. It can also be easily integrated with fault tree reliability methodologies. The criticisms of THERP are on its assumption that human errors can be accurately quantified and predicted. In addition it requires an enormous effort to obtain reliable HEPs and provides no guidance in modelling of scenarios and impacts of PSFs on human errors (Kirwan, 1994; 1996, 1997a; 1997b; Hollnagel, 1996; 1998).

2.5.2.2 Human Error Assessment and Reduction Technique (HEART)

HEART is used to evaluate the probability of human error occurring throughout the completion of a specific task. On obtaining the human error, error reduction can be performed to prevent similar human error from reoccurring within a management system. The HEART begins by classifying the task under analysis into the HEART generic categories, which have an associated human error probability (HEP). This is followed by identifying and determining the assessed proportion effects of the Error Producing Conditions (EPCs) associated with the task. Finally, a formula is used to compute the established proportion effects of the EPCs (Salmon et al., 2003).

Some of the advantages of using HEART are that it is simple to use, it takes into account the reduction of the occurrence of errors, it is flexible resulting in its application in wider domains and the EPCs and their multipliers are based on experimental data on human performance, meaning that HEART comes with everything required to perform an HRA (Kirwan, 1994; Salmon et al., 2003; Sandom and Harvey, 2004). However, one of the criticisms of using HEART is that it relies heavily on expert judgment to obtain HEPs and the assessed proportion of EPC effects. Furthermore, the interdependence of EPCs, which is not modelled in the methodology, is not taken into consideration, and guidelines on performing task classification and determining the assessed proportion of EPC effects are not provided. Furthermore, the EPCs are concentrated on individual performance, despite the fact that many incident/accident situations are the result of team performance, and it also pays limited attention to the factors influencing cognitive performance (Kirwan, 1994; Salmon et al., 2003; Sandom and Harvey, 2004).

2.5.2.3 Human Cognitive Reliability (HCR)

HCR model was developed to a specific operator model on the basis of the skill-based, rule-based and knowledge-based characteristics. This model is used to classify the cognitive processing required by operators' actions. Its methodology includes identifying actions that need to be analysed, and classifying type of cognitive processing required by the actions such as skill based, rule based and knowledge based. It also provides the determination of the median response time to perform the required task, by adjustment of median response times to allow for performance influencing factors. The methodology also supports determining the system time window in which action must be taken and obtaining of a normalised time value by computation of dividing the system time window by median response time. It makes use of the correlation of human reliability versus time availability to provide a HEP. The HEP calculation is taken as a product of cognitive and manual error probabilities. The cognitive error probability is inversely proportionate to nominal experience and training, stress level and man machine interface. The HCR model can assist identify actions that need to be analysed and can classify the types of cognitive processes that are required by the actions (Antolin, 2001; Collier, 2001).

The main advantages of using the HCR are that the approach can be easily assimilated with modelling assessment and that it takes into account cognitive and environmental PSFs. In addition, this approach can be substantiated continuously by using the HCR correlation curves, which can be developed from the results of simulator experiments. However, one of the criticisms of using the HCR is that the applicability of the HCR is currently limited to the nuclear industry. The HCR correlation was originally developed for use within the nuclear industry. The HCR model's use for all human activities is not verified, and the relationships of PSFs and non-response probabilities are not well addressed. It also does not comprehensibly address the details of cognitive processes resulting in information about intentional failures not being obtained (Kirwan, 1994; Hollnagel, 1996; Modarres, 2006). The HCR model has already been updated to a Probabilistic Human Reliability Assessment (PHRA) and subsequently the PHRA has been superseded by the Méthode d'Evaluation de la Réalisation des Missions Opérateur pour la Sûreté (MERMOS), which is categorised as a second generation HRA method (Bell and Holroyd, 2009).

2.5.2.4 Systematic Human Error Reduction and Prediction Approach (SHERPA)

SHERPA was developed by Embrey (Embrey, 1986) to predict human error. It uses taxonomy of human error by applying a psychological mechanism. SHERPA has been applied in nuclear power generation, the petrochemical industry, oil and gas extraction, and the power distribution industries. It uses a computerised question and answer formation to identify likely errors of steps in the task analysis. The error modes identified are based on the skill, risk, knowledge model produced by Rasmussen et al. (1987) and Reason's (1990) generic error modelling system. The approach allows for ascertaining whether errors can be recovered immediately, at later phase or not at all. The SHERPA procedure begins with the construction of a Hierarchical Task Analysis (HTA), followed by the classification of the tasks that need to be performed. Then, a Human Error Identification (HEI) step is carried out in relation to the activity that needs to be performed. This is followed by consequence analysis, where the consequence of each error on a system is considered, and recovery analysis, where recovery potential is determined from the recognised error. Subsequently, an ordinal probability analysis can be carried out to rate the probability of the error occurring. If the consequence of the error is deemed to be critical, then a critical analysis is performed. Finally, an error reduction process is carried out to prevent a similar error from its reoccurrence (Salmon et al., 2003).

The advantages of applying SHERPA are that it provides well structured and comprehensive procedures that prompt analysts for identifying potential errors, it involves error prediction along with error reductions, novice analysts are able to acquire the approaches with relative ease, and it uses a generic error taxonomy, allowing for easy adaptation to other domains. The major criticisms of using SHERPA are that it may be time consuming for complex tasks, the construction of HTA can be an additional workload if not available, and it does not model cognitive components of error mechanisms (Stanton and Barber, 2002; Salmon et al., 2003). Recently some research efforts have been made to utilise SHERPA in health care by Lane et al. (2006) and Lyons et al. (2006) and in aviation by Harris et al. (2005) and Stanton et al. (2009).

2.5.2.5 Success Likelihood Index Methodology (SLIM)

SLIM is a structured expert judgement based method. It is also known as Failure Likelihood Index Methodology (FLIM). The methodology begins by selecting tasks that have similar task characteristics, such as a similar set of Performance Shaping Factors (PSFs), to form a single category. This is followed by assigning the relative importance among the PSFs and determining the rating of PSFs for the tasks assessed. Then, the Success Likelihood Index (SLI) is obtained by multiplication of the relative importance weight and the rating of PSFs for each task. Finally, the SLI value is converted into HEPs using a logarithm. The SLIM comprises two techniques, which are Multi-attribute Utility Decomposition (MAUD) and Systematic Approach to the Reliability Assessment of Humans (SARAH). MAUD provides PSFs probabilities affecting human performance on scaling the relative success likelihood in performing a range of tasks, while SARAH calibrates the success likelihood values with known HEP values to provide a final HEP value. The recent studies on SLIM include those by Khan et al. (2006), where SLIM was used to develop a HEP index (HEPI) for the offshore muster process, and Park and Lee (2008), where an Analytic Hierarchy Process (AHP) method was used to estimate HEP, known as AHP-SLIM.

The benefits of using SLIM are that it is a flexible technique and that it enables gross cost benefit evaluations to take place. It is found that the major criticisms of SLIM are that it requires an expert panel to perform an assessment, its methods are poorly structured resulting in various results for different analysts, it is resource intensive, and there is a lack of theoretical foundation on its quantification procedures (Mosleh and Chang, 2004; Kim, 2008; Bell and Holroyd, 2009).

In general, the criticisms of the first generation HRA approaches are described as follows (Kristiansen, 2005):

a). Mechanical view of humans where the HRA approaches only consider human actions being observed and neglect to contemplate the hidden and obvious features of human actions.

b). Insufficient treatment of PSFs such as those on safety culture and management attitudes, etc.

c). Inadequate error reduction strategies revealed in the HRA whereas the purpose of performing HRA is to reduce the estimated human error probabilities resulting in the improvement of safety within any system.

d). Lack of consistency in treating EOC where well intended actions with undesired consequences are not taken into consideration in HRA.

e). High level of uncertainty is reflected by varying human error probability values produced using different quantitative methods for the same task.

f). Inadequate treatment of dynamic situations where the HRA approach does not take into account the dynamic situations surrounding the tasks being performed.

g). Their inability to deal with scarcity of data where the majority of data used for HRA were taken from simulator studies.

h). Inadequate psychological pragmatism where dubious assumptions were made on human behaviour while conducting HRA.

i). Lack of systematic task analysis structure disclosed whereas judgment of HRA was made on the information basis on task analysis.

j). Inadequate proof of accuracy with reference to HRA on non-routine tasks.

These led to the birth of second generation HRA methods. In addition to providing detailed theory based taxonomies and analysis processes for error prediction and quantification based on a cognitive model, the second generation HRA methods also provide detailed types of error and performance influencing factors which enable HRA analysts to identify types of error and their causes more accurately (Boring, 2005; Jung et al., 2001). Recent research studies on HRA were carried out by Hollnagel and Amalberti (2001), Hollnagel (2005) and Kristiansen (2005). Hollnagel and Amalberti argued on the existence of fundamental ambiguity in using human error term itself due to doubts that are present in differentiating between error as action and error as cause. They suggested using performance variability instead of human error in analysing causes or events. Hollnagel (2005) had drawn attention to HRA of being of partial value as an input for probabilistic safety assessment due to its conception of human performance. Kristiansen (2005) had provided a good comparison of first and second generation HRA methods.

Some well-known second generation HRA methods are described as follows.

2.5.2.6 Cognitive Environment Simulator (CES)

CES is a computerised tool that is used to simulate how an operator would respond to a given situation. CES makes use of a detailed artificial intelligence model of problem solving. The CES generates, using an analytical approach, the actions that an operator is likely to perform under different operating conditions. Activities performed by the CES include monitoring the state of a system via a virtual display monitor, generating an explanation to account for observation when something goes wrong within the system, and selecting appropriate responses to cope with the system abnormality. In terms of its advantages, the CES produces a time reliability curve for specific events. It detects the presence of systematic errors by operators, taking into account the effects of the man machine interface, procedures and training changes on time reliability curves. It indicates the probabilities of crew recovery from an error. It accounts for the impact of time and equipment failures on error probabilities. The disadvantages of CES are that it is unable to provide accurate data on operator errors, it is unable to take into consideration the impact of one human failure upon another human interference, its use is limited to the nuclear industry, and there is no evidence of development of CES (Gertman and Blackman, 1994; Hollnagel, 1996; Bell and Holroyd, 2009).

2.5.2.7 Méthode d'Evaluation de la Réalisation des Missions Opérateur pour la Sûreté (MERMOS)

MERMOS which refers to in English as assessment method for the performance of safety operation, was developed for the probabilistic safety assessment of reactors in nuclear power plants. It is utilised to assess the performance of safety operations, particularly for the probabilistic safety assessment of reactors in nuclear power plants. It provides a systemic accident model and a qualitative description of the system failure. It takes into consideration ergonomics, psychology and accidentology in modelling management system behaviour and safe system failure in the operation of nuclear power plants. It utilises consistent configurations/orientations (CICA) of the system. The quantitative features of MERMOS include predominantly using expert judgment based on full scale simulators' test knowledge. The quantification of errors of commission within a system is computed by quantifying the sum of probabilities of failure of each MERMOS scenario and a residual probability. Residual probability refers to the remaining failure probability caused by unknown risks after the other known risks have been accounted for in the quantification of failure probability.

The benefits of using this method include that MERMOS requires an in depth functional analysis resulting in improving procedures in a system, its analyses take into consideration the wider sequence of failure causes and it takes into account the inherent risks to the human operations. The main criticisms of using MERMOS are lack of published information on MERMOS's application in HRA and lack of guidance on the identification of functional failure modes and CICAs. Furthermore, MERMOS has only been applied to the nuclear industry resulting in being a nuclear specific tool and only been tried for emergency operations, hence leaving doubts on whether it could be used satisfactorily for normal operations (Collier, 2001; Pesme et al., 2007; Reer, 2008; Bell and Holroyd, 2009).

2.5.2.8 Human Reliability Management System (HRMS)

HRMS is used to determine error reduction mechanisms. It is related to the PSFs contribution to the assessed error probabilities and provides fully computerised assessments. The quantification approach of HRMS is primarily associated with extrapolation from real data to the desired HEPs, based on a comparison between the real PSF profiles and the task to be assessed. The major PSFs used in this model are the time scale involved, quality of the interface, training/experience/familiarity, degree of adequacy of procedures, organisation, and complexity of task.

The advantages of using HRMS are that it allows for PSF based sensitivity analysis, and that it focuses on quantitative modelling and PSF based justifications. Furthermore, its error reduction module is more explicit compared to the other HRA methods. Among the criticisms of using HRMS are that it requires an analyst with good human reliability experience and that its exhaustive stages have resulted in its less use for HRA purposes, with a trend of being superseded by the much simpler HRA method (Kirwan, 1994; 1997; Bell and Holroyd, 2009).

2.5.2.9 Cognitive Reliability and Error Analysis Method (CREAM)

CREAM was developed by Hollnagel (1998), and can be used retrospectively to analyse and quantify error, and prospectively to identify potential human error for an incident/accident that is possibly encountered. It is based on a set of principles for cognitive modelling with detailed classification of erroneous actions. The CREAM utilises a cognition model, which is known as a COCOM. It has four control modes of Scrambled Control, Opportunistic Control, Tactical Control and Strategic Control. The scale of control that a management system is categorised in determines the reliability of the system's performance. Hollnagel (1998) stated that the reliability of a management system performance would increase when the level of the management control rises. The CREAM uses a classification scheme that describes the error modes and causes of an erroneous action. The error modes, known as phenotypes, are divided into eight erroneous actions, which include timing, duration, force, distance, speed, direction, object and sequence. Meanwhile, the causes of an erroneous action, known as genotypes are divided into three groups that include person, technological and organisational related genotypes. Additionally, the CREAM also uses a set of nine CPCs, which take into account the objective circumstances of a management system to describe the scenario context that is being analysed.

The main advantages of CREAM are that it provides a well structured systematic approach to identifying and quantifying human error, it can be utilised for retrospective and prospective analyses, and it, being a generic method, can be used for different domains. However the method is criticised as that its classification scheme is large, resulting in this method being exhaustive, it has not been widely used, resulting in lack of data to enhance and support its performance in HRA, it does not provide a solution to the established human error and its application could take a longer time for simple analyses (Salmon et al., 2003; Konstandinidou et al., 2006).

2.5.2.10 A Technique for Human Event Analysis (ATHEANA)

ATHEANA integrates advances in psychology with engineering, human factors, and PRA disciplines to provide an HRA quantification process and PRA modelling interface that can accommodate and represent human performance in event management of a system. It uses error forcing contexts (EFCs), which are combinations of working conditions and other influences that affect and probably cause the human error, to obtain qualitative and quantitative HRA results. It utilises psychology, human factors, engineering knowledge and probabilistic risk assessment for retrospective and prospective analyses. The technique involves identifying human failure event sequences and recognising the working conditions and limitations in the human machine interface. A systematic structured approach is used to determine reasons for the occurrence of a human failure event, taking into account the working conditions and PSFs. The ATHEANA also provides the quantification of the EFCs and the probability of human failure events (Bell and Holroyd, 2009).

The benefits of using ATHEANA are that it is capable of estimating HEPs for various conditions of events and that it allows for a focused approach in predicting specific error and significant factors influencing that specific error. It provides a holistic approach emphasising the importance of the whole and the interdependence of its components and comprehension of the perspective concerning human factors being the cause of an incident/accident. Meanwhile, the criticisms of using ATHEANA are that there are a limited number of ATHEANA applications and rigorous methods are applied in identifying the influencing factors used for quantification purposes (Forester et al., 2004; 2007).

The CREAM has been selected for use in this research because it can be easily integrated into an overall safety system allowing assessors to adapt to the context of the initiating events of an incident/accident being analysed. In addition, the specification of CPC that takes into account the objective circumstances of an incident/accident and their possible favourable or unfavourable influence on the occurrence process of the incident/accident enhances the use of CREAM. Furthermore, it can be utilised for retrospective and prospective analyses, and it, being a generic method, can be used for different domains.

2.5.3 Quantification Analysis of HRA

Recently some research efforts have been made to improve HRA quantification including a simplified CREAM prospective quantification process and its application (He et al., 2008), an AHP-SLIM method to estimate HEPs (Kyung and Jae, 2008), a fuzzy set approach (Konstandinidou et al., 2006), HEPs for offshore operation (Khan et al., 2006), HEPs for offshore platform musters (Dimattia et al., 2005), probabilistic techniques (Fujita and Hollnagel, 2004) and the quantitative developments in CREAM (Marseguerra et al., 2006). Other relevant studies on HRA quantification focusing on using simulators to obtain human reliability values are simulation methods for determination of human reliability function taking stress into consideration in the maritime domain (Hann, 2008), simulation of operating crew response to accidents in nuclear power plants (Chang and Mosleh, 2007), HRA methods for space safety where National Aeronautics and Space Administration (NASA) simulation architecture is used (Boring, 2005), simulation in the manufacturing sector (Baines et al., 2004) and a simulator study of CREAM to predict cognitive errors (Collier, 2001). Data available for Human Error Quantification (HEQ) relevant to the maritime industry is limited. Hence a fuzzy logic approach could be appropriate to quantitatively evaluate the human reliability probabilities in the maritime domain. Fuzzy logic is a precise logic of imprecision and approximate reasoning (Zadeh, 2008). Fuzzy logic theory assists in addressing qualitative information considering that it can accommodate the ambiguities presented in maritime human decision factors while investigating a maritime accident.

2.6 MCDM Methods

Naturally the selection of RCOs is a MCDM process. Research studies on human judgements and decision making indicate that human beings are inclined to be biased in their assessments of alternatives. These assessments can be classified into the representativeness heuristic and the availability heuristic. The representativeness heuristic refers to assessments of alternatives that can more readily be linked to what is familiar, whereas the availability heuristic refers to assessments of alternatives that can be unduly influenced by recent, memorable events or successful experiences (Dodgson et al., 2009). The basic ingredients of MCDM include a finite or infinite set of actions, at least two criteria and one decision maker. The actions can be in the form of alternatives, solutions or courses of action. The MCDM is a procedure that facilitates decision making processes, such as choosing, ranking or sorting actions.

The history of MCDM can be traced back to approximately 105 AD in Rome, where the ternary approval of voting strategy was studied. Nevertheless, MCDM is generally considered to have been officially established in the 1970s, as a conference on MCDM was organised by Cochrane and Zeleny at Columbia University in South Carolina in 1972 (Figueira et al., 2005). MCDM is one of the most recognised branches of decision making studies (Triantaphyllou, 2000). The MCDM can be divided into Multi-objective Decision Making (MODM) and Multi-attribute Decision Making (MADM). The MODM analyses decision problems where the decision field is continuous, such as mathematical programming problems with multiple objective functions. The MADM, on the other hand, focuses on problems with discrete decision fields where the decision alternatives have been predetermined. MCDM in this research is the MADM type. Each MCDM problem is associated with multiple attributes. The attributes represent the different dimensions from which the alternatives can be viewed.

In MCDM methods, the choice of objectives and criteria that a decision maker made initially can be further reviewed and modified if they are felt to be inappropriate. Another advantage of MCDM is that it facilitiates the auditing process of the MCDM method used for administration purposes (Dodgson et al., 2009). The difficulties of using MCDM have been seen as the conflicts among criteria, where different criteria represent different dimensions of the alternatives and incommensurable units, where different criteria could be associated with different units of measurement (Triantaphyllou, 2000). There are many MCDM methods available in the literature and each method has its own characteristics. The MCDM can be classified based on the type of data used, such as deterministic, stochastic, fuzzy and combined MCDM methods. Another way of classifying MCDM methods is according to the number of decision makers involved in the decision process, including a single decision maker and a group decision makers MCDM methods. A general decision making process can be described in the following steps (Baker et al., 2002):

a). Define the problems by providing a concise problem statement, which describes the initial condition and the desired condition.

b). Determine the requirements where there are constraints by describing the set of the feasible solutions to the decision problems.

c). Establish goals by stating the objectives that need to be achieved.

d). Identify alternatives by considering a set of solutions fulfilling the constraints of the requirement stated in (b).

e). Define criteria by taking goals into consideration. The objectives of the decision problems are represented in the form of criteria.

f). Select a decision making tool based on the distinct decision problem taking into account the objectives of the decision makers.

g). Evaluate alternatives against criteria where an assessment could be objective based on factual data using scale of measurement, or subjective using expert judgment based on the subjective assessment of the selected experts.

h). Validate solutions against the problem statement referring to the requirements and goals of the decision problem.

Some of the MCDM methods are described in more detail in the following sections. However, each MCDM method has its own benefits and shortcomings. An appropriate MCDM method to solve a decision making problem can only be selected once all the elements relating to the concerned problem have been developed in detail (Bufardi et al., 2004).

2.6.1 Simple Additive Weighting (SAW)

The SAW method is one of the traditional MCDM methods. The application of this method begins with the identification of the objectives of and alternatives to a decision making problem. This is followed by evaluating alternatives and determining objective weights. Then, an additive aggregation of weighted partial preferences values is performed. Finally a sensitivity analysis is carried out to assess the degree of sensitivity of the MCDM model's variables. The SAW method uses direct rating on a standardised scale in case of purely qualitative attributes. For numerical attributes, scores are calculated by normalising observed attribute values to match the standardised scale. Local and global scales are usually used. A local scale is defined as the best and worst existing alternatives forming the reference points for the bounds of the scale. Meanwhile, the global scale is defined as a relative to absolute values for best and worst performance. Furthermore, the global scale allows the decision maker to define objective weights independent of observed attribute values. The objective weights are obtained using a direct estimation method. The combination of a simple scoring method and a ratio or swing weights approach is also referred to as the Simple Multi-Attribute Rating (SMART) technique (Belton and Stewart, 2002; Goodwin and Wright, 2004).

Although showing some advantages, the SAW method still reveals some problems, including that its direct scoring of alternatives and direct estimation of weights often lead to the results that lack an argumentative justification, and that the resulting preference values are lacking in economic interpretation. Additionally, it is also not possible to perform consistency checks on the decision maker's inputs (Hubner, 2007).

2.6.2 Analytic Hierarchical Process (AHP)

An AHP, developed by Saaty to solve MCDM problems, has been extensively used to deal with the fundamental need for subjective judgment involving MCDM (Mahmoodzadeh et al., 2007). It enables a complex problem to be structured and presented in a simple hierarchy form. It uses the procedure of deriving weights by converting subjective assessments of the relative importance of each criterion made by decision makers, based on pairwise comparisons. This is followed by specifying a preference for each decision alternative using each criterion. Finally a set of ranked decision alternatives is obtained. Saaty (2008) also provided a nine point scale expressing the preference of decision alternatives for performing pairwise comparisons. On developing the pairwise comparisons, a synthesisation process is carried out to obtain priorities of the compared elements. The AHP also provides a means of checking the consistency of pairwise comparison, to assess the quality of judgment made during a series of pairwise comparisons, by computing a consistency ratio. The consistency ratio is obtained by computing a ratio of the consistency index derived from computation, and a random index that is taken from standard average random index values, which are provided based on the size of the pairwise comparison matrix. The pairwise comparison matrix is considered consistent if the obtained consistency ratio value is less than or equal to 0.1. For a consistency ratio of more than 0.1, the re-evaluation of ratios needs to be performed (Anderson et al., 2008; Li and Li, 2009).

The advantages of using AHP are that it is suitable for decision making processes with both quantitative and qualitative criteria, the approach of applying an analytical hierarchy method provides a structured model to solve a problem, and it provides a method to verify the consistency of the performed pairwise comparisons. Some of the criticisms of the AHP include concerns over rank reversal upon changing the structure of the decision and the theoretical foundation of the rigid fundamental scale (Baker et al., 2002; Saaty, 2008).

2.6.3 Data Envelopment Analysis (DEA)

DEA is a technique used to evaluate efficiency in cases where multiple input and output factors are observed and where it is not possible to turn them into one aggregate input or output factor. For example, this technique could be used to evaluate the efficiency of non-profit entities, such as public universities, which are not focused on obtaining profits and for which the main source of finances does not come from the sale of goods and services. The DEA provides a comparative efficiency indicator of the units to evaluate. The analysed units are referred to as Decision Making Units (DMUs). The relative efficiency of a DMU is defined as a ratio of the total weighted output to the total weighted input. The inputs and outputs can be expressed in any unit of measurement provided that consistency is maintained. The actual inputs and outputs observed are used to estimate a benchmark production frontier. The efficiency indicator obtained is relative because it is elaborated by referring to the rest of the DMUs. The

DEA allows each DMU to choose the vectors of input and output weights which maximise its own ratio of weighted output to weighted input. However, it is subjected to a constraint which does not allow a DMU to achieve a ratio of weighted output to weighted input in excess of unity. The DEA technique was extended by the study of Banker et al. (1989), who introduced a concept of most productive scale size to define the size of scale that maximises the efficiency of the DMU. Additionally, the extended approach further demonstrated that it is possible to separate the global efficiency into technical and scale efficiencies. The technical efficiency is determined by the situation of the DMU on the frontier of the efficient production. The efficiency of scale is given by the size of the DMU, which makes it possible to operate in a zone of constant or variable returns. The selection of the variables to be included in the model is one of the most important phases in the development of a DEA analysis because the acceptability and reliability of the results depend to a great extent on the accurate selection of the indicators that are best adapted to the objective of the study (Pina and Torres, 2001).

The advantages of the DEA for the evaluation of the efficiency include that it can readily incorporate multiple inputs and outputs without requiring any judgments, and that it only requires information on output and input quantities. It is ideal for solving a problem for which it is difficult or impossible to assign prices to many of the outputs. It allows for nominated researchers to choose inputs and outputs to represent a particular approach and is a useful tool for benchmarking because it identifies targets for inefficient units and indicates what improvements can be made to achieve efficiency. It also determines possible sources of efficiency and inefficiency (Tomkins and Green, 1988; Johnes and Johnes, 1993; McMillan and Datta, 1998; Avkiran, 2001). One of the criticisms of using DEA is that it does not provide any clarification as to how to improve the performance of empirically efficient units, as the efficiency is measured in a relative form. Furthermore, a high percentage of efficiency could be registered in DMU due to the limited quantity of resources of inputs or outputs. Although the DEA assists in setting targets, it does not provide any means of how to reach the targets (Johnes and Johnes, 1993; Avkiran, 2001; Sowlati and Paradi, 2004; Mantri, 2008).

2.6.4 Elimination and Choice Expressing Reality (ELECTRE)

The outranking approach of Elimination and Choice Expressing Reality (ELECTRE) was developed by Roy (Figueira et al., 2005) in 1965 to overcome the drawbacks of the then used *Méthode d'Analyse, de Recherche, et de Sélection d' Activités Nouvelles* (MARSAN), which used a weighted sum based technique to solve decisions dealing with the selection of new activities. It was referred to as ELECTRE I and was used to construct a partial ranking and to choose a set of promising alternatives. This was followed by the birth of ELECTRE II, which was developed in order to rank the alternatives using the thresholds approach. The original ELECTRE was further developed to ELECTRE III, which used pseudo-criteria and fuzzy binary outranking relations where an outranking degree is established, representing an outranking creditability between two alternatives. ELECTRE IV then emerged, which allowed actions to be ranked without using the relative criteria importance coefficients and was equipped with an embedded outranking relations framework. Continuous evolution of ELECTRE resulted in the emergence of ELECTRE A and more recently ELECTRE TRI. The ELECTRA A was developed to cater for the needs of decision making problems in banking institutions, while ELECTRE TRI is the latest simplified version (Figueira et al., 2005).

The ELECTRE method is based on two processes of construction of one or several outranking relations and the exploitation process. The construction of one or several outranking relations refers to comprehensively comparing each pair of actions. The exploitation process is used to elaborate on recommendations from the results obtained from the previously performed outranking. Hwang and Yoon (Hwang and Yoon, 1981) considered the ELECTRE collection of methods to be one of the best methods for decision making because of the way it uses the information available in the decision matrix and due to its simple logic. However, Belton and Stewart (Belton and Stewart, 2002) criticised ELECTRE methods because they do not provide any allowance to perform a sensitivity analysis on the weights and the thresholds values. Additionally, they argued that weights and thresholds do not clearly indicate elucidation of the decision maker's preferences. Furthermore, they stated that the aggregation procedures of ELECTRE II and III are difficult to associate and that with ELECTRE III, if an alternative is added or removed, contradictory results and rank reversal may occur.

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

TOPSIS was developed by Hwang and Yoon (Hwang and Yoon, 1981) as a substitute for the ELECTRE method (Triantaphyllou, 2000). The hypothesis of TOPSIS is that the shortest distance from the Positive Ideal Solution (PIS) and the farthest distance from the Negative Ideal Solution (NIS) in an Euclidean sense is the selected best alternative. The preference order of alternatives is obtained by comparing the relative distances to the ideal solutions. The sequence of the TOPSIS method comprises the construction of a normalised decision matrix and a weighted normalised decision matrix, determination of the PIS and NIS values, computation of separation measures of positive ideal and negative ideal solutions and the obtaining of relative closeness to the ideal solutions. The TOPSIS can be modified to fuzzy TOPSIS by absorbing a human's assessment of uncertainty when complex decision making problems are considered (Percin, 2008). Some recent research studies on TOPSIS included those in business (Tsou, 2007; Percin, 2008; Sun and Lin, 2009), maritime operations (Celik et al., 2009a), computer operating systems (Ball and Korukoglu, 2009), finance (Mahmoodzadeh et al., 2007; Salehi, 2009) and manufacturing (Li and Huang, 2009; Zeydan and Colpan, 2009).

The criticisms of TOPSIS include its inability to adequately handle the ambiguity associated with mapping of the decision maker's perception to crisp values (Dagdeviren, 2009) and its inability to provide weight elicitation of various compared attributes (Celik et al., 2009b).

2.6.6 Decision Making Trial and Evaluation Laboratory (DEMATEL)

The DEMATEL technique originated from the Science and Human Affairs Programme of the Battelle Memorial Institute of Geneva (Tzeng et al., 2007). It is used to solve complex problems by developing a better understanding of the existing groups of elements within the problems (Lin and Tzeng, 2009). The DEMATEL technique allows for a complicated structure of causal relationships to be apparently illustrated using a causal diagram. The causal diagram displays the cause and effect groups. The causes illustrate the reasons why something occurred, whereas the effects are the results of the occurrence. Recent research studies on DEMATEL included those in business (Lin and Tzeng, 2009; Noori and Amiri, 2009; Wu and Lee, 2007; Wu, 2008), engineering

(Seyed-Hosseini et al., 2006), safety management systems (Liou et al., 2007; Liou et al., 2008) and education (Tzeng et al., 2007).

DEMATEL can accommodate subjective human judgments in determining relationships among the components within a complex system or subsystem. It involves a simple application to solve complex relationships, and has been proven to be successful in large domains such as business (Hu et al., 2009; Lin and Tzeng, 2009; Noori and Amiri, 2009; Tseng, 2009a; 2009b; Wu and Lee, 2007; Wu, 2008), engineering (Hori and Shimizu, 1999; Seyed-Hosseini et al., 2006), safety management systems (Liou et al., 2007; Liou et al., 2008), education (Tzeng et al., 2007) and social studies (Tamura et al., 2002; Tamura and Akazawa, 2005).

The entire process of MCDM can be computed and presented using Decision Making Software (DMS). The DMS is an application that incorporates decision analysis tools to facilitate a person's decision making process, which results in a choice of a course of action or a variant among several alternatives. The DMS belongs to the class of decision support systems used to structure information, identify and solve problems, and make decisions. Some of the available DMSs are 1000Minds, Analytica, Criterium DecisionPlus, Decision Lab, Decision Manager, Electre Tri, Expert Choice, Vanguard Studio, Logical Decisions, TreeAge Pro and RPM-Decisions (Weistroffer et al., 2005).

2.7 Conclusion

In this chapter, the difficulty in apprehending the definition of human error is analysed. This is followed by a brief description of human factors being a part of the human error element. Detailed analysis of past oil tanker incidents/accidents from 1974 to 2008 is presented to establish and substantiate the need for research on HRA incorporating HOF in the management of oil tankers to prevent oil spills. An effectual way of incorporating the human elements of human error and human factors in preventing oil tanker spills is through the use of HRA. Brief descriptions of HRA and reasons for the selection of CREAM as a theme of this research are provided. MCDM methods are also reviewed for the study of RCOs' selection in this research. The research will address some of the shortcomings raised in the literature review such as of the generic HRA and FSA methodologies that exist independently in the management of oil tankers to prevent oil spills. CREAM's inability of providing solutions to an incident/accident investigation and robust quantification of human reliability features will be overcome by proposing an advanced CREAM and a human reliability quantification model. Furthermore, lack of CREAM studies on relationships among CPCs will be addressed by proposing a DEMATEL model, which allows for an inclusive understanding of relationships and interdependencies among the CPCs. Finally, the research will be concluded with an integrated AHP and fuzzy TOPSIS model for determining the selection of an appropriate RCO while performing an incident/accident investigation by taking subjective judgments of decision makers into consideration as an alternative to the present practice of making RCO selection.

Chapter 3

Use of HRA for Facilitating FSA: An Oil Tanker Case

Summary

Following the literature review, this chapter addresses the application of HRA for facilitating FSA incorporating HOF in the management of oil tankers to prevent oil spills. The FSA and HRA are scrutinised. A new framework of an application of HRA to FSA is developed. The application of HRA to FSA onboard oil tankers is examined and critically evaluated. Identification of RCOs for HOF of various networks within the management of an oil tanker is analysed and presented to provide means of risk control. The proposed framework is demonstrated with a case study. Hierarchical Task Analysis (HTA) on status of cargo tanks' inert gas valves during discharging operations onboard oil tankers is presented. Finally, recommendations that should be adopted by tanker owners to reduce the risk of oil spills are presented.

3.1. Introduction

Human reliability refers to the probability that a person correctly performs an action required by the system in a required time without performing any extraneous activity that can degrade the system (Pyy, 2000). HRA aims to assess and reduce human error potential in a system and has been used since the early 1980s. It becomes more prominent following the Three Mile Island accident in 1979, from which the approach became customary in the nuclear industry, and spread to others such as oil, gas and chemical industries (Kirwan et al., 2008). The purpose of HRA is to render a complete description of the human contribution to risk and to identify ways of reducing that risk. The assessment of human reliability provides a means to represent the human contribution to risk as part of the total risk in a system leading to prevention and reduction of human error which is significant for the improvement of safety within that system (Kariuki and Lowe, 2006). HRA is also a critical element of Probabilistic Risk Assessment (PRA) since it is a tool used to assess the implications of various aspects of human performance on risk (Konstandinidou et al., 2006). The PRA relates to comprehensive systematic identification of damage due to a possible result from the operation of some systems. It also includes a quantitative assessment of the probability of similar incidents. The introduction of automation and advancement in system designs has resulted in a reduced number of accidents attributed to technological failures, however it has increased accidents due to human performance failures and organisational factors of management systems (Hollnagel, 2005). This chapter investigates the feasibility of applying HRA to Formal Safety Assessment (FSA) to overcome the above mentioned problems in the management of oil tankers. The effort of incorporating HRA to FSA can provide a better comprehensive coverage of human factors instead of merely using an isolated HRA or FSA framework for the purpose of reducing human errors. The framework of applying HRA to FSA incorporates HRA's comprehensive stages of Kirwan (Kirwan, 1994) into FSA. Although the IMO and maritime communities have echoed the need for human factors' element to be included in FSA, none has come forward with comprehensive HRA elements assimilated into the FSA framework as proposed. In addition, this framework has also introduced a CBA element, which plays an important role for maritime industry stakeholders in selecting appropriate RCOs, into HRA.

3.2 The FSA Methodology

3.2.1 The Five Steps of FSA

Figure 3.1 illustrates the flow chart of FSA steps.

Figure 3.1 The Flow Chart of FSA Steps (IMO, 2002b)

3.2.1.1 Hazard Identification (HAZID)

Hazard can be defined as an undesirable outcome in the process of meeting an objective, performing a task or engaging in an activity (Kuo, 1998). The undesired outcome could involve injury to the crew, damage to the vessel, pollution of the environment or a combination of all three. In this step, a list of all relevant accident scenarios with potential causes and outcomes needs to be produced. Such a list of accident scenarios can be obtained using various hazard identification techniques. The frequency of occurrence and consequence of each possible outcome can be estimated based on expert judgement, historical data, or a combination of the two. Consequently, all the various hazards are ranked in order to set priorities for more detailed risk evaluation by using a risk matrix approach. A risk matrix is an approach whereby a risk level is assigned as the product of the appropriate levels from the consequence and frequency bands and is illustrated in Table 3.1. Additionally, with reference to Table 3.1, low frequency is equivalent to less than one incident in the lifetime of all ships of a particular type and high frequency refers to incidents that occur on average to each ship every year.

Table 3.1 Risk Matrix (Billington, 1999)

3.2.1.2 Risk Assessment (RA)

In this step, risk factors contributing to the identified hazards with high risk from Step 1 are evaluated. Historical data and expert judgement are used to carry out the evaluation. Risk can be defined as a measure of a hazard's significance involving simultaneous examination of its consequence and probability of occurrence using a combination of practical experience and relevant information on the system and its operating environment (Kuo, 1999). The probability of occurrence, which is expressed as "events per year", can be determined from historical data if a significant number of events occurred in the past. When the risk analysis is focused on severe consequences events, which have the lowest number of historical data, a RA model is used to compute the event probability. The consequence, which is expressed "per event", refers to the number of people injured or killed, property damaged and amount of spill, etc. Meanwhile, the quantitative risk measures are expressed as "consequences per year". Figure 3.2 illustrates an example of the RA process that uses a combination of quantitative and qualitative risk assessments to assess a risk significantly.

Figure 3.2 The Risk Assessment Process (ABS, 2000)

3.2.1.3 RCOs

In this step, the regulatory measures to control and reduce the risk factors identified in Step 2 are established. The RCOs can be performed based on the following hierarchy:

i). Eliminate the hazard.

ii). Prevent the occurrence.

iii). Mitigate the consequences.

Some of the techniques used in executing the RCOs are described as follows.

3.2.1.3.1 As Low As Reasonably Practicable (ALARP) Principle

The ALARP principle refers to the analysis of costs versus benefits. The risk is reduced to the lowest level, as far as it is practical to do so, following the ALARP parameter. There are risks that can only be tolerated if the risk mitigation measures are in place, which reduce the risks within the ALARP region. In addition, the risk cannot be reduced further without grossly disproportionate cost or disruption. Figure 3.3 illustrates the risk level of a hazard upon applying the frequency and consequence of the hazard parameters with reference to the ALARP principle.

Figure 3.3 Risk Matrix with reference to ALARP (Leedham and Riding, 2001)

For example, when the frequency of an event is EXTREMELY REMOTE and the consequence of the event taking place is MINOR or almost insignificant, the risk falls within the ACCEPTABLE level. Thus, no control measures are required to reduce the risk and in the operational phase this risk should be kept within this region. Meanwhile, when an event's frequency and consequence are FREQUENT and CATASTROPHIC respectively, the risk falls within the INTOLERABLE level. Hence, control measures are required to reduce this particular risk to the ALARP level. Figure 3.4 provides a self-explanatory diagram of the ALARP principle.

Figure 3.4 Diagram of the ALARP Principle (Vlachos and Nikolaidis, 2002)

3.2.1.3.2 Management Method

This is another RCO technique, which deals with the management of an organisation. The implementation of this method relies on the motivation provided by the shipboard management to instil the safety culture and safety practices among crew members onboard. This method involves continuous training of crew members in all aspects of safe operation onboard a vessel. In addition, means of monitoring the performance of the crew members, by maintaining good records of any incident/accident and near misses that occur in the fleet, are adopted. The types of training to be carried out could be determined and emphasised based on the past incident/accident records. A longer period of time is required to see the outcome of this method.

An example of this method is to conduct monthly departmental meetings, followed by a monthly safety meeting onboard vessels. These meetings enable all the crew members to raise various safety matters affecting their daily shipboard operation. It is a continuous process of implementing, monitoring and revising any step taken to reduce risk factors of existing hazards onboard a vessel. In return, the shore management rewards good safety practice and nil incident/accident records with an annual Safety Award Certificate along with cash distribution to purchase recreational equipment onboard. Crew members are motivated to nurture a safety culture shipboard community in order to reduce human errors in shipboard operations as the effect of implementation of the ISM Code (IMO, 2002c; Subramaniam, 2003).

3.2.1.3.3 Engineering Method

This RCO technique deals with the initial stage of the designing and building of a ship. This method can also be used to install new safety equipment onboard vessels. An example of this RCO method is the introduction of double hull tankers to prevent and minimise pollution from oil tankers (Kuo, 1998).

3.2.1.3.4 Operational Method

This RCO deals with the operational procedures of equipment onboard vessels. This method addresses the human error aspects by the introduction of appropriate procedures to carry out various tasks onboard a vessel. The utilisation of this method enhances the competency of seafarers in carrying out tasks onboard safely. Training of crew is emphasised again in this method. The application of management, engineering and operational methods as RCOs all together provides a better means of controlling the existing various risks onboard a vessel.

3.2.1.4 CBA

CBA is a technique used in decision making that evaluates the costs and benefits of the RCO alternatives on a financial basis. It will determine the costs and benefits involved in implementing each RCO identified in Step 3. The cost effectiveness of each RCO is compared with a base case. A base case refers to the existing level of risk associated with the shipping activity before the implementation of risk controls. Consequently, the RCOs are ranked in terms of their cost to achieve a unit reduction of risk. Some of the aspects taken into account in determining the costs include capital costs and items requiring replacement, labour costs, operating costs, installation and commissioning costs, maintenance costs, inspection, surveying and certification costs, off hire and delay costs, and training costs.

The benefits of the implementation of the RCOs include reduced injuries and fatalities, reduced vessel casualties, reduced environmental damage including cleaning up costs, reduced salvage costs and increased availability of assets. Costs and benefits are perceived differently by the various stakeholders in the shipping industry, and are affected by risk management decisions. Stakeholders' feedback on the distribution of cost of reducing risk and the remaining risk is also to be taken into consideration (Rosqvist and Tuominen, 2004). Furthermore, the acceptable risk level as per ALARP may itself change in time as the standard of safety increases. Figure 3.5 illustrates some of the principal stakeholders in the shipping industry.

Figure 3.5 Principal Stakeholders in the Shipping industry (Subramaniam, 2003)

Some of the criticisms of the application of CBA are that relevant data may not be available or may be too costly to collect. In addition, there could be results that cannot readily be quantified in a way that could be established against a scale of monetary values (Dodgson et al., 2009).

3.2.1.5 Recommendations for Decision-making

In this final step, information about the hazards, their associated risks and the cost effectiveness of alternative RCOs are provided to regulatory decision makers. The FSA can facilitate identification of the stakeholder to whom the risks, costs or benefits fall. An equitable and fair RCO can be selected upon scrutinising the available RCOs. An example in selecting an ideal RCO can be performed by following the Risk Balance concept by the UK MCA. First, an overall risk balance is used to assess the proposed recommendations from the aspect of cost effectiveness on an industry wide basis. If the initial proposal is accepted, it will be followed by the assessment of the effects of the proposed measures on each affected stakeholder. If the implementation of risk control measures, however, results in one or more stakeholders bearing a risk or cost that is disproportionate to their expected benefits, the proposed measures will be revised in order to address the imbalance prior to submitting to the decision makers (Peachey, 1999). Figure 3.6 illustrates the stakeholder risk balance.

Figure 3.6 Stakeholder Risk Balance (Billington, 1999)

The risk balance scale shows that the right hand side of the balance outweighs the left-hand side. This reflects the stakeholder benefits are greater than the sum of the risks and costs, which is the aim of decision makers. Following the description of FSA, an HRA is reviewed, because an effectual way of incorporating the human elements in preventing oil tanker spills by conducting FSA is through the use of HRA (IMO, 2002b).

3.3 Application of HRA to FSA: An Oil Tanker Case.

The majority of maritime accidents are initiated by human errors that included slips, lapses, mistakes and violations (DNV, 2002). Recent views on the development of human errors indicate that they are the symptom of a deeper fault within a management system and are an initiating point for an investigation of an accident (Dekker, 2006). These human errors can be assessed by means of HRA that consists of various techniques to estimate the occurrence probability of human errors.

Figure 3.7 illustrates the application of HRA to FSA. It begins with the definition of the problem, followed by a task analysis and Human Error Analysis (HEA). Accordingly, various techniques are used to estimate the probabilities of human errors in the particular activity examined. Subsequently, a logical representation is provided to illustrate various elements that contributed to the investigated incident/accident.

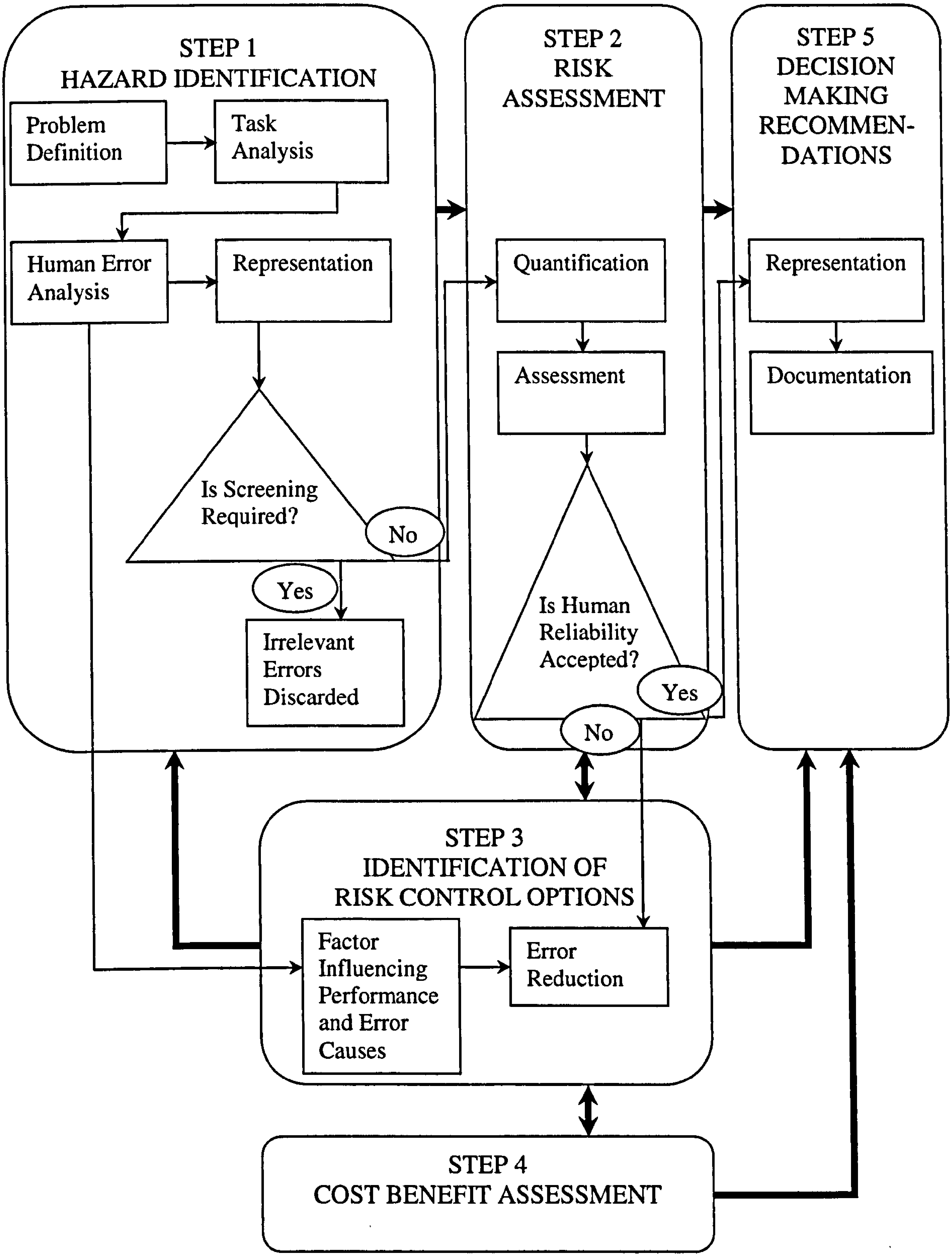

Figure 3.7 Application of HRA to FSA

This is followed by screening where irrelevant errors are discarded by HRA and quantification. On completion of the assessment of probability, if it is found that the human reliability is at an acceptable level for a stakeholder, then representation and documentation is performed. Otherwise, error reduction will be employed to reduce those unacceptable errors taking into account CBA, meeting the requirements of the stakeholders. Although Figure 3.7 includes comprehensive stages of the HRA process, selection of HRA methods would be the determining factor on whether to use all the stages while carrying out HRA in an incident/accident investigation.

3.3.1 HAZID [Step 1]

3.3.1.1 Problem Definition

Problem definition allows for determination of HRA scopes. In fact the definition of problem is a focal point in conducting HRA in investigating an incident/accident. There is a tendency for the problem definition to shift as the HRA progresses. Hence, it is important for the team leader carrying out the HRA to ensure direction of the investigation, in order to achieve a desirable outcome to solve an incident/accident.

3.3.1.2 Task Analysis

Task analysis refers to methods of describing and analysing human system interactions including the one between the operator, the system, and other personnel within the system (Kirwan, 1994). In addition, the presence of more circumstances onboard vessels could result in the high chance of disruption of performance of a system. Thus, a high-level risk analysis needs to be selected using a screening technique. It can be carried out by analysing data collected from interviews, design information, information on critical incident/accident, observation and past experience. Upon finding the list of key human interactions within the examined system, decisions need to be made to list out the potential contributors to human error. Among the available task analysis techniques, HTA is the most often used technique due to its ease of assimilating a large amount of information relatively quickly (Shepherd, 2001). Some of the benefits of using the HTA include the hierarchical structure of HTA that allows the analysts to concentrate on imperative features of the task and it can be used at an initial phase to examine the human error in an incident/accident investigation. The disadvantages of HTA are that the analyst needs to develop skills to analyse the task effectively and it requires collaboration between the analyst and the personnel involved with the incident/accident to develop a realistic description of the task (Salmon et al., 2003). The methodology of constructing an HTA is shown in Figure 3.8.

Figure 3.8 Methodology of HTA Construction (Kirwan and Basra, 1998)

Upon completion of HTA, a review of the accident events will be carried out. A thorough analysis of the accident and collection of data will be executed by means of direct observation, searching training records and engaging experts in the concerned field investigated. In addition, information deduced from expert judgement will be scrutinised and categorised under paired comparison and absolute probability judgment. Finally, an HEP can be derived. A detailed description of the methodology is demonstrated by a case study in Section 3.4.

3.3.1.3 HEA

In HEA, a list of potential human errors including the typical physical and mental human errors that can lead to undesired consequences are identified and classified. Figure 3.9 illustrates some of the typical physical and mental human errors. Both errors are categorised in five types of actions.

Figure 3.9 Typical Physical and Mental Human Errors (IMO, 2002b)

Some examples of potential human error classification are as follows (MCA, 2001):

a). The supposed cause of the human error.

b). The potential for error-recovery, either by the operator or by another person.

c). The potential consequences of the error.

3.3.1.4 Representation and Screening

Representation refers to logical presentation of the whole HRA incorporating aspects of human, hardware, software and environmental contributions to risk on the investigated incident/accident. Recently cultural differences have also been assimilated in developing HRA where influence of different cultures is used to increase the realism of HRA modelling (Gertman et al., 2006). Screening deals with restriction of quantification process where irrelevant errors are discarded based on the HEPs which contribute above a certain level to the overall risk level in the system. Mainly the screening involves a large HRA. Some of the difficulties that arise from representation and screening are decisions on when to cease categorising human errors into yet more detailed causes and overlaps of contributions of human, hardware, software, environmental and cultural elements in failure data used for HRA.

3.3.2 Risk Assessment [Step 2]

3.3.2.1 HEQ and Assessment

Identification and evaluation of areas that pose high risk to the examined system will be carried out in risk assessment. One of the most frequently used methods for this purpose is HEQ. It is also known as Human Reliability Quantification (HRQ). When the Human Error Probability (HEP) is required to be put into a quantitative FSA, HRQ is developed. It can be illustrated as follows (IMO, 2002b):

$$\text{HEP} = \frac{\text{Number of human errors that have occurred}}{\text{Number of opportunities for human errors}} \tag{3.1}$$

However, the numbers in Equation 3.1 may sometimes not be easy to obtain. A new HEQ approach of human reliability quantification is proposed in Chapter 6 using a combined AHP and fuzzy logic approach. At the end of HEQ and assessment, if it is found that the human reliability is at an acceptable level for a stakeholder such as the ALARP level, then representation and documentation is performed if further risk reduction cannot be justified. On the contrary if the stakeholder finds that the proposed human reliability is still at an unacceptable level, error reduction needs to be carried out in the next step.

3.3.3 Identification of RCOs [Step 3]

3.3.3.1 Error Reduction, Factors Influencing Performance and Error Causes

This step is to identify the measures of controlling and reducing the risks estimated in Step 2. This is carried out with the evaluation of four important networks in the management of an oil tanker. The networks are technical and engineering systems, working environment systems, personnel systems and, organisational and managerial systems. The identification of RCOs can be specified in order to (IMO, 2002b):

a). Reduce the frequency of failure.

b). Mitigate the effects of failure.

c). Alleviate the circumstances in which failures occur.

d). Mitigate the consequence of accidents.

Each risk control measure needs to be assessed for human intervention in the system to prevent emergence of any new hazard. Examples of RCOs for a generic oil tanker can be described as shown in Figures 3.10, 3.11, 3.12 and 3.13. The figures illustrate examples of RCOs for HOF for various networks within the management of an oil tanker.

3.3.3.2 RCOs for HOF of Technical and Engineering Systems

The illustration of RCOs for HOF of the technical and engineering systems onboard an oil tanker is shown in Figure 3.10.

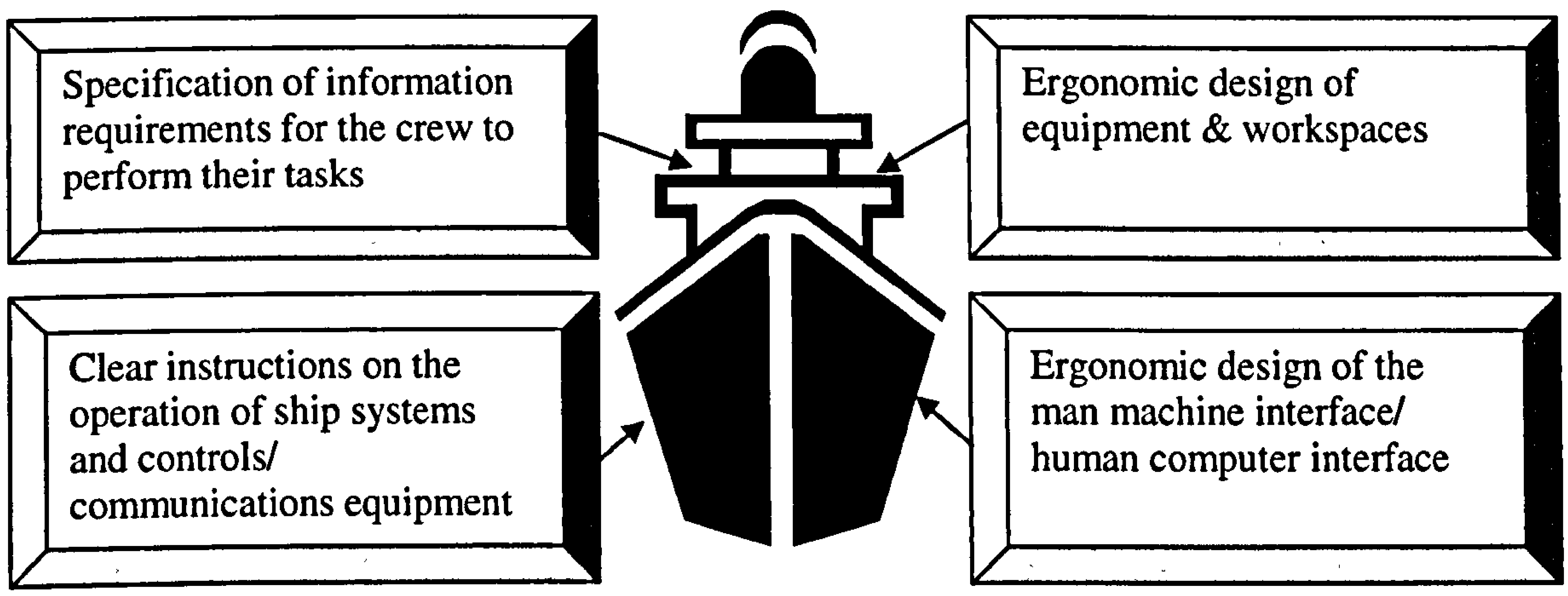

Figure 3.10 RCOs for HOF of the Technical and Engineering Systems

Specification of information requirements for the crew to perform their tasks onboard is addressed by shipping companies through the use of maritime English as a means of communications onboard. The variety of crew nationalities onboard emphasises this aspect. Ergonomic needs in the man machine and human computer interfaces, design of equipment and workplaces onboard have been implemented gradually in newer vessels. This is yet to be deployed in the majority of shipping companies due to increased operating costs.

3.3.3.3 RCOs for HOF of Working Environment Systems

Figure 3.11 presents the RCOs for HOF of the working environment systems onboard an oil tanker.

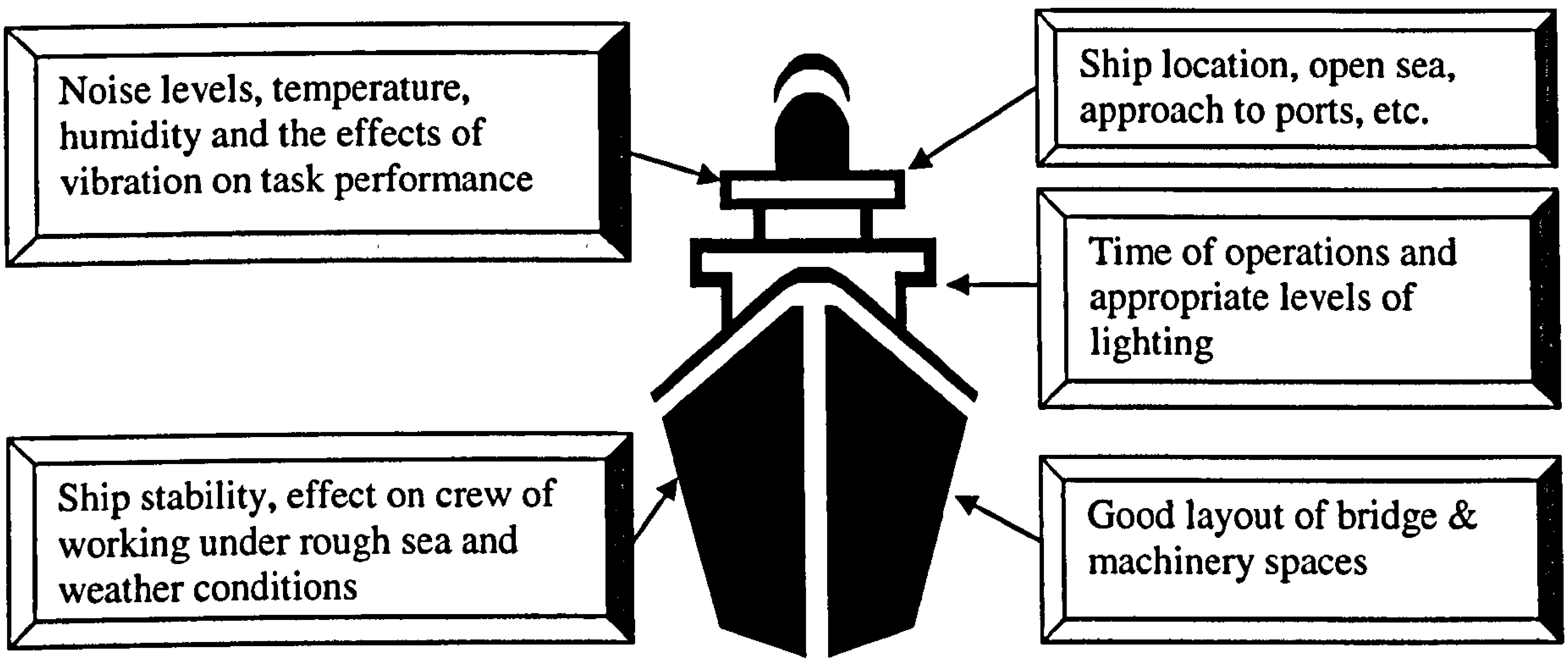

Figure 3.11 RCOs for HOF of the Working Environment Systems

The implementation of safety rules such as the use of safety equipment and permits to carry out tasks could be adopted by seafarers to reduce the working risk that comes along with the job scope. The enforcement of the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW 1995) related to working hours onboard produces scheduling and sufficient manning which has certainly reduced the ill effects that could lead to mental illness and fatigue among seafarers. The advancement in ship design and construction along with the use of modern technology contributes to a better modern navigating bridge and engine room layout providing a better conducive working environment onboard. In addition better ship design also reduces the level of vibration while sailing at higher speed. The advancement in modern technology allows a ship loadicator to be used to monitor the ship stability throughout any shipboard operation. These have emphasised the need of training seafarers to upgrade skills and knowledge to meet the requirements to operate modern vessels.

3.3.3.4 RCOs for HOF of Personnel Systems

The RCOs for HOF of the personnel systems onboard an oil tanker are presented in Figure 3.12.

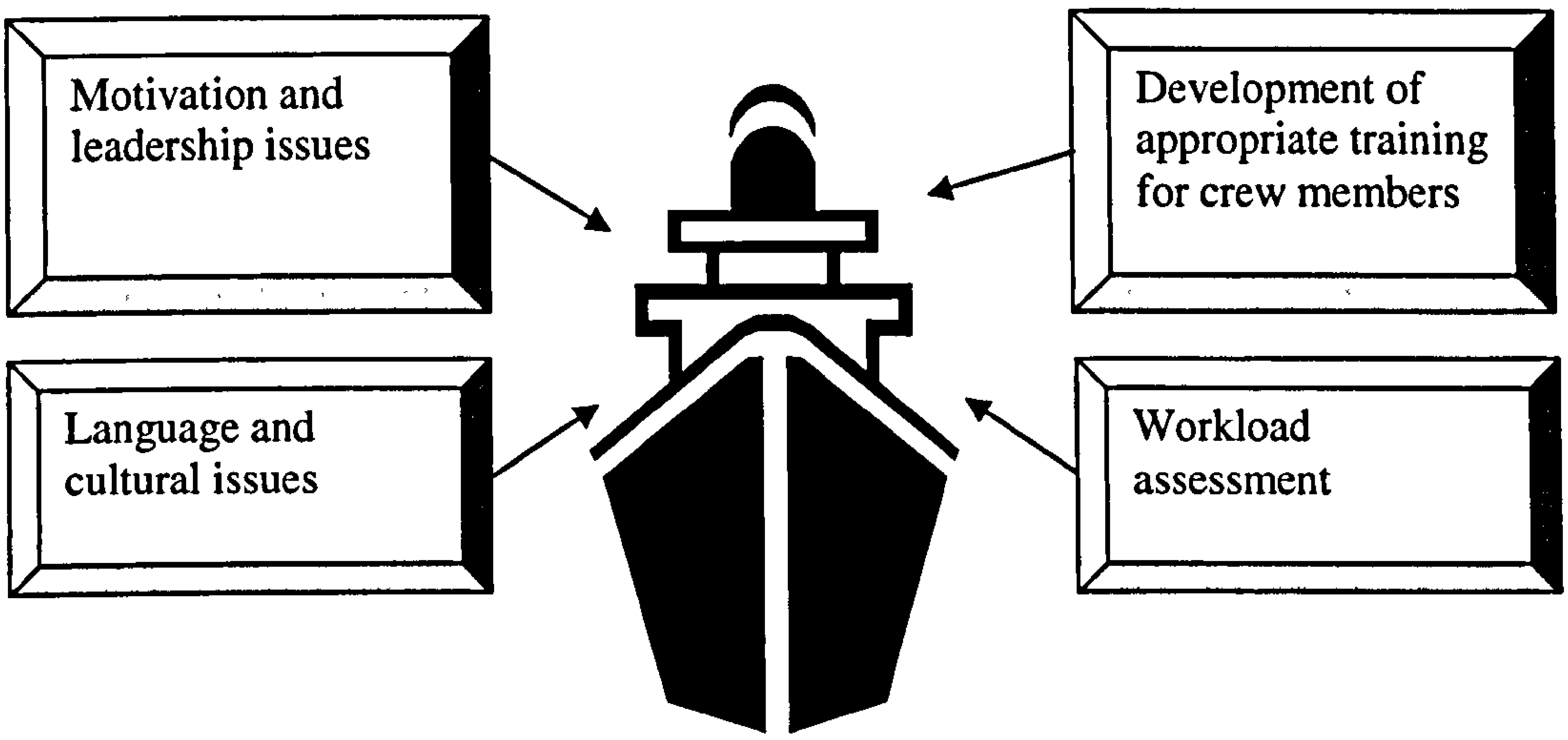

Figure 3.12 RCOs for HOF of the Personnel Systems

Shipping companies have to address language and cultural issues among the crew onboard vessels by using the common maritime working language of English. The implementation of the ISM Code and STCW 1995 requires oil tanker companies to follow a mandatory requirement of training their crew. The introduction of various training sessions and workshops on leadership, security and practical skills and knowledge base classes as per requirement of the ISM Code and STCW 1995 could contribute to the improvement of the management of modern oil tankers. Additionally the requirement for vessels to comply with STCW 1995 fitness for duty regulations has further enhanced the shipboard management to ensure that seafarers have sufficient rest. This is necessary given that excessive workload could cause the crew to lose concentration while carrying out tasks onboard and result in an accident.

3.3.3.5 RCOs for HOF of Organisational and Managerial Systems

Figure 3.13 illustrates the RCOs for HOF of the organisational and managerial systems onboard an oil tanker.

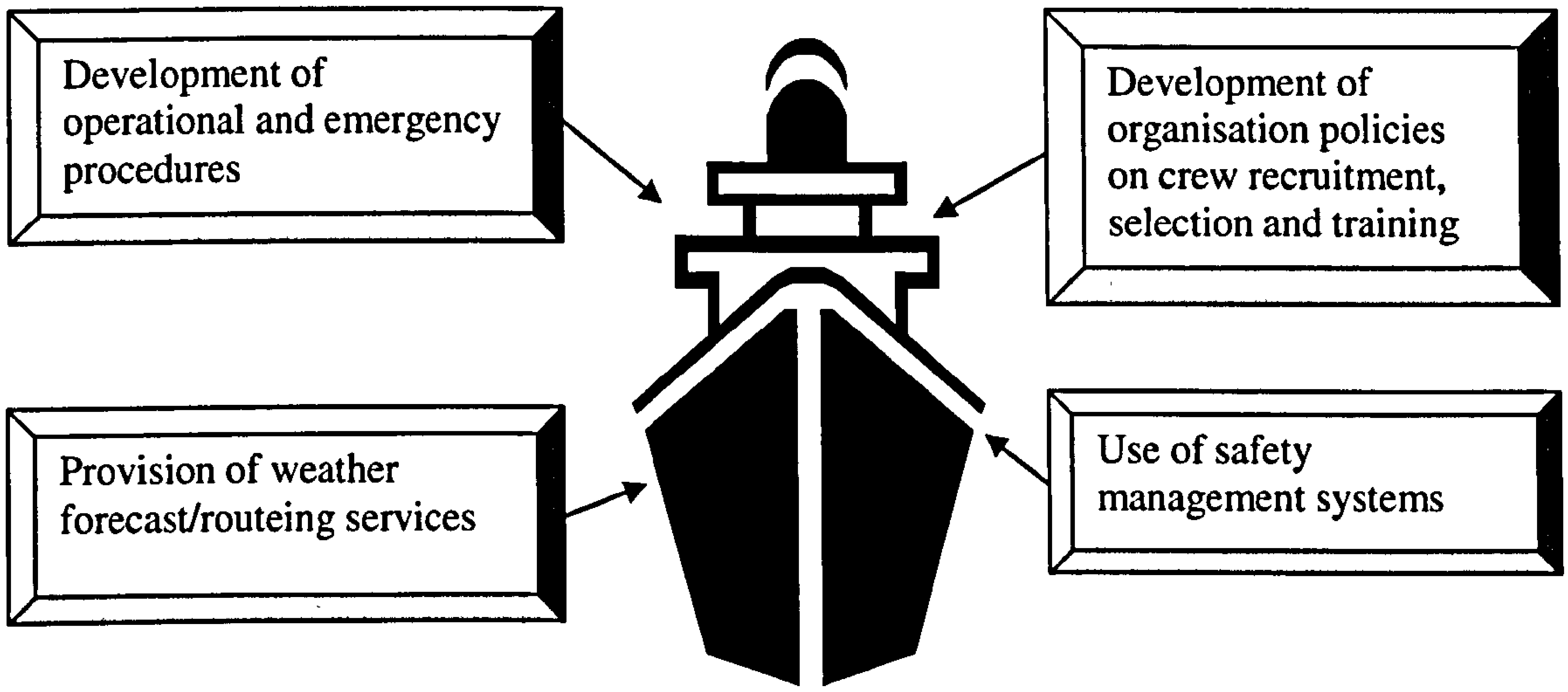

Figure 3.13 RCOs for HOF of the Organisational and Managerial Systems

The implementation of the ISM Code requires any type of vessel including oil tankers to be certified to carry a Safety Management System (SMS) certificate onboard. This system provides a defined level of authority on ship and ashore management. The system also contains a safety policy with procedures for reporting accidents and non-conformities along with an environmental protection policy with procedures for responding to emergency situations. Therefore, a continuous monitoring safety system already exists in the shipping practice with the implementation of the ISM Code. In addition, safety and security concerns are also included in the shipboard SMS along with the implementation of the International Ship and Port Facility Security Code (ISPS). Manning onboard oil tankers is based on the minimum manning requirements stipulated by the flag state administration of the vessel's port of registry. The implementation of rules, procedures and regulations by the shipowners needs close monitoring by the Port State Control (PSC) surveyors when a vessel calls at a port. This could be achieved if the PSC employs a more stringent and increased frequency of vessel inspections. Shortage of seafarers in the maritime industry is yet to be addressed by the principal stakeholders in the shipping industry (Li and Cheng, 2007). Thus, it is necessary to have a long-term policy of recruitment and training to support the reduction of experienced seafarers due to family commitment and increase of shore job opportunities. Modern technology provides weather routeing and a vessel position reporting system to monitor a vessel's transit throughout her sea passage. This allows vessels to carry out the passage plan more prudently on every passage to sea and reduces the risk of a vessel coming across a typhoon or hurricane.

3.3.4 CBA [Step 4]

CBA will determine the costs and benefits involved in implementing each identified RCO with reference to HOF prudently. Costs should be expressed in terms of life cycle costs and may include initial, operating, training, inspection, certification and decommission considerations. Benefits may include reduction in fatalities, injuries, casualties, environmental damage and clean-up, indemnity of third party liabilities and an increase in the average life of ships (IMO, 2002b).

3.3.5 Recommendations for Decision-making [Step 5]

Practical use of the results of the HRA study should contribute to balanced decisions and recommendations of the whole FSA study (MCA, 2001). The recommendations should be presented in such a way that they can be well understood by all the principal stakeholders in the shipping industry irrespective of their experience in the application of risk and CBA and related techniques.

3.4 A Case Study on 'Open/Shut' Status of Cargo Tanks' Inert Gas Valves during Discharging Operations

3.4.1 Background

The case study is presented to illustrate the application of the proposed HRA to the FSA framework. The assessment is concentrated on a crude oil tanker's inert gas valve status whilst discharging at an oil terminal. The example provided here is qualitative in nature which emphasises errors that can lead to faulty status of cargo tanks' inert gas valves during discharging operations. The presence of inert gas inside the cargo tanks creates an atmosphere that does not support combustion of the hydrocarbon oil vapours. Hence, it is of paramount importance to ensure that the status of cargo tanks' inert gas valves is closely monitored. This case study incorporates all the phases involved in the HRA to the FSA framework. More detailed analysis about the quantification phases, CBA and decision making is elaborated in the following chapters.

3.4.2 Problem Definition

The primary task of the case study is to identify the potential errors related to the status of an oil tanker inert gas valves' that could lead to a dangerous situation during discharging operations, subsequently resulting in breaching of cargo tanks leading to an explosion. The secondary task will include providing error reduction recommendations.

3.4.3 Task Analysis

3.4.3.1 Data Collection

Data collection for this case study is based on observations and experience of master mariners carrying out numerous discharging operations onboard crude oil tankers. In addition, documentation on cargo operation procedures and related inert gas incident reports are also reviewed (IMO, 2006a).

3.4.3.2 System Description

The whole oil tanker cargo tanks' inert gas valves operations during discharging could be described as follows:

a). All the cargo tanks' inert gas valves are required to be in an open position when the oil tanker is carrying one grade of crude oil.

b). Isolation of cargo tanks' inert gas valves could be required when more than one parcel of cargo is carried onboard to prevent vapour of one grade of cargo from contaminating another parcel of cargo.

c). The inert gas plant should be in operation throughout the discharging operations ensuring the oxygen concentration level of the inert gas provided into the cargo tanks to be less than 5% by volume. The inert gas operation checklist needs to be completed and other operations related on inert gas plant are not within the scope of this case study.

d). A Ship Shore Safety Checklist needs to be completed prior to commencement of discharging operations and should be duly monitored at intervals as required by the checklist.

e). Deck cargo watchkeeepers are required to check the status of cargo tanks' inert gas valves during discharging operations at frequent intervals.

3.4.3.3 HTA

An example of HTA on the status of cargo tanks' inert gas valves onboard an oil tanker is presented in Figure 3.14. It shows the hierarchical approach that describes the task from the top goal of monitoring the status of cargo tanks' inert gas valves including of the venue where the checking of the valves will be performed, systematically downwards to each individual level of operations.

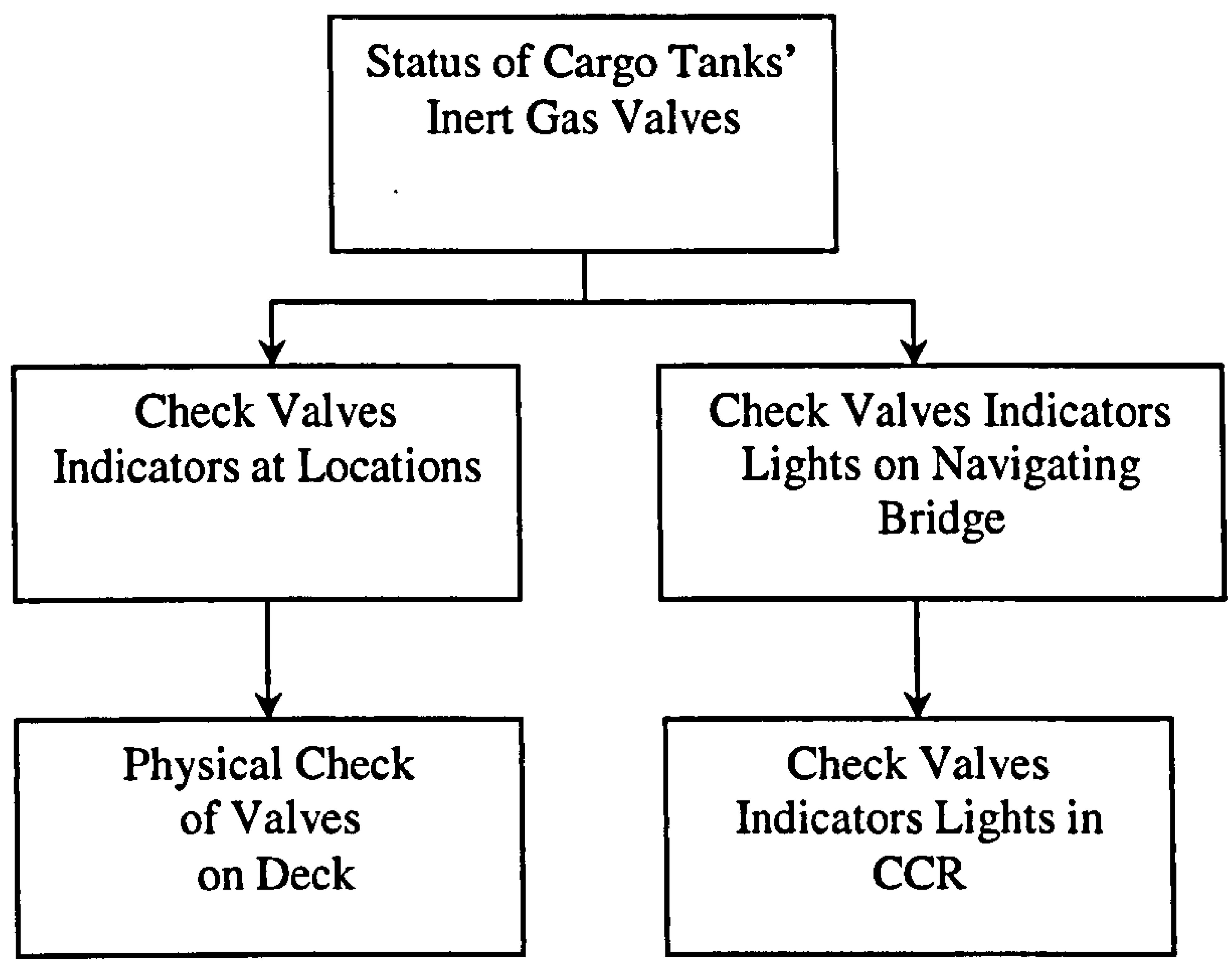

Figure 3.14 HTA on Status of Cargo Tanks' Inert Gas Valves

Some of the plans that could be derived from the HTA are as follows:

a). Procedures for checking cargo tanks' inert gas valves.

b). The standardisation of frequency to check the status of cargo tanks' inert gas valves.

c). Improved locking arrangement of cargo tanks' inert gas valves with padlocks and keys arrangements.

d). Maintenance plans of cargo tanks' inert gas valves including the indicator lights in the navigating bridge/cargo control room (CCR).

e). Record keeping the status of cargo tanks' inert gas valves during cargo operations.

3.4.4 HEA

Using the SHERPA method, a list of potential human errors that could lead to undesired consequences are identified and established in Table 3.2.

Table 3.2 HEA for Status of Cargo Tanks' Inert Gas Valves

Task	Error Modes	Description	Consequences
Check valve indicators in navigating bridge/CCR	Action omitted	Failure of risk recognition	Failure to monitor valve status could lead to catastrophic situation
	Action too little	Lack of awareness on the need to check valve status frequently	
	Action wrong direction/Lack of knowledge of system	Not knowing what direction the valve should be	
	Lack of attention	Not noticing the indicator lights need replacement	
Check valve indicators physically at locations	Lack of attention/ Communication breakdown	Not checking IG valves properly	Failure to monitor valve status could lead to catastrophic situation
		Forgets to check the valve position during cargo watchkeeping	

SHERPA involves three stages which are identification of the set of tasks, HTA and HEA. It was selected because:

a). It allows for simple presentation of elements provided in the proposed application of HRA to the FSA framework.

b). Its approach allows for determination of whether errors can be recovered immediately, at a later stage in the task or not at all.

c). It also incorporates error reduction measures to overcome causes of human errors.

3.4.5 Representation and Screening

Table 3.3 provides a logical presentation of the error modes, recovery and error reduction reflecting the HRA on the status of cargo tanks' inert gas valves. None of the errors were discarded whilst screening due to the nature of grave consequences.

Table 3.3 Error Modes and Error Reduction for Status of Cargo Tanks' Inert Gas Valves

Task	Error Modes	Recovery	Error Reduction
Check valve indicators in Bridge/CCR	Action omitted	No	a).Safety training to accentuate inert gas use in cargo operation b).Introduce record keeping of inert gas valve status
	Action too little	Yes, monitor cargo tank inert gas pressure	
	Action wrong direction/ Lack of knowledge of system	Yes, monitor cargo tank inert gas pressure	
	Lack of attention	Yes, monitor cargo tank inert gas pressure	
Check valve indicators physically at locations	Lack of attention/ Communication breakdown	Yes, monitor cargo tank inert gas pressure	a). More than one crew to be designated to check the valves b).Clear communication of feedback on open / shut valve status c).Introduce IG valves locking system using padlocks and keys
		Yes, monitor cargo tank inert gas pressure	

3.4.6 Error Reduction, Factors Influencing Performance and Error Causes

These stages are incorporated and illustrated in Tables 3.2 and 3.3. One of the networks in the management of an oil tanker (i.e. technical and engineering systems) is taken into account during this assessment on a crude oil tanker's inert gas valve status whilst discharging at an oil terminal.

3.4.7 Representation and Documentation

Many potential human errors are raised, due to the crew's poor time management and hectic cargo operation schedules, slips and lapses of crew's actions while performing cargo watchkeeping duties. Furthermore, the use of SHERPA method facilitates external human reliability analysis, which can easily review the whole HRA process and enhance the justification and judicious error reduction modes raised.

3.5 Discussion

The fundamental information and development of the application of HRA is addressed and the followings are derived.

a). In view with the requirement of the ISM Code along with a SMS on safety policy, the maritime industry should have a good means of collecting and maintaining reliable data on the occurrence of any accident or near miss. A similar data base as found in the nuclear and aviation industries can be developed for the maritime industry and should be made easily accessible by maritime communities. Increased transparency of this information by establishing common formats for onboard vessels and ashore information should be initiated.

b). Good dissemination of reliable data on any accident or near miss would further assist in preventing similar accidents from reoccurring.

c). The requirement for more stringent and increased frequency of internal and external inspections onboard oil tankers emphasising shipboard management is to be enforced.

d). The requirement of a good structured training regime and motivation of crew and officers onboard oil tankers should be cultivated to nurture and produce a committed crew with good attitudes and perceptions towards safety, that would significantly avoid shipboard operational errors, and subsequently, will prevent oil spills.

e). Tanker owners should ensure that the crew members are trained to anticipate the worst scenario and equip ship's crew effectively to deal with incident/accident related to oil spills at all levels of the organisation within a shipboard management. This could be further emphasised by implementing a safety organisational culture. An organisation where the crew's pursuit of safety is not so much about preventing isolated human failures or technical failures but more towards making the organisation robust as practicable to its human operational hazards.

f). Tanker owners should be willing to invest on an initial good design of oil tanker during the shipbuilding phase itself which, could then help prevent oil spills in the future.

g). Use of a good preventive management system of all tanker operational equipment supported with good emergency repairs of equipment if broken should be accentuated. Subsequently this would play a long-term role in reducing operational errors in oil tanker fleets.

3.6 Conclusion

This chapter focuses on the application of HRA to FSA in order to improve the oil tanker shipboard operations and to control the risk of an oil spill. A newly developed HRA to the FSA framework is presented. The need for human factors' element to be assimilated into FSA has been highlighted by the research community for some time, however no solution has been forwarded. The proposed framework addresses this aspect judiciously by adding HRA elements into FSA and at the same time incorporating the CBA element into HRA. Finally, it is timely for the principal stakeholders in the shipping industry to take the initiative in applying HRA to FSA more comprehensively as proposed instead of idle application using sole FSA or HRA, in general and in the management of oil tankers in particular, to continuously improve the shipboard operation to prevent oil spills. In addition, continuous application of this approach will further refine it and subsequently, will improve the decisions made by the oil tanker owners leading to a safer oil tanker shipping community.

Chapter 4

Use of CREAM to Facilitate HRA in Oil Tanker Operations

Summary

This chapter presents a CREAM tailored for its application to a maritime context succeeding the critical review of FSA and HRA in Chapters 2 and 3. To address the shortcomings of the generic HRA and FSA methodologies in the management of oil tankers in order to prevent oil spills, a new framework of CREAM is developed and presented to study the human error and reliability associated with oil tanker operations.

4.1 Introduction

The development of modern technology has resulted in human work from being mostly manual skills to knowledge intensive functions as cognitive tasks. The word cognitive denotes relating to, being, or involving conscious intellectual activities such as thinking, reasoning or remembering. Hence, the development of modern technology has led to a change from conventional ergonomics to cognitive ergonomics. Meanwhile, ergonomics is defined as a scientific discipline concerned with the understanding of the interactions among humans and the other elements of a system and the profession that applies theories, principles, data and methods to design in order to optimise comfort of human well being in executing any tasks and overall system performance (Grech et al., 2008). CREAM presents a consistent error classification system, which integrates individual, technological and organisational factors. The reason of selecting this method in this study is due to its feature of being a promising HRA model for identifying root causes of human errors (Kim, 2001). Past evidence from a large number of incident/accident inquiries indicates that the incident/accident initiating events are more often the result of error prone situations and error prone activities, which are mainly caused by human factors (Reason, 1997). Human factor researchers viewed human errors as originating from human behaviours including those due to poor management, inadequate supervision and lack of communication (Dekker, 2002; Reason, 1997).

The CREAM accentuates the important influence of the context on human performance and has a useful cognitive model and framework, which could be used in retrospective and prospective analysis (He et al., 2008). The method is based on a COCOM and deals with EOC (Kennedy et al., 2007). Four control modes used in COCOM are Scrambled Control, Opportunistic Control, Tactical Control and Strategic Control. It is explicitly based on a set of principles for cognitive modelling with detailed classification of erroneous actions. The classification describes the relations between causes and effects by defining some interactive tables. These tables are provided for the error modes and cognitive functions required by COCOM along its general system and organisational causes. In each table, causes and consequences are further divided into general and specific categories. These methods of going through tables of classification describe how an analysis can progress recursively through the tables, where the possible links are defined by the underlying operator model. Thus, CREAM allows a possible distinction between the classification scheme, the method and the cognitive model. It can therefore be used to identify the most likely cause of an observed incident/accident or erroneous action. CREAM is a promising approach in identification of cognitive failure types (Reer, 2008). A specialised version of CREAM for use in the analysis of traffic incidents/accidents has been developed. The adapted version was named DREAM, for Driver Reliability and Error Analysis Method (Sagberg, 2007). Some research was carried out on Bridge Reliability and Error Analysis Method (BREAM) for use in the maritime accident analysis (Nygren, 2006). Furthermore, the principles of CREAM have been successfully applied to the analysis of aircraft incidents/accidents (Subotic et al., 2007).

4.2 Literature Review

CREAM was developed by Hollnagel (1998) upon analysing the existing HRA approaches. It can be used retrospectively to analyse and quantify human error, and prospectively to predict potential human error in an incident/accident investigation. Some of the advantages of CREAM are that it can be easily integrated into an overall safety system and allow assessors to adapt to the context of the initiating events of the incident/accident being analysed. Another significant element in the CREAM is the specification of CPCs, which takes into account the objective circumstances of an incident/accident and their possible favourable or unfavourable influence on the occurrence process of the incident/accident. In a maritime context, an assessment of the CPCs can provide an overall prediction of how likely it is for the ship's crew and the related shipboard systems to lose controls. The CREAM can be used for both retrospective and prospective analyses. On the other hand, some of the criticisms of CREAM include that it does not take into account collaborative work to a great extent, it may be time and resource intensive, it is demanding in terms of the need of expertise in human factors, it suffers the problems of subjectivity and lack of data to enhance and support its work in HRA. Furthermore, it does not provide a solution to the root causes of the incident/accident investigated (Salmon et al., 2003; Konstandinidou et al., 2006). Based on Hollnagel's approach (Hollnagel, 1998), an advanced CREAM, which incorporates additional features of RCOs and CBA to provide solutions to an incident/accident investigation, is proposed in this chapter.

4.3 CREAM Principles

4.3.1 CREAM Classification Scheme

CREAM was originally developed to analyse safety critical incidents/accidents in nuclear power plants. It is based on Man-Technology-Organisation (MTO) genotypes. It includes taxonomy for causal categories covering the three elements of man, technology and organisation. The method begins with characterising the action, which is directly connected to a critical event. The critical event could be an incident/accident. This action characteristic is an error mode (Hollnagel, 1998). For a given incident/accident, a general phenotype is selected from a list of eight diverse classes. The classes are timing, duration, sequence, object, force, direction, speed and distance. The error modes are further specified according to the general phenotypes. A given genotype is always an antecedent to a phenotype or to different genotypes, which means that the given genotype could also be a consequent of other genotypes. The taxonomy specifies the possible connections backward from a consequent to an antecedent, which in turn is the consequent of one or more other antecedents. As a result, a network of causal relationships is constructed.

Antecedents and consequences are used in the CREAM classification methodology to prevent confusion among the paths between the categories of the classification scheme (Hollnagel, 1998). The antecedent can give rise to a specific consequent or consequents, given the premises of the classification scheme. In this research, domain specific causal categories have been added to the general categories (genotypes) of CREAM tabulated in Appendix II to realise its application in the maritime context. Furthermore it allows for easier reference related to maritime tasks to HRA analysts when using the classification tables. Among the changes that have been made in the classification scheme of Appendix II to suit the maritime domain are:

a). Added new descriptions on the functional impairment and cognitive style of general consequent of the permanent person related functions categories (Table AII.9).

b). Improvised general consequent of the categories of equipment failure by creating navigation bridge, cargo control room and engine room sections to allow more detailed description of equipment failures (Table AII.10).

c). Added new descriptions on the specific consequent of the incomplete information of general consequent of the temporary interface problems categories (Table AII.12).

d). Added new description on the specific antecedent of incorrect prediction general consequent of the general and specific antecedents for interpretation (Table AII.21).

e). Added new descriptions on general antecedent and specific antecedent for fear and psychological stress general consequent of the general and specific antecedents for temporary person related functions (Table AII.23).

f). Added new descriptions on general antecedent for functional impairment, cognitive style and cognitive bias general consequents of the general and specific antecedents for temporary person related functions (Table AII.24).

g). Added new description on the specific antecedent of software fault general consequent of general and specific antecedents for equipment (Table AII.25).

h). Added new description on the specific antecedent of incomplete information general consequent of general and specific antecedents for temporary interface problems (Table AII.27).

i). Added new description on the specific antecedent of access problems general consequent of general and specific antecedents for permanent interface problems (Table AII.28).

j). Added new description on the specific antecedent of insufficient skills general consequent of general and specific antecedents for training (Table AII.31).

k). Added new description on the specific antecedent of adverse ambient conditions general consequent of general and specific antecedents for ambient conditions (Table AII.32).
l). Added new descriptions on the specific antecedent of excessive demand, inadequate work place layout and inadequate team support general consequent of general and specific antecedents for working conditions (Table AII.33).

4.3.1.1 COCOM

COCOM is presented to show the relationship between components of the classification scheme. It describes a set of cognitive functions that can be used to explain human erroneous actions. Human performance is a result of the controlled use of competence adapted to the requirements of the surrounding environment and situation at the time of incident/accident initiating events. This corresponds to a fundamental principle of cognitive systems of engineering that human action is intentional as well as reactive. The COCOM model is shown in Figure 4.1.

Figure 4.1 The Contextual Control Model of Cognition (Hollnagel, 1998)

Scrambled Control – It characterises a situation where there is little or no thinking involved in choosing what to do. The extreme case of this control is the state of momentary panic resulting in the choice of next action in a random manner. It can be concluded that there is no relationship between the situation and the actions, in situation assessment.
Opportunistic Control – This is determined by the salient features of the current context. Little anticipation is involved due to time constraint, lack of understanding of the situation or due to poor working conditions. It results in an inefficient choice of actions.
Tactical Control – The performance in this mode is based on planning by following a known procedure. The planning is of limited scope resulting in some actions taken unprepared.
Strategic Control – It considers wider time horizon and focuses on higher level of goals. It provides more robust and efficient performance. This control can be attained by the competence of a person.

The control mode is determined by analysing CPCs for an incident/accident investigated. Each CPC is described by means of a linguistic descriptor. The CPCs are associated to a particular contextual effect on the performance reliability. The performance reliability is categorised into improved reliability effect, reduced reliability effect and non-significant reliability effect. The ratio application of improved reliabilities and reduced reliabilities will establish the control mode acted by ship's crew on the incident/accident investigated (Marseguerra et al., 2007). The linguistic descriptors and its performance reliability effects of the nine CPCs comprise adequacy of shipboard organisation (ASO), shipboard working condition (SWC), adequacy of man machine interface and shipboard operational support (MMI), availability of plans/procedures (APP), number of simultaneous goals (NSG), available time (QAT), time of day (circadian rhythm) (CRT), adequacy of shipboard training and preparation (ASP) and shipboard crew collaboration quality (SCQ) are illustrated in Table 4.1.

Finally, there are two important aspects of the control modelling in the COCOM. The first aspect deals with the conditions under which a person changes from one control mode to another. Meanwhile, the second feature deals with the characteristic performance in a given control mode. A given control mode refers to how and what determine the actions chosen and carried out. The relation between the control modes and its performance reliability is illustrated in Figure 4.2.

Table 4.1 The Linguistic Descriptors and Performance Reliability Effects of CPCs

CPCs	Linguistic Descriptors and its Performance Reliability Effects			
ASO	Very Efficient [Improved]	Efficient [Not Significant]	Inefficient [Reduced]	Deficient [Reduced]
SWC	Advantages [Improved]	Compatible [Not Significant]	Incompatible [Reduced]	
MMI	Supportive [Improved]	Adequate [Not Significant]	Tolerable [Not Significant]	Inappropriate [Reduced]
APP	Appropriate [Improved]	Acceptable [Not Significant]	Inappropriate [Reduced]	
NSG	Less than actual capacity [Not Significant]	Matching current capacity [Not Significant]	More than actual capacity [Reduced]	
QAT	Adequate [Improved]	Temporarily inadequate [Not Significant]	Continuously inadequate [Reduced]	
CRT	Night-time (unadjusted) [Reduced]	Daytime (adjusted) [Not Significant]	Night-time (adjusted) [Reduced]	
ASP	Adequate with vast experience [Improved]	Adequate with limited experience [Not Significant]	Inadequate experience [Reduced]	
SCQ	Very Efficient [Improved]	Efficient [Not Significant]	Inefficient [Not Significant]	Deficient [Reduced]

Figure 4.2 Relations between Control Modes and Human Performance Reliability (Hollnagel, 1998)

Type of Control

The COCOM model has been tested and found to be satisfactory by Stanton (Stanton et al., 2001). It has been found that human behaviour could be categorised reliably into the four control modes as elaborated above. Each control mode is also associated to a Human Performance Failure Probability (HPFP) interval. Table 4.2 illustrates the HPFP intervals between the four control modes.

Table 4.2 COCOM and HPFP Intervals (Marseguerra et al., 2007)

COCOM	HPFP Intervals
Scrambled	$1.0 \times 10^{-1} < p < 1.0 \times 10^{0}$
Opportunistic	$1.0 \times 10^{-2} < p < 0.5 \times 10^{0}$
Tactical	$1.0 \times 10^{-3} < p < 1.0 \times 10^{-1}$
Strategic	$0.5 \times 10^{-5} < p < 1.0 \times 10^{-2}$

Meanwhile Figure 4.3 illustrates the ship crew's likely action by means of comparing the improved and reduced reliability effects influence determined from the nine types of CPCs.

Figure 4.3 Basic Diagram of CREAM Methodology for Ship Crew's Control Mode (Konstandinidou et al., 2006)

An example application of Figure 4.3 is that six of the analysed CPCs were found to have improved reliability effects whereas two CPCs fell into reduced reliability effects, having a negative effect on human reliability. Meanwhile the remaining one CPC was having a non-significant effect on human performance. With reference to Figure 4.3, according to CREAM, the control mode in which ship's crew acted on the assumed example of an incident falls in 'Strategic' Control. It reflects that a very low probability for a human erroneous action is expected on the incident. Further detailed demonstration on the use of Figure 4.3 to determine the type of control mode that ship crews are likely to act is provided in the study cases of '*Carina*' and '*Prestige*'.

4.3.1.2 CREAM Classification Categories

The CREAM classification consists of three categories. The first category contains the genotypes associated with human psychological characteristics. It includes genotypes relating to cognitive functions, psycho-physiological variables, emotional state and personality traits, etc. The second category consists of the genotypes associated with the technological system. This category deals with the state of components and subsystems, man-machine interaction, the man-machine interface and technological hardware including software, etc. The third category contains the genotypes that characterise the organisation, the working environment and the interaction between people. It includes permanent features of the system, aspects of the organisation and environmental conditions. It also includes other genotypes that do not fit in the previous two categories (Hollnagel, 1998). Figures 4.4 and 4.5 illustrate the differentiation of genotypes and the classification categories applied in CREAM respectively.

4.3.1.2.1 Error Modes

The term "Error Modes" signifies the particular form in which an erroneous action can explain itself. It also refers to the systematic phenotypes. The eight types of erroneous actions shown in Figure 4.5 are included as Error Modes. They are Timing, Duration, Force, Distance, Speed, Direction, Object and Sequence. The error modes are presented in Tables AII.1, AII.2, AII.3, AII.4 and AII.19.

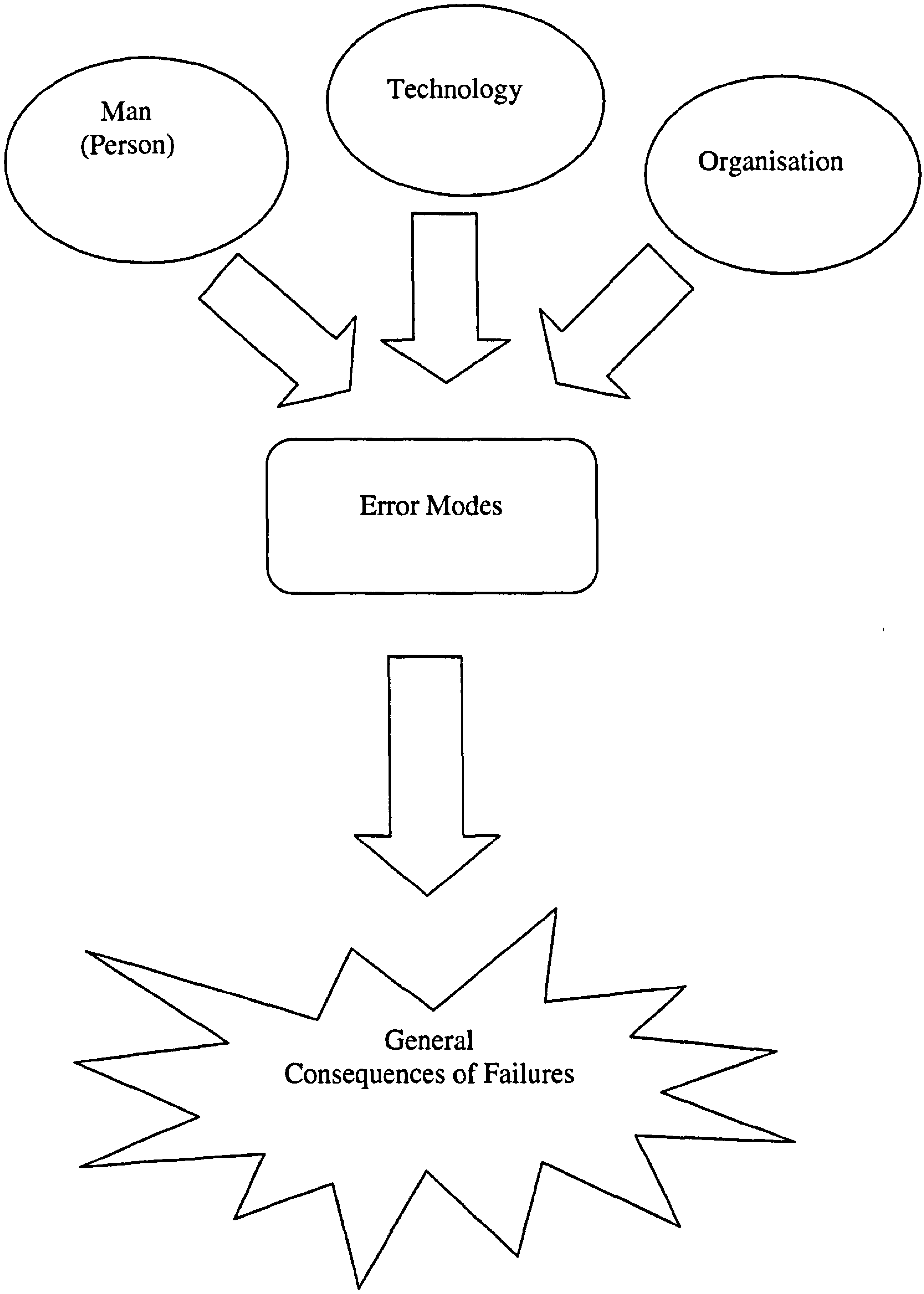

Figure 4.4 Differentiations of Genotypes

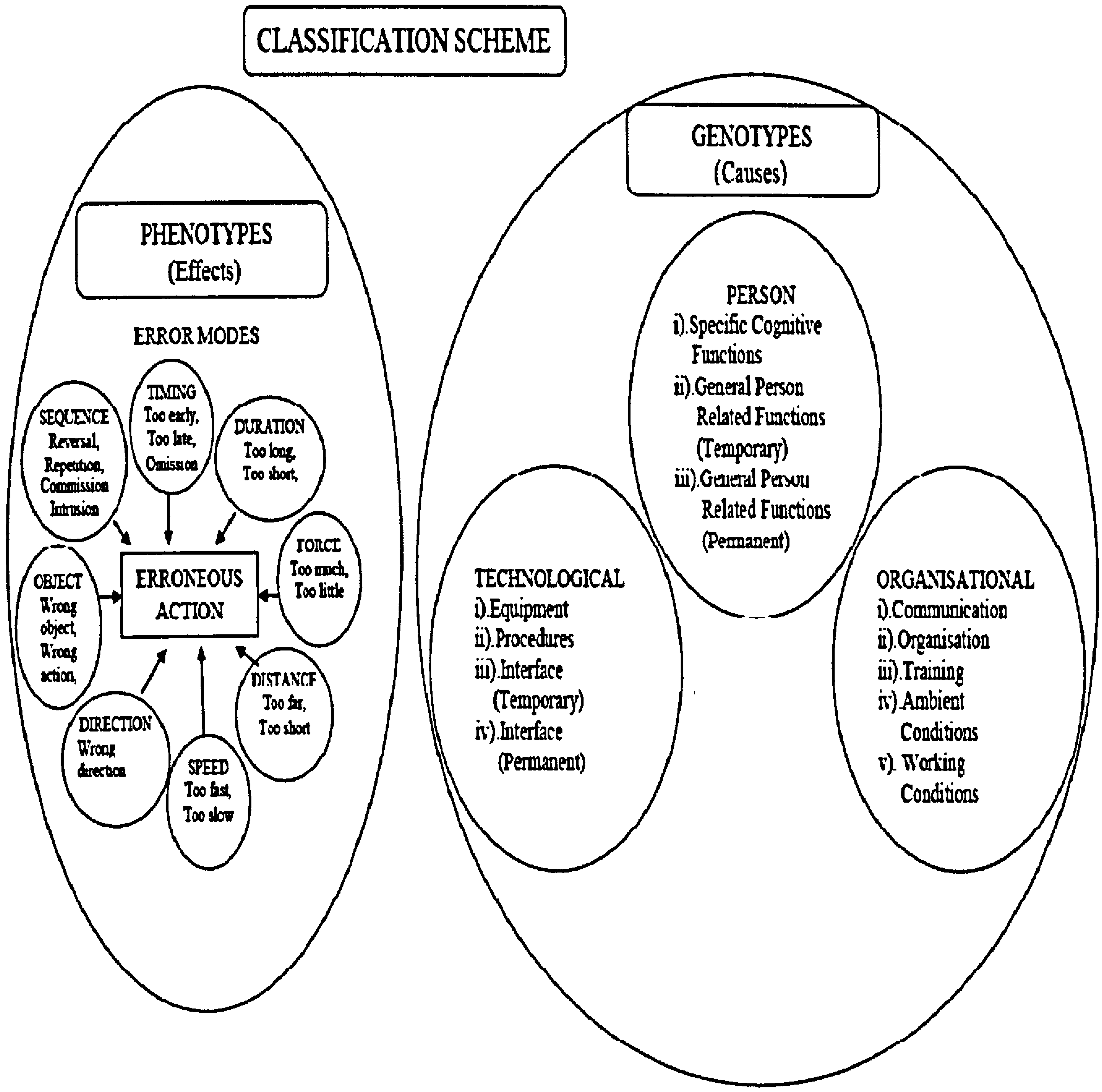

Figure 4.5 CREAM Classification Categories

4.3.1.2.2 Person Related Genotypes

Person related genotypes contain the groups of antecedents that can be associated with a person (Hollnagel, 1998).

i). Specific Cognitive Functions

Specific cognitive functions describe the functions that are assumed to constitute the basis for meaningful human action. The cognitive functions must reflect the principles of the underlying model of cognition. In CREAM, these principles are taken from the

COCOM that includes observation, interpretation, planning and execution. These functions are presented in Tables AII.5, AII.6, AII.7, AII.20, AII.21 and AII.22.

ii). General Person Related Functions (Temporary)

Temporary person related functions are physiological states or emotional states that refer to characteristics of a person at a given time. Examples from this classification group are circadian rhythm, memory failure, fatigue, time pressure, distraction, psychological stress and physiological stress. These functions are presented in Tables AII.8 and AII.23.

iii). General Person Related Functions (Permanent)

Permanent person related functions are constant characteristics of an individual that include colour blindness or cognitive biases in thinking and judgement. These functions are presented in Tables AII.9 and AII.24.

4.3.1.2.3 Technology Related Genotypes

Technology related genotypes contain the groups of antecedents that can be associated with the technological systems. The antecedents are ordered in the following four groups.

i). Equipment

This group refers to the technological elements such as mechanical or electronic components including their software, subsystems and control systems, etc. This group may coincide with antecedents in the temporary interface group. These functions are illustrated in Tables AII.10 and AII.25.

ii). Procedures

This classification group refers to the system specific procedures or prescriptions on how a task shall be carried out. It may have similarities with the organisation group. These functions are illustrated in Tables AII.11 and AII.26.

iii). Interface (Temporary)

This group describes the antecedents related to temporary conditions of the man machine interaction, such as failure of equipments operating in navigation bridge, cargo control room or engine room. These functions are presented in Tables AII.12 and AII.27

iv). Interface (Permanent)

This group describes the antecedents related to permanent features such as faulty design, maintenance failure, poor layout or working space and oversights, etc. These functions are presented in Tables AII.13 and AII.28.

4.3.1.2.4 Organisation Related Genotypes

Organisation related genotypes contain the groups of antecedents related to the organisational environment, such as working conditions in general. The antecedents are categorised in the five groups described as follows:

i). Communication

This classification group aims on communication systems in running operation of a vessel. It involves communication between ship and shore management, and includes communication among vessels. This group may coincide with the temporary interface and ambient condition groups. These functions are illustrated in Tables AII.14 and AII.29.

ii). Organisations

This classification group refers to antecedents that deal with the management of the organisation. Among the features included are management problems, quality control policy, design failure, safety climate, social climate, reporting procedures, lines of command and responsibility, inadequate task allocations, social pressure and maintenance failure, etc. These functions are illustrated in Tables AII.15 and AII.30.

iii). Training

This classification group refers to the antecedents that emphasise on skills and knowledge achieved by ship's crew members in performing their routine tasks. Thus, this classification group weighs on the ship management in providing training in the development of crew members operating the vessels. These functions are presented in Tables AII.16 and AII.31.

iv). Ambient Conditions

This classification group refers to the antecedents that characterise the ambient conditions, such as temperature, time of day (or night), humidity, sounds and illumination, etc. These factors have impacts on the well being of the ship's crew in performing their routine tasks efficiently. These functions are presented in Tables AII.17 and AII.32.

v). Working Conditions

This classification group concentrates on antecedents that characterise the working conditions, such as task demands, work place design, team support and working hours. Changes in working conditions have more influence on crew management than the ones in ambient conditions. These functions are presented in Tables AII.18 and AII.33.

4.3.2 CPCs in Maritime Operations

Detailed descriptions of the nine CPCs used in CREAM produced in the maritime context are described as follows:

i). ASO

This CPC describes the characteristic and responsibilities of crew onboard ships, additional support, communication systems, Safety Management Systems (SMS), instructions and guidelines in carrying out the activities resulting in initiating events of an incident/accident.

ii). SWC

This CPC includes the nature of the physical working conditions onboard ships including ambient lighting, glare on screens, noise from alarms and any interruption from carrying out relevant tasks, etc.

iii). MMI

This CPC consists of the information available on control panels, navigation bridge, cargo control room, engine control room and shipboard operational support provided by specifically designed decision aids such as marine navigation equipments, cargo operation and engine room instruments. Furthermore, this CPC requires thorough analysis to be conducted due to the increased automation in shipboard operations.

iv). APP

This CPC is used to match the existing operating and emergency instructions and procedures in carrying out ship operations.

v). NSG

This CPC describes the number of tasks a crew is required to carry out at the same time.

vi). QAT

This CPC refers to the time available to carry out a task competently resulting in a reasonable outcome.

vii). CRT

This CPC relates to the time of the day or night when the task is carried out. Emphasis lies in how the crew can get well adapted to the current time. Examples are the nature of four hourly of navigation bridge and engine room watch keeping sequence.

viii). ASP

This CPC describes the quality of training provided to the crew in carrying out their routine tasks onboard ship. It includes familiarisation training and refreshers' courses to new joiners and experienced crew respectively within the shipboard management.

ix). SCQ

This CPC relates to the efficient manner in which crew works among them to complete a task efficiently onboard ship.

The nine CPCs have interdependencies. Table 4.3 illustrates the dependency between CPCs. The characteristic of CPC_{SWC} is influenced by the CPC_{ASO}, CPC_{MMI}, CPC_{QAT}, CPC_{CRT} and CPC_{ASP}. The features of the CPC_{MMI}, CPC_{APP} and CPC_{ASP} are influenced by a sole CPC_{ASO}. Meanwhile, the characteristic of CPC_{NSG} is influenced by the CPC_{SWC}, CPC_{MMI} and CPC_{APP}, whereas the CPC_{QAT} is influenced by the CPC_{SWC}, CPC_{MMI}, CPC_{APP}, CPC_{NSG} and CPC_{CRT}. Finally, the feature of CPC_{SCQ} is influenced by CPC_{ASO} and CPC_{ASP}.

Table 4.3 Dependency between CPCs (Adapted from Hollnagel, 1998)

Principal CPC (Influenced CPC)	Component CPCs (Influencing CPCs)
SWC	ASO, MMI, QAT, CRT and ASP
NSG	SWC, MMI and APP
QAT	SWC, MMI, APP, NSG and CRT
SCQ	ASO and ASP
MMI	ASO
APP	ASO
ASP	ASO

When four out of five component CPCs within a CPC group have improved or reduced reliability effects then, the reliability effect of a principal CPC will be changed from the initial analysed non-significant reliability effect, to the similar reliability effects of the four component CPCs in the group. Otherwise, the principal CPC will retain the analysed non-significant reliability effect feature. This rule applies to the principal CPC_{SWC} and CPC_{QAT}. Meanwhile, in the cases of principal CPC_{NSG} and CPC_{SCQ}, two component CPCs within the group are to have the same improved or reduced reliability effects in order to allow for changes in the non-significant reliability effects of the principals CPC_{NSG} and CPC_{SCQ}. Finally, no rules of changing the reliability effects apply to the principal CPCs CPC_{MMI}, CPC_{APP} and CPC_{ASP} because they are dependent solely to CPC_{ASO} (Hollnagel, 1998).

4.4 Methodology

4.4.1 New Advanced CREAM Framework

CREAM can be applied by means of prospective or retrospective analysis. Prospective analysis deals with predictive application, typical design and Probabilistic Safety Assessment (PSA). Meanwhile, retrospective analysis refers to the identification of the root causes of an incident/accident investigation. The CREAM methodology also takes into account the dynamic interaction between human and machines.

4.4.1.1 Prospective Analysis

Prospective analysis is applied when qualitative performance prediction of CREAM is carried out prior to quantifying the risk associated with the human actions under a study.

It allows a good retrieval of qualitative information input for detailed quantitative prediction to follow. A performance prediction describes the development process and external environment of a scenario. Figure 4.6 illustrates the CREAM performance prediction methodology. Its main steps consist of task analysis, opportunities for error reduction and consideration of human performance on overall safety system.

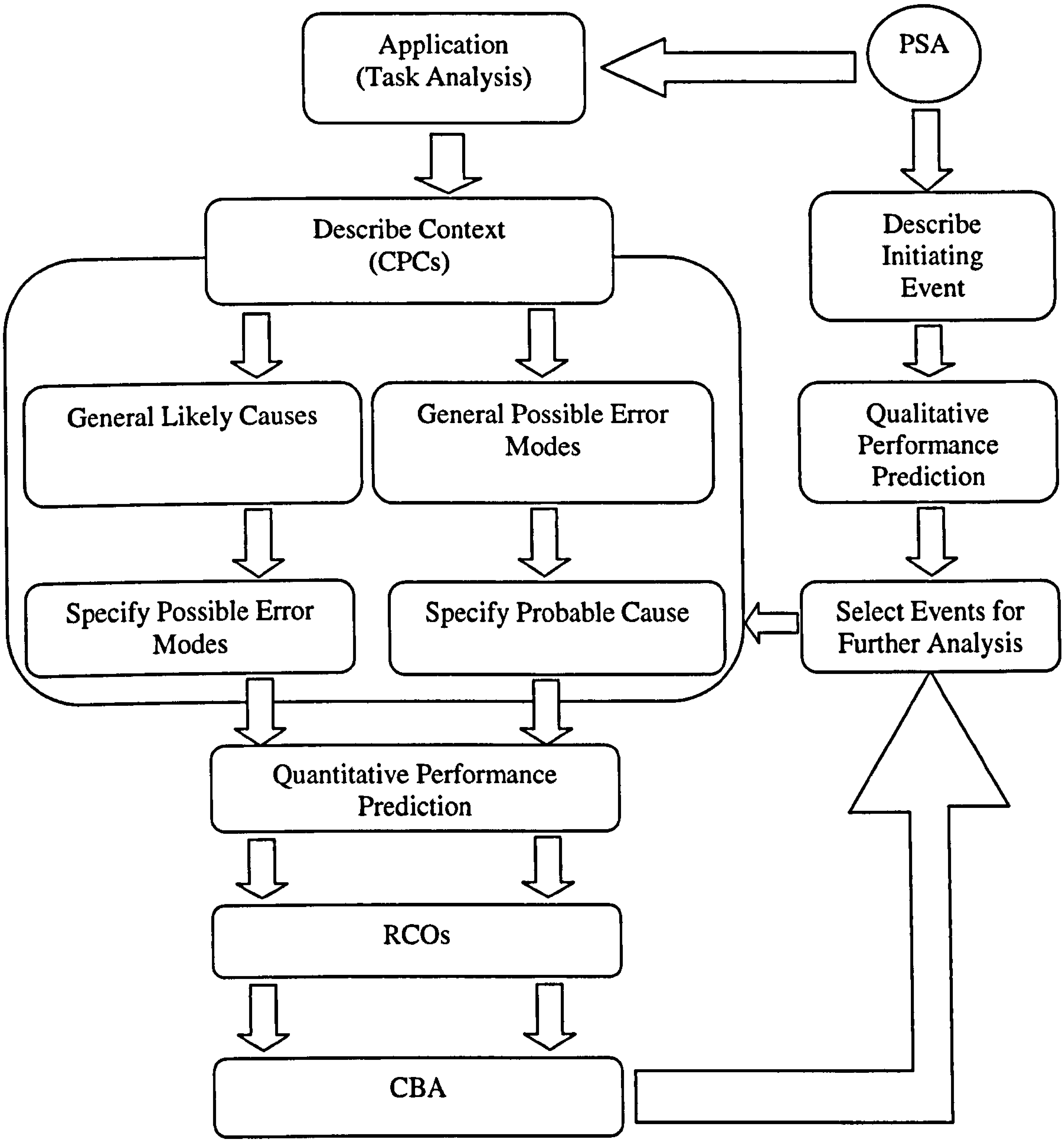

Figure 4.6 CREAM Performance Predictions

Detailed explanation of the above framework is provided as follows:

i). Task Analysis

This step is to analyse a task and a situation such as a marine incident/accident. The analysis will include the consideration on organisations, technical systems, involved ship's crew and the control task to be carried out emphasising on all the systems and activities towards a safe maritime operation.

ii). Context Description

The context is described by means of CPCs through identifying the probable external and internal antecedents and the possible error modes.

iii). Describing Initiating Event

Task analysis from the first step would assist in carrying out the description of initiating events by means of suggesting events and conditions that should be instigated. This step will produce a set of initiating events for which a performance prediction can be made.

iv). Qualitative Performance Prediction

It utilises the classification scheme, as adapted by the context, to describe the expected development of an initiating event. A detailed classification scheme is originally developed in a maritime domain as shown in Appendix II. It allows the maritime incident/accident to be analysed in depth to ascertain the possible error modes and probable causes.

v). Selecting Events for Further Analysis

Based on the results of the qualitative performance prediction, a quantitative performance prediction can be carried out for some selected events.

vi). Quantitative Performance Prediction

A detailed qualitative performance needs to be carried out prior to conducting quantitative performance prediction. This step will produce a final action failure probability figure for the analysed event.

vii). RCOs

Upon completion of detailed qualitative performance prediction by means of specifying possible error modes and causes, appropriate RCOs can be identified and obtained to prevent the reoccurrence of the same incident/accident in the future.

viii). CBA

The CBA determines the costs and benefits involved in implementing the RCOs identified above. This action enables the prioritisation of the RCOs for supporting decision making.

4.4.1.2 Retrospective Analysis

Detailed illustration of retrospective analysis is presented in Figure 4.7.

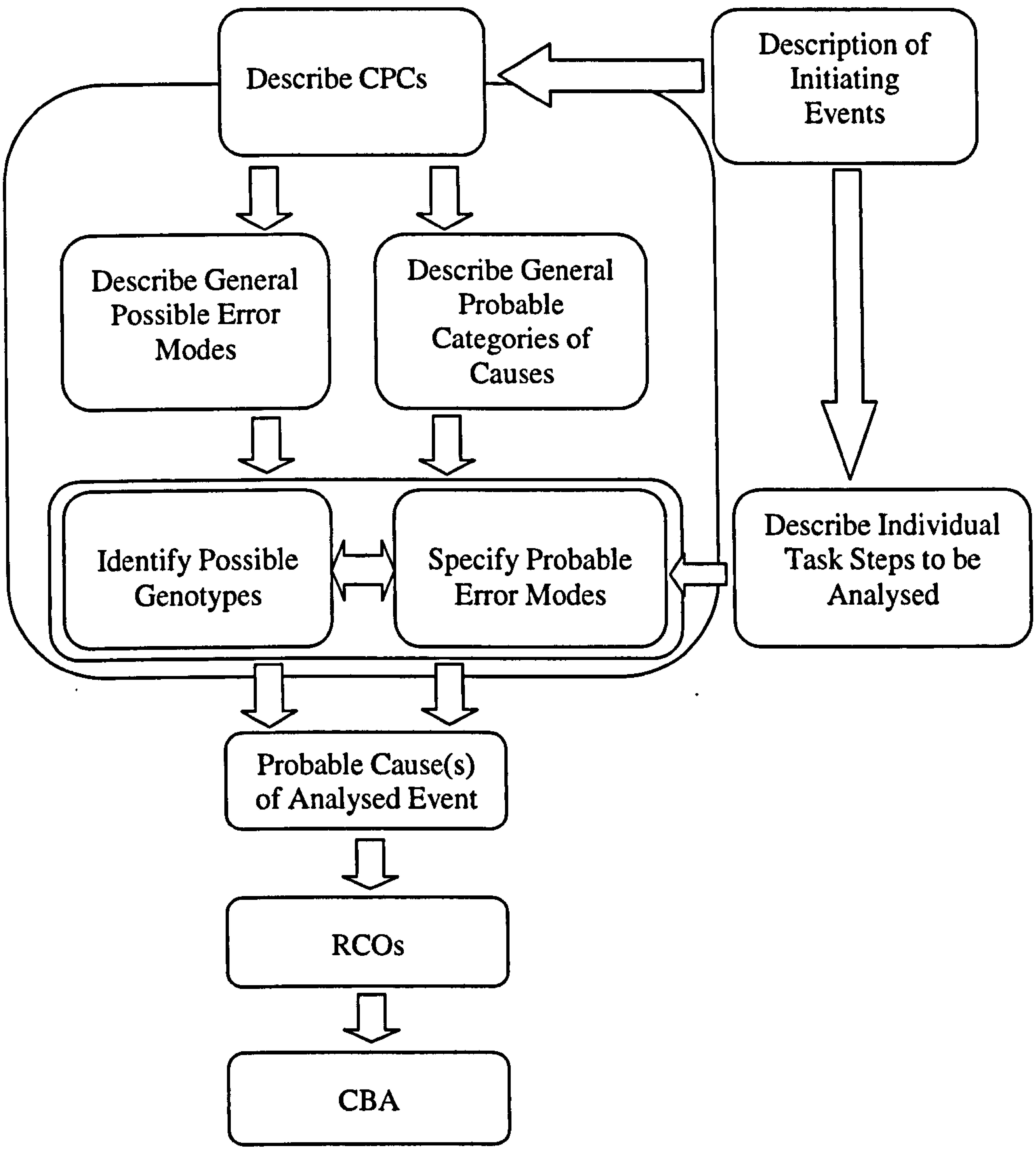

Figure 4.7 Retrospective Analysis

The analysis begins with a description of initiating events by describing nine CPCs relevant to the incident/accident investigated. Each CPC is evaluated and possible error modes are determined. Detailed analysis of an accident is further carried out by referring to three groups of genotypes in determining the weight of each towards the nine CPCs. This allows more detailed clarification of the probable error causes of the accident. The retrospective analysis deals with traditional and conservative means of analysis. The two new features, the RCOs and CBA, added to the advanced CREAM framework are elaborated in the following sections.

4.4.1.3 RCOs

This step assists in determining regulatory measures and actions required to be carried out based on the outcome of detailed qualitative performance analysis taking into consideration the hazard elimination, mitigating the consequences and preventing the occurrence of same incident/accident. The quantitative risk analysis related to the RCO selection is provided in Chapter 7. All the intolerable risks from detailed qualitative analysis need to be reduced to an ALARP level. It can be carried out by evaluating the important networks in the management of oil tankers as described in Section 3.3.3 from the following aspects:

a). Management aspect that deals with human and organisational factors such as the application of administrative controls including attending of a Bridge Resource Management course.

b). Operational aspect that deals with human and organisational factors such as training crew in error management strategies to increase comprehension of critical situation onboard.

c). Engineering aspect that deals with the technical factors.

4.4.1.4 CBA

CBA determines the costs and benefits involved in implementing the RCOs that are deduced from the detailed analysis of main task steps. The cost effectiveness of each RCO is compared with a base case. A base case reflects the existing levels of risk associated with the shipping activities before the implementation of any risk control. Consequently, the options are ranked in terms of their costs to achieve a unit reduction of risk (Subramaniam, 2003). The costs include capital costs and items requiring replacement, labour costs, operating costs, installation and commissioning costs, maintenance costs, inspection, surveying and certification costs, off hire and delay costs, and training costs. The benefits of the implementation of the risk controls include reduced injuries and fatalities, reduced vessel casualties, reduced environmental damage including cleaning up costs, reduction of salvage costs, and increased availability of assets.

A good guide of CBA can be illustrated by Table 4.4. The amounts provided as benchmarks are for illustrative purposes only. Appropriate cost and benefit benchmarks need to be determined and documented by different shipping organisations or companies. The benefit gained on the implementation of the RCOs can be divided into four categories. The maximum benefit achieved on the implementation of a RCO is categorised as 'High', whereas the minimum benefit achieved as 'Low'. Meanwhile, those benefits attained between maximum and minimum are categorised as 'Medium' and 'Moderate', whichever the benefits are close to the maximum or minimum respectively. The benefit is categorised as the following upon taking into consideration all the items listed above.

a). If it is 'High' then the outcome of applying CBA is "Outstanding" provided that less than £10, 000 was spent to implement the selected RCO.

b). If it is 'High' then the outcome of applying CBA is categorised as "Good" provided that cost required to implement the selected RCO falls within the range of £10,001 and £100,000.

c). If it is 'High' then the outcome of applying CBA is only "Average" provided that more than £100, 000 was spent to implement the selected RCO.

d). If it is 'Medium' then the outcome of applying CBA is "Good" provided that the budget spent to implement the selected RCO is less than £50,000. In addition, a qualitative comparison should distinctly show that some improvement can still be gained, compared to 'High' categorisation.

e). If it is 'Medium' then the outcome of applying CBA is "Average" provided that amount spent to implement the selected RCO falls within the range of £50,001 and £100,000.

f). If it is 'Medium' then the outcome of applying CBA is "Poor" provided that more than £100, 000 was spent to implement the selected RCO.

g). If it is 'Moderate' then the outcome of applying CBA is "Good" provided that less than £10, 000 was spent to implement the selected RCO.

h). If it is 'Moderate' then the outcome of applying CBA is only "Average" if the amount spent to implement the selected RCO falls within the range of £10,001 and £50,000.

i). If it is 'Moderate' then the outcome of applying CBA is categorised as "Poor" if the cost spent to implement the selected RCO was more than £50, 000.

j). If it is 'Low' then the outcome of applying CBA is "Average" provided that less than £10, 000 was spent to implement the selected RCO.

k). If it is 'Low' then the outcome of applying CBA is "Poor" provided that the budget spent to implement the selected RCO is between £10,001 and £100,000. In such a case the cost to implement the selected RCO is higher than the benefit gained.

l). If it is 'Low' then the outcome of applying CBA is "Very Poor" provided that more than £100, 000 was spent to implement the selected RCO.

Table 4.4 CBA Matrix

Assessment / Cost / Benefit	Less than £10,000	£10,001 to £50,000	£50,001 to £100,000	£100,001 to £1,000,000
High	Outstanding	Good	Good	Average
Medium	Good	Good	Average	Poor
Moderate	Good	Average	Poor	Poor
Low	Average	Poor	Poor	Very Poor

With reference to Table 4.4, assume the cost to implement the RCO from a detailed analysis of the main task steps is less than £10,000. Meanwhile the benefit gained from the application of the selected RCO is at a 'Medium' level. Thus, it can be considered that the RCO is "Good" in terms of its cost effectiveness. If the cost of implementing a RCO is £51,000 and the benefit achieved is estimated at a 'Low' level, then the RCO is considered "Poor". Table 4.3 can provide a guide to the shipboard management in determining which RCOs should be implemented.

The matters of costs and benefits are perceived differently by the various stakeholders in the shipping industry affected by risk management decisions. Stakeholders' feedback on the distribution of costs of reducing risk and the remaining risk should also be taken into consideration (Rosqvist and Tuominen, 2003). Furthermore, the acceptable risk level as per ALARP may itself change with time as the standard of safety increases.

4.5 Case Studies

The following case studies are focused on a qualitative analysis, whereas the quantitative analysis feature is provided in the following chapters.

4.5.1 A Case Study of 'Carina'

The following case study of '*Carina*' incident is presented to illustrate the prospective application of CREAM, which can be used to identify possible sources of human errors for an incident that has not been encountered. A simulated incident is assumed to have taken place onboard '*Carina*' while she was discharging crude oil at one of the US Gulf of Mexico ports.

4.5.1.1 Chronicle of 'Carina'

M.T. CARINA, an ABS classed double hull tanker of 16 years old was discharging crude oil at one of the US Gulf of Mexico oil terminal. While the vessel was discharging in daytime, it was found that two branches of cargo tanks inert gas valves were in a closed position. The vessel was using non return butterfly valves. The closing mechanism takes in the form of a disc. The disc is located in the centre of the inert gas pipe, passing through the disc is a rod connected to the lever of the valve. The valve can be opened and closed by turning the lever at an angle of 90 degrees. The valve could close by itself due to vibration or poor locking arrangement or even due to poor maintenance. The presence of inert gas inside the cargo tank ensures that the cargo tank atmosphere is retained at a lesser percentage of oxygen content to prevent any combustion that could lead to tank explosion. Therefore, discharging crude oil without having a positive supply of inert gas could result in cargo tank to collapse and subsequently results with an explosion. It was found during routine deck cargo watch that both inert gas valves of four wing cargo tanks were in a closed position. Upon seeing the status, the deck cargo watch keepers, immediately, opened the valves and had prevented an immediate danger from occurring.

4.5.1.2 Detailed Analysis of Main Task Steps

The following comprises the detailed analysis of the '*Carina*' incident utilising CREAM illustrated in Figure 4.8.

i). The initiating event was the delay in noticing the status of the inert gas valves as to whether they were in an open or a close position.

ii). Therefore, the most likely Error Mode was timing. The specific consequent was a delay in noticing and awareness on the status of cargo tank inert gas valves.

iii). With reference to General and Specific Antecedents for Error Modes in Table AII.19, there are six possible general antecedents and two specific antecedents. The six general antecedents are Inattention, Inadequate plan, Inadequate procedures, Communication failure, Faulty diagnosis and Observation missed. Meanwhile the two specific antecedents of Omission and Trapping Error can be disregarded due to irrelevancy to the initiating event.

The delays in noticing and reporting the status of cargo tank inert gas valves could have led to vessel explosion and human casualties. Tables 4.5, 4.6 and 4.7 present the CPCs, probable Error Causes and possible Error Modes for the '*Carina*' incident respectively. In Table 4.5, all the nine CPCs were analysed in detail to produce an evaluation on each CPC. For example, on the CPC_{ASO}, failure to frequently monitor the status of inert gas branch valves of each cargo tank reflects an inefficient shipboard organisation. With reference to Table 4.5 six of the CPCs, the CPC_{ASO}, CPC_{SWC}, CPC_{APP}, CPC_{NSG}, CPC_{QAT} and CPC_{ASP} fall into reduced reliability effects. Meanwhile, the remaining two CPCs, CPC_{MMI} and CPC_{SCQ} fall into non-significant effect on human performance. The CPC_{CRT} is not relevant for the case study. With reference to the ratio application of improved and reduced reliabilities for the '*Carina*' incident in Figure 4.3, it can be deduced that the ship's crew acted in a 'Scrambled' control mode.

Table 4.5 CPCs for the '*Carina*' Incident

CPCs	Description of Evaluation	CPC Linguistic Terms
ASO	Failure of monitoring to ensure that all the cargo tanks inert gas branch valves are kept in open position during discharging cargo operations.	Very Efficient/Efficient/ **Inefficient**/Deficient
SWC	Cargo operations could distract the shipboard working condition.	Advantages/Compatible/ **Incompatible**
MMI	Manual monitoring of inert gas branch valves to indicate open/shut position can be carried out.	Supportive/Adequate/**Tolerable/** Inappropriate
APP	Lack of procedures to monitor the status of inert gas branch valves while cargo operation is in progress.	Appropriate/Acceptable/ **Inappropriate**
NSG	Vessel was having a vetting inspection along with discharging cargo operations.	Less than actual capacity/ Matching current capacity/ **More than actual capacity**
QAT	Continuous cargo operations could distract monitoring the status of inert gas branch valves.	Adequate/Temporarily inadequate/**Continuously inadequate**
CRT	Time of the day is not relevant for the case.	Night time (Unadjusted)/**Day time (Adjusted)**/Night time (Adjusted)
ASP	Lack of training and awareness on the importance of monitoring inert gas branch valves.	Adequate, vast experience/ Adequate, limited experience/ **Inadequate experience**
SCQ	Inefficient crew management during cargo operations in port.	Very Efficient/Efficient/ **Inefficient**/Deficient

In Table 4.6, identification of CPCs in relation to the three genotypes was carried out. Ticks denote the importance of a particular CPC to the ticked type of genotypes. Double ticks represent more weight than single ones. For example, the CPC_{ASO} has more importance/weight to organisation related genotype than CPC_{SWC} does. Upon meticulous analysis of CPCs along with identification of various genotypes, probable error causes are comprehended. Thus, detailed analysis of Table 4.6 assists in producing an informative Table 4.7 in which each of the eight error modes is clarified to determine the probability of each error mode that caused the incident. Finally, Figure 4.8 illustrates the analysis of the '*Carina*' incident in a graphical presentation for ease of understanding of the analysed incident. The analysis begins with Table AII.1 which presents an error mode of timing which describes the late action of the crew to inspect the inert gas branch valves. This is followed by analysis of Table AII.19 that presents six specific consequents. On further analysis of each specific consequent, the general and specific antecedents are obtained. The specific antecedent becomes the attributed cause and result in the end point of the analysis. An example of analysis on 'Inattention' specific consequent is described as follows. From Table AII.19, following the 'Inattention' consequent, Table AII.23 is analysed to derive 'Adverse ambient conditions' general antecedent. The analysis is continued to Table AII.32 under 'Adverse ambient conditions', to select 'Distraction' of general antecedent. Finally, 'Poor cargo planning' is derived as the specific antecedent, which becomes the attributed cause of the incident. A similar approach of analysis is performed on the remaining five specific consequents.

Table 4.6 Probable Error Causes for the '*Carina*' Incident

CPCs	Person related genotype	Technology related genotype	Organisation related genotype
ASO: Inefficient	✓	✓	✓✓
SWC: Incompatible	✓	✓	✓
MMI: Tolerable	✓	✓✓	✓
APP: Inappropriate	✓	✓✓	✓✓
NSG: More than Capacity	✓✓	✓✓	
QAT: Continuously inadequate	✓		
CRT: Daytime			
ASP: Inadequate experience	✓	✓	✓✓
SCQ: Inefficient	✓		✓✓

Table 4.7 Possible Error Modes for the '*Carina*' Incident

Error Mode	Points of Clarification	Possibility
Timing	Failure of the cargo watchkeepers to frequently monitor the status of inert gas branch valves during discharging operations.	Possible
Duration	Failure in verifying the status of inert gas branch valves in time could have resulted in cargo tank explosion.	Possible
Force	Level of force is not a parameter in this incident investigation.	Impossible
Distance/ Magnitude	Distance/Magnitude is not a parameter in this type of incident investigation.	Impossible
Speed	The speed of action in opening the inert gas branch valves is important for this event scenario.	Possible
Direction	Direction is not a parameter in this type of incident investigation.	Impossible
Wrong Object	Object is not a parameter in this nature of incident investigation.	Impossible
Sequence	The sequence of action in opening the inert gas branch valves immediately is important for this event scenario.	Possible

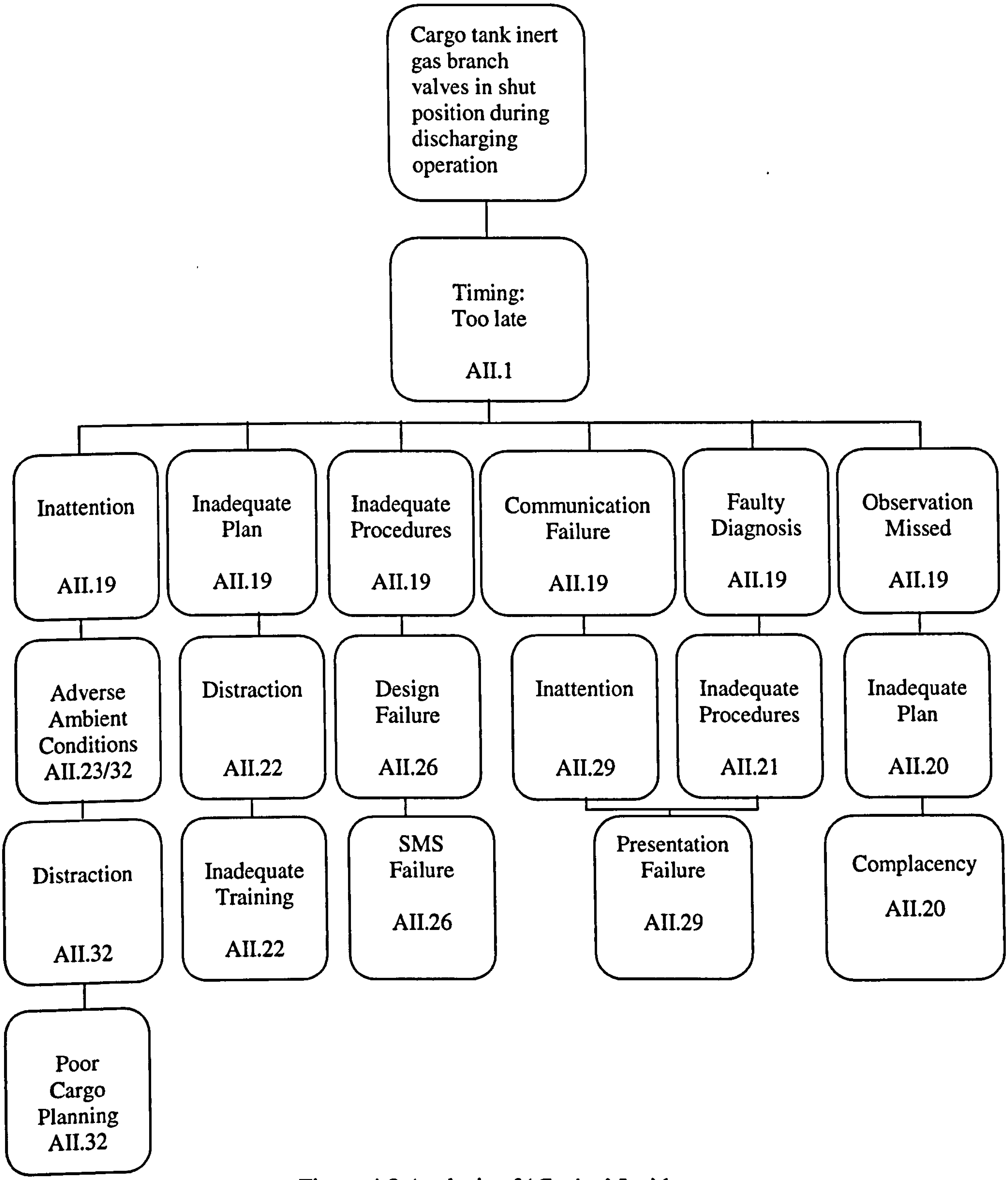

Figure 4.8 Analysis of '*Carina*' Incident

iv). RCOs

The RCOs that can be taken into consideration to prevent reoccurrence of this incident can be divided into three aspects.

a). Management aspect

The shore management should implement a policy that provides a periodical checking of the cargo tank's inert gas branch valves. Ideally, the whole cargo tanks' inert gas valve system should be dismantled during vessels drydocking and verified for its integrity.

b). Operational aspect

Continuous training of crew onboard oil tankers is to be conducted to emphasise the significance of proper use of cargo tanks' inert gas branch valves. All new crew onboard should be provided with the training along with a vessel familiarisation briefing.

c). Engineering aspect

The shore management should ensure that at the shipbuilding phase itself, an oil tanker is built with a good structural design taking into consideration the shipboard operational needs. Thus, much better and more reliable design of a locking arrangement of cargo tanks' inert gas branch valves should be constructed. In addition, an appropriate means of a warning system such as an audible alarm, visual light warning signals, or the combination of the two may be provided in the cargo control room on the status of the cargo tanks' inert gas branch valves.

v). CBA

The incident could result in a structural failure of the oil tanker leading to oil spill and even human casualties. The following elucidation by comparing cost of oil spill and cost of training officers and crew helps to determine and select suitable RCOs. It also further strengthens the need of an oil tanker crew training regime to overcome and prevent any oil spill in the future (Subramaniam, 2003).

A). Cost of Oil Spills

The following are among the factors that determine the cost of oil tanker spills:

a). Type of oil spilled.

Light crude oil tends to evaporate easily. Thus, it does not persist on the surface of the sea. In addition, if rough seas are present, the light crude oil tends to disperse and dissipate naturally. Meanwhile, heavy crude oil such as heavy fuel oil is highly persistent when spilt resulting in the oil travelling great distances far from the original spilt location. Therefore, clean-up cost for heavy crude oil is much higher than the one for light crude oil. It is mainly due to the large areas covered by the heavy crude oil, followed by the oil characteristics of being difficult to clean.

b). Location of oil spill

The location of oil spill will determine the degree of damage to the environment and economic resources. It also determines the extent of the clean-up operation required. State of sea, wind direction and speed, tidal range, currents, depth of water and distance of coast from the location of oil spill will determine the extent of coastal contamination and clean-up response.

c). Amount of oil spilt

This factor works parallel with the location of oil spilt. More amount of oil spilt will result in much greater damage to the environment and far more extensive clean-up operation. The location of spill, however, plays a role in determining the cost. A good example is of the oil tanker spill from *M.T. Castillo De Bellver* off South Africa in 1983. The tanker spilt 252,000 tonnes of crude oil but the clean-up and damage costs were not much due to the fact that the spill did not contaminate any coastlines.

d). Economic resources at risk at the oil spilt area

Compensation to be paid for affecting the environment and the economic resources at the location of oil spill such as the fishing industry and the tourism industry could further increase heavily the cost of an oil tanker spill.

e). Clean-up Cost

Clean-up cost of an oil spill depends on the extent of damage the oil spill had caused. In addition, the location of oil spill will also determine the clean-up cost. Among the few factors that will be accounted for in the clean-up cost are damages to roads and piers during clean-up operation, expenses related to the disposal of the recovered oil and residues, cost of personnel utilised for clean-up operation and, clean-up and restoration of the damaged properties.

B). Cost of Training Officers and Crew

The implementation of STCW 1995 results in training being a way of life in the shipping industry. Hence, the shore management is obliged to provide various training courses to the officers and crew onboard oil tankers. The crew competence increases by receiving appropriate training, thus, resulting in less shipboard operational errors. This will, subsequently reduce the occurrence probability of oil spill.

One oil spill tanker incident could destroy the image and reputation of the tanker owner that has taken decades and millions of dollars to build up. Furthermore, the large amount of money required to compensate due to the oil spill alone is enough to reflect clearly that whatever costs spent on training of crew onboard oil tankers will be the advantage to the tanker owners or the ship management company. In addition, continuous training and retaining same crew in the fleet will produce a safety culture within a fleet and subsequently, in the maritime community itself. Such well trained crew will play a large role in the future of the oil tankers' safety leading to lesser occurrence of oil spills. With reference to Table 4.4, comparison can be made between the costs required for masters and senior officers to attend oil tanker cargo handling simulator courses and the costs required to repair the damaged shell plating of cargo tanks due to possible explosion. The loss of the affected oil tanker from service while carrying out repair of cargo tanks also needs to be taken into consideration when determining the costs.

4.5.2 A Case Study of '*Prestige*'

The following case study of '*Prestige*' accident is presented to illustrate the retrospective analysis use of CREAM. The accident occurred to '*Prestige*' while sailing off the West Coast of Galicia on November 13, 2002. All the data available related to the accident had been collected and restricted to the ABS analysis.

4.5.2.1 Chronicle of 'Prestige'

On November 13, 2002, '*Prestige*', a 26 years old Bahamian registered Ship to Ship oil transfer (STS) ship and ABS classed single hull tanker, carrying 77 000 tonnes of heavy oil developed a substantial starboard list. She was underway in heavy seas and high winds in the region of Cape Finisterre, between 25 to 30 nautical miles, off the coast of Galicia in the northwest of Spain (ABS, 2003). A large crack was found in the starboard side of the hull. Vessel lost her main propulsion due to list and began to drift. Twenty four out of twenty seven crewmembers were evacuated by helicopter from the Spanish authority. The remaining onboard, Master, Chief Engineer and Chief Officer managed to counter flood port side ballast tanks and reduced the list to about 3 degrees starboard list. The vessel, however, was still adrift. On November 14, 2003, SMIT, a Dutch salvage company, took control of the vessel upon a request from '*Prestige*' owner and insurer. Two of the SMIT's tugs, the Rio De Vigo and Sertosa 32 with difficulty managed to secure towlines onboard '*Prestige*'. The ship was towed out to sea into heavy weather away from Spanish coast. Meanwhile, discussions were going on to find a safe haven for the vessel to lighten its cargo to another vessel, the condition however, deteriorated onboard. Consequently, '*Prestige*' structure gave away and collapsed; subsequently the vessel broke into two and sank about 133 nautical miles off the coast of Spain on November 19, 2002. Prior to the accident, she was engaged heavily on STS trade, which includes 174 oil transfers from June 2001 to October 2002 (ABS, 2003).

4.5.2.2 Detailed Analysis of Main Task Steps

The detailed analysis of the '*Prestige*' accident using CREAM retrospective analysis is described as follows:

i). The initiating event is the delays in taking the vessel to a safe haven to offload the remaining cargo.

ii). Therefore, the most likely error mode was timing. The specific consequent was a delay.

iii). With reference to General and Specific Antecedents for Error Modes in Table AII.19, there were six possible general antecedents and two specific antecedents. The six general antecedents are Inattention, Inadequate plan, Inadequate procedures, Communication failure, Faulty diagnosis and Observation missed. The two specific antecedents of Omission and Trapping Error can be disregarded due to their irrelevance to the initiating event.

The delays of the coastal authorities at the vicinity where the vessel was drifting, to provide permission for the vessel to be brought in for removal of the remaining cargoes safely at a secured safe haven resulted in the vessel finally breaking and sinking. Tables 4.8, 4.9 and 4.10 present the CPCs, probable Error Causes and possible Error Modes for the '*Prestige*' accident respectively. In Table 4.8, all the nine CPCs were analysed in detail to produce evaluation on each CPC. For an example on the CPC_{SWC}, the presence of rough weather, which does not provide reasonably good condition, to deal with the accident reflects an incompatible working condition. Six of the CPCs, CPC_{ASO}, CPC_{SWC}, CPC_{APP}, CPC_{NSG}, CPC_{QAT} and CPC_{ASP} fall into reduced reliability effect. Meanwhile, the remaining two CPCs, CPC_{MMI}, and CPC_{SCQ} fall into non-significant effect on human performance. The CPC_{CRT} is not relevant for the case study. The ratio can be determined of improved and reduced reliabilities for the '*Prestige*' accident with reference to Figure 4.3. Then it can be concluded that the ship's crew acted in a 'Scrambled' control mode. Finally, a graphical presentation of analysis of the '*Prestige*' accident is shown in Figure 4.9. The analysis is carried out using Tables in Appendix II with a similar approach to the analysis for '*Carina*' incident.

Table 4.8 CPCs for the '*Prestige*' Accident

CPCs	Description of Evaluation	CPC Linguistic Terms
ASO	Failure of getting the vessel to a safe haven does reflect a reasonable level of inefficiency in management	Very Efficient/Efficient/ **Inefficient**/Deficient
SWC	Rough weather does not provide reasonably good condition to deal with the accident	Advantages/Compatible/ **Incompatible**

MMI	Shipboard operation was reasonably carried out to overcome the emergency listing of the vessel	Supportive/Adequate/**Tolerable** /Inappropriate
APP	Vessel had the standard contingency plan for quick action to alleviate the flooding	Appropriate/Acceptable/ **Inappropriate**
NSG	It is the case for any emergency situation in general	Less than actual capacity/ Matching current capacity/**More than actual capacity**
QAT	Quick action to get the vessel to safe haven is vital due to the encountered rough weather	Adequate/Temporarily inadequate/**Continuously inadequate**
CRT	Time of the day is not relevant for the case	Night time (Unadjusted)/**Day time (Adjusted)**/Night time (Adjusted)
ASP	Crew onboard are qualified and had received standard training as required by STCW 1995	Adequate, vast experience/ Adequate, limited experience/ **Inadequate experience**
SCQ	Crew had not responded well under stress	Very Efficient/Efficient/ **Inefficient**/Deficient

Table 4.9 Probable Error Causes for the '*Prestige*' Accident

CPCs	Person related genotype	Technology related genotype	Organisation related genotype
ASO: **Inefficient**			✓✓
SWC: **Incompatible**	✓	✓	✓
MMI: **Tolerable**	✓	✓✓	✓
APP: **Inappropriate**		✓✓	✓✓
NSG: **More than Capacity**	✓✓	✓✓	
QAT: **Continuously Inadequate**	✓✓		✓
CRT: **Daytime**			

ASP: **Inadequate experience**		✓	✓✓
SCQ: **Inefficient**	✓		✓✓

Table 4.10 Possible Error Modes for the '*Prestige*' Accident

Error Mode	Points of Clarification	Possibility
Timing	Failure of the vessel brought to safe haven in time along with longer exposure to the rough weather subsequently resulted in the sinking of the vessel	Possible
Duration	Duration of action e.g. upright the vessel upon listing is not considered as important factor for this event scenario	Impossible
Force	Level of force is not a parameter in this accident investigation	Impossible
Distance/ Magnitude	Distance/Magnitude is not a parameter in this type of accident investigation	Impossible
Speed	The speed of action to get the vessel protected within the safe haven is important for this event scenario	Possible
Direction	Direction is not a parameter in this type of accident investigation	Impossible
Wrong Object	Object is not a parameter in this nature of accident investigation	Impossible
Sequence	The sequence of action in the recovery procedure upon flooding and towing is important for this event scenario	Possible

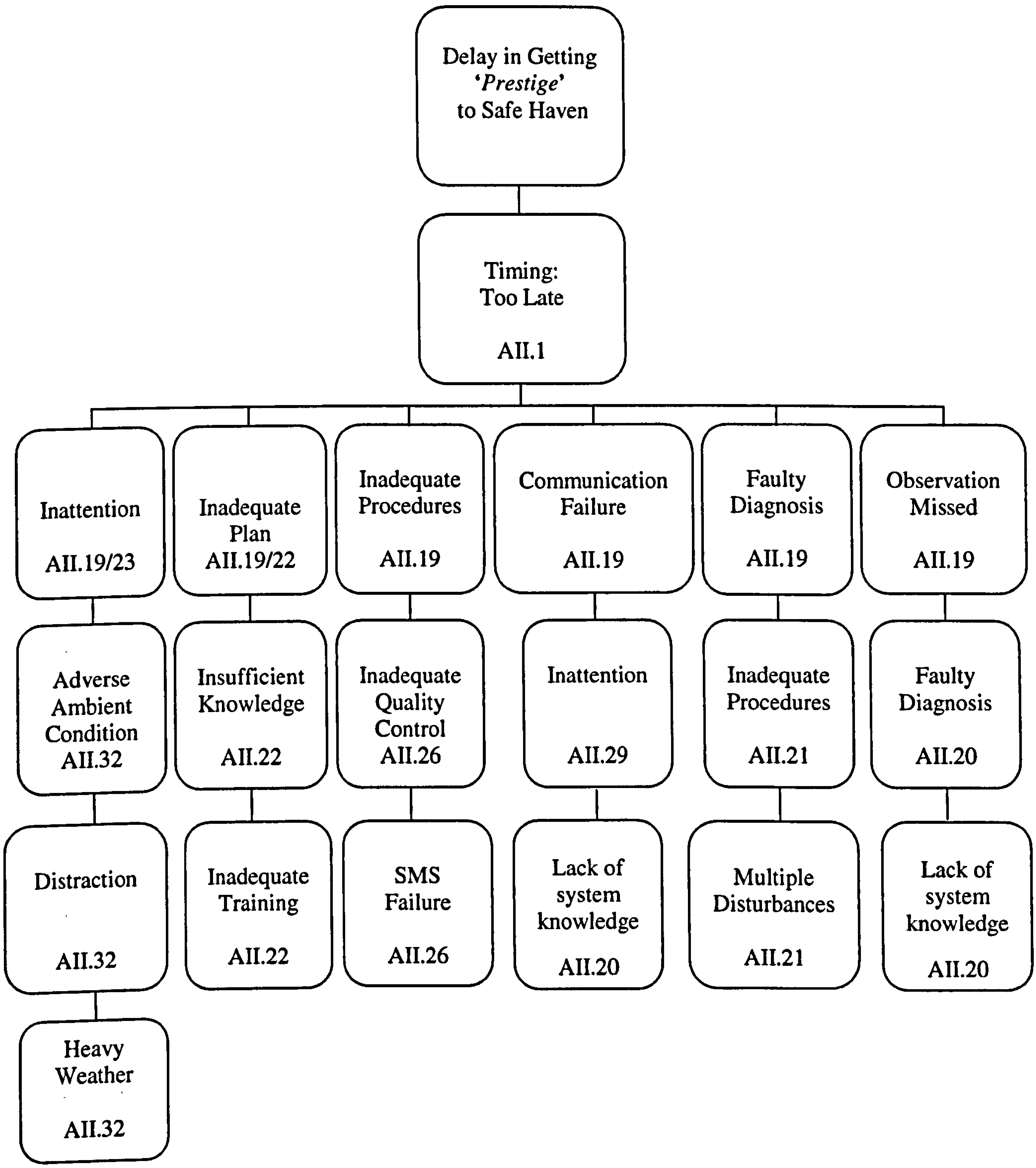

Figure 4.9 Analysis of '*Prestige*' Accident

iv). RCOs

The RCOs that can be taken into consideration to prevent reoccurrence of this accident can be divided into three aspects (Subramaniam, 2003).

a). Management aspect

It is required to implement a policy that ensures all the ship officers involved with cargo operations to attend training on ship stability and cargo operations including training on a cargo operation simulator course. The shore management should implement a policy that stipulates the criteria on the state of weather at which Ship to Ship (STS) cargo transfer operation can be carried out. The entire mooring masters and masters onboard vessels engaged with STS activities should be well trained in STS operations. Doubling up master or mooring master rank engaged in STS operations could be one way of training on this matter. Feedback from the senior master or mooring master on the performance of the doubling up junior master or mooring master to the management should exist. The shore management should ensure that at the shipbuilding phase itself, an oil tanker is built with a good structural design. The shipbuilders should take into account the stress concentration factors while building a vessel. Stringent inspection during surveys should be carried out on the vessel's structure. This could allow an early detection of any fatigue sign of the structure. The shore management should have in place some means of monitoring corrosion of oil tanker structures. Periodical inspection of ballast tanks is a good example. In addition, continuous follow up on the monitoring and repair works carried out on these structures are to be closely examined and well documented. The shore management should have a policy that all oil tankers are equipped with spare sets of gas detecting or measuring equipment to be used onboard. Furthermore, various training on fire fighting onboard oil tankers should be provided to all officers and crew serving on oil tankers. The shore management should have a policy that ensures all fire fighting equipment spare parts are sufficiently stored onboard oil tankers. Technical or safety inspection carried out by superintendents onboard oil tankers can enhance this aspect.

b). Operational aspect

The master should verify the stress condition of the vessel prior to its departure from any port. A copy of the report on the vessel's stress condition while departing port should be transmitted to the head office. Vessel stresses should be monitored at all times during cargo operation while the vessel is in port. The senior officers should provide guidance on this matter to the junior officers. All the crew involved on board STS tankers should be well versed in STS operations. This could only be achieved by ensuring that well experienced STS tanker crew sail with less experienced crew, running the ship operation onboard STS oil tankers. This shipboard training is an effective way that allows the experienced senior officers to pass their professional skills to their subordinates onboard. Thus, manning of crew onboard tankers should be well planned by the shore management. In addition, a good preventative management system, in which the planned maintenance program is carried out on all tanker operational equipment periodically supported with good emergency repairs of equipment if broken, can be an alternative to prevent operational errors in STS oil tankers. A dedicated senior officer onboard oil tankers should diligently carry out water ballast tank inspections. The visual inspection of ballast tanks should be planned in such a way that all the ballast tanks are inspected thoroughly within a six-month period. This allows the detection of any ship structure failure at an early stage. A proper documentation on the inspections should be recorded and filed. A copy of the inspection reports needs to be sent to the head office for superintendent's review. This will ensure continuous follow up on the state of ballast tanks and its structure on any oil tanker within the company's fleet of vessels.

Application of better paint coatings to prevent or reduce corrosion should be practiced onboard oil tankers. There are significant difficulties in reinstating an effective coating system if the ballast tank coating failure occurs before the end of the projected operational life (OCIMF, 2003). Once significant ballast tank coating failure is experienced, the rate of corrosion on exposed areas will accelerate resulting in extensive replacement of steelwork. Therefore, it is prudent to ensure that good ballast tank coatings are applied initially at the stage of building the vessel itself. In addition, close monitoring of the level of corrosion onboard oil tankers can prevent structural failure resulting from corrosion. The presence of hydrocarbon gases in the ballast tanks of oil tankers especially, the double hull tankers should routinely be monitored during loaded passage. Any presence of hydrocarbon gases in the ballast tank could be the initial sign of a tank bulkhead structural failure. This can even result in fire or explosion onboard double hulled oil tankers.

Pump room atmosphere should be checked every day at all times whether the oil tanker is at sea or in port. Pump room ventilators should be kept in good working order. Proper maintenance on all the running parts of ventilators should be carried out periodically as recommended in the manufacturers' manual. All equipment used to detect presence of gasses onboard tankers should be kept in a good working condition at all times. In addition, sufficient spare parts of the detecting equipment and gas sensors should be kept onboard. The expiry dates of these sensors also need to be closely monitored. A monthly inventory of all the gas detecting equipment spare parts and sensors is required to ensure sufficient spares onboard at all times. Checklists and hot work permits should be utilised whenever carrying out any hot work onboard oil tankers. Furthermore, a head office approval should be requested prior to any hot work to be carried out on deck or in the ballast tanks. Fire extinguishers onboard should be routinely checked and tested. All the fire hoses, fire hydrants, fire nozzles including their spares are to be kept in a good working condition at all times.

c). Engineering aspect

Every vessel should be fitted with a reliable continuous ship stress monitoring equipment such as a loadicator. A spare set of all the replaceable parts of the loadicator should be carried at all times onboard an oil tanker. All oil tankers involved with STS operation should use Yokohama fenders as recommended in STS Transfer Guide (Petroleum) OCIMF (1997). Provisions can be made to fit fender cradles and allocate fenders onboard the oil tanker. This should be planned at the shipbuilding stage itself. Those older vessels can get the fender cradles to be fitted at dry dock. Furthermore, the location of fairleads, chokes and bitts on deck are also, important in proper STS mooring operations. Thus, the shore management should consult with a shipyard to ensure that a tanker meant to operate in STS trade is built by considering the following:

1). The location of chokes, fairleads and bitts on deck.

2). The capacity and the winch power fitted on board designated for lifting the Yokohama fenders.

3). Fitting of fender cradles onboard for carrying own Yokohama fenders.

4). Sufficient number of mooring tails onboard for quick replacement if the used one parted during STS operation.

The shore management should implement a policy that provides a scheme where periodical hull thickness measurement is carried out on every oil tanker based on the vessel's nature of trade regions and its age. Hull scanning of ageing tankers provides owners and managers with an effective tool to optimise the requirements for steel renewal. The shore management could also fit equipment such as hull stress monitoring system onboard vessel to provide data on the level of stress encountered during the vessel's service. This could allow any badly affected structures to be refitted while drydocking the vessel. The fitting of sacrificing anodes in ballast tanks should be practiced onboard oil tankers. The conditions of anodes are to be closely monitored and documented together with the ballast tank inspection report. Heavily wasted anodes are to be renewed promptly. All the fire fighting equipment onboard oil tanker should be kept in a good working condition. All the smoke and heat detectors fitted onboard should be tested weekly and recorded on a test log. The automatic sprinkler system should be tested monthly to ensure that the nozzles are not choked. Foam samples should be tested annually from fixed high and low expansion foam fire fighting systems filling tanks. A weekly test should be carried out on all the fixed fire detection and fire alarm systems fitted onboard. Fire pumps should be kept in good working condition. Maintenance on fire pumps should be well planned. Tankers fitted with a fixed carbon dioxide (CO_2) release system should ensure that all the CO_2 cylinders are weighed and kept in a good working condition. Nozzles that are used for releasing CO_2 should be tested routinely with compressed air to ensure that they are not choked. Engine room and pump room CO_2 release alarms should be tested monthly to verify their working conditions. Fixed gas detecting equipment fitted onboard should be tested weekly to ensure that the detecting gas sensors are working within the safe parameters to detect gasses. Inert gas plants should be kept well maintained at all times. Maintenance of the Inert Gas System (IGS) should be well planned and sufficient spare parts should be kept onboard.

v). CBA

Well elaborated clarification in Section 4.5.1.2 part (v) narrates that a huge amount of capital required to compensate any oil spill is adequate and provides a rational reason to implement RCOs described above to prevent the occurrence of similar accidents in the future. It is possible to make a comparison using Table 4.4, between the costs required to carry out above listed RCOs and the costs required to repair the ship if she was salvaged successfully to a port of refuge.

4.6 Conclusion

The significance of addressing human cognitive functions and context in the human error analysis leads to the creation and development of CREAM. The CREAM framework provides a practical approach to its prospective and retrospective analysis. The successful application of the CREAM principle in the analysis of aviation and nuclear power plant incidents/accidents triggers its use to the maritime domain. In addition to applying the methodology, two new phases of RCOs and CBA are added to a newly advanced CREAM framework. Therefore, the new framework of maritime CREAM not only finds the causes of incident/accident investigated but also provides the corresponding solutions to the causes in a cost effective way. Furthermore, changes in the classification schemes including renaming of a few CPCs, introduction of a CBA matrix and addition of classification categories have made CREAM more adaptable to the maritime domain. Case studies of '*Carina*' and '*Prestige*' incident/accident are used to demonstrate that CREAM could be applied to deal with human error analysis related to maritime incidents/accidents. The issues about CPC dependencies, HEP quantification, CBA analysis and RCO ranking, which as essential parts complement the framework, will be investigated in the following chapters.

Chapter 5
Reprioritisation of CPCs in CREAM Using a DEMATEL Technique

Summary
In Chapter 4, an advanced CREAM has been outlined in detail. Lack of CREAM research studies on relationships among CPCs is addressed in this chapter. It presents a novel approach using a DEMATEL technique to reprioritise CPCs in the CREAM. Qualitative analysis is used to describe linguistic terms of CPCs in CREAM. Each linguistic term of CPCs is related to a particular contextual effect on the performance reliability. The resultant number of effects of CPCs will provide the state of the COCOM of CREAM. The interdependencies of CPCs are taken into account when the effects of principal CPCs in designated CPC groups fall into non-significant reliability effect. A careful literature review indicates that few previous studies analyse the prioritisation of CPCs, suggesting that all the CPCs are of different importance. This has led to the introduction of the proposed approach using a DEMATEL model, taking subjective judgments of decision makers into consideration, which allows for reprioritisation of CPCs within the designated CPC groups. This innovative approach provides an effective solution for decision makers to determine which CPCs need to be emphasised to prevent a similar incident/accident from occurring. The proposed model is demonstrated by a case study and validated using a sensitivity analysis.

5.1 Introduction
This chapter introduces a novel approach using a DEMATEL technique to reprioritise CPCs in the CREAM. The specification of CPCs takes into account the objective circumstances of an incident and their possible favourable or unfavourable influence on the occurrence process of the incident. There are nine CPCs, which are described by variable linguistics, in CREAM. The variable linguistics are classified into three sets in terms of their effects on human reliability performance, which include improved reliability effect, non-significant reliability effect and reduced reliability effect. The

state of the COCOM of CREAM, which concentrates on predicting the dynamic equilibrium between human actions and system response, is determined by the total resultant number of effects of CPCs derived from a comprehensive qualitative analysis (Konstandinidou et al., 2006). The COCOM has four characteristic control modes: Scrambled, Opportunistic, Tactical and Strategic modes. The interdependencies and relationships among the CPCs can be shown distinctly with nine CPCs being separated into seven groups and each group being affiliated with two to six CPCs. The interdependencies among the CPCs in a designated CPC groups is illustrated in Table 4.3.

Whilst carrying out a qualitative analysis, if a principal CPC's effect falls into non-significant reliability effect, its relevant component CPCs' effects within the designated CPC group needs to be observed. The state of the principal CPC is determined on the basis of the component CPCs' effects within the designated CPC group. Some of the previous studies analyse the prioritisation of CPCs, suggesting that all the CPCs are of different importance (Marseguerra et al., 2007). However, no prioritisation of CPCs exists within the designated CPC groups, suggesting that the CPCs are of equal importance and influence within the particular designated CPC group. This has led to the introduction of the proposed approach using the DEMATEL model that would allow for reprioritisation of CPCs within the designated CPC groups, taking subjective judgments of decision makers into account. Additionally, the reprioritisation of CPCs takes into account the interdependencies of CPCs within the designated CPC groups. The proposed approach provides a better solution in knowing the relationships among the CPCs rather than the traditional CREAM, which relies merely on the interdependencies of CPCs in determining the effects of the principal CPCs in the designated CPC groups. The traditional CREAM leaves a gap in illustrating relationships between the CPCs. The proposed innovative approach using the DEMATEL model plays a significant role in providing a comprehensive illustration of relationships and interdependencies among CPCs within the designated CPC groups. Detailed knowledge of the relationships and interdependencies among the CPCs would provide decision makers with an alternative of determining an appropriate CPC that needs to be improved to prevent similar incidents/accidents from reoccurring.

5.2 Literature Review

5.2.1 Overview on DEMATEL

The DEMATEL technique was developed by the Geneva Research Centre of the Battelle Memorial Institute (Fontela & Gabus, 1976; Gabus and Fontela, 1973). This technique allows the involved factors of a system or subsystem to be separated into cause group and effect group (Wu, 2008). The causes illustrate the reasons why something occurred whereas the effects are the results of the occurrence. The DEMATEL technique presents the cause and effect groups within a system or subsystem by applying matrices and digraphs to visualise the structure of complicated causal relationships. This technique can be used to develop the relationships and interdependencies among CPCs in CREAM. It is based on a graph theory and results in a causal diagram that illustrates the causal relationships among CPCs within a designated CPC group. The DEMATEL has been successfully applied in many fields including maritime operations (Topcu, 2008), business (Chiu et al., 2006; Hu et al., 2009; Lin and Tzeng, 2009; Noori and Amiri, 2009; Tsai and Chou, 2009; Tseng, 2009a; 2009b; Wu and Lee, 2007; Wu, 2008), engineering (Hori and Shimizu, 1999; Seyed-Hosseini et al., 2006), safety management systems (Liou et al., 2007; Liou et al., 2008), education (Tzeng et al., 2007) and social studies (Tamura et al., 2002; Tamura and Akazawa, 2005). The DEMATEL technique could assist HRA analysts to visualise and simplify components of a complex system or subsystem via a series of simple illustrations of causal diagrams and digraphs. This technique has been preferred to distinguish the relationships of the CPCs within a designated CPC group due to (Lin and Wu, 2008); (Lin and Tzeng, 2009):

(a). Its simplicity in illustrating the complex relationships via a simple causal diagram.

(b). Its wide application in many domains.

(c). Its reliability in producing consistent results of causal diagrams.

(d). Its capability of allowing for a large quantity of criteria to be considered.

(e). Its capability of accommodating human subjective judgments in determining the relationships among the components within a complex system or subsystem.

5.3 Methodology

Most of the research in CREAM was focused on quantification aspects, which included the HRA quantification using fuzzy approaches (Konstandinidou et al., 2006;

Marseguerra et al., 2007), using probabilistic techniques (Fujita and Hollnagel, 2004; Kim et al., 2006), using CREAM prospective quantification (He et al., 2008) and some quantitative developments in CREAM (Marseguerra et al., 2006). This leaves a void in the research on relationships of CPCs in CREAM, despite the fact that CPCs play an important role and are a core element in the CREAM. The developed novel approach of using a DEMATEL technique to illustrate relationships and interdependencies of CPCs could reduce the gap left in CREAM research in terms of understanding and prioritising CPCs. The general framework of the proposed model is illustrated in Figure 5.1. Initially a digraph is constructed to demonstrate the directed relationships of CPCs within a designated CPC group on completion of a qualitative analysis of CREAM modelling an incident. This is followed by solving various matrices, beginning with a pairwise comparison of CPCs within the designated CPC groups to a final total relation matrix. Finally, a causal diagram is produced to illustrate distinctly the relationships and interdependencies of CPCs within the designated CPC group. The research methodology is elaborated in detail in the following subsections.

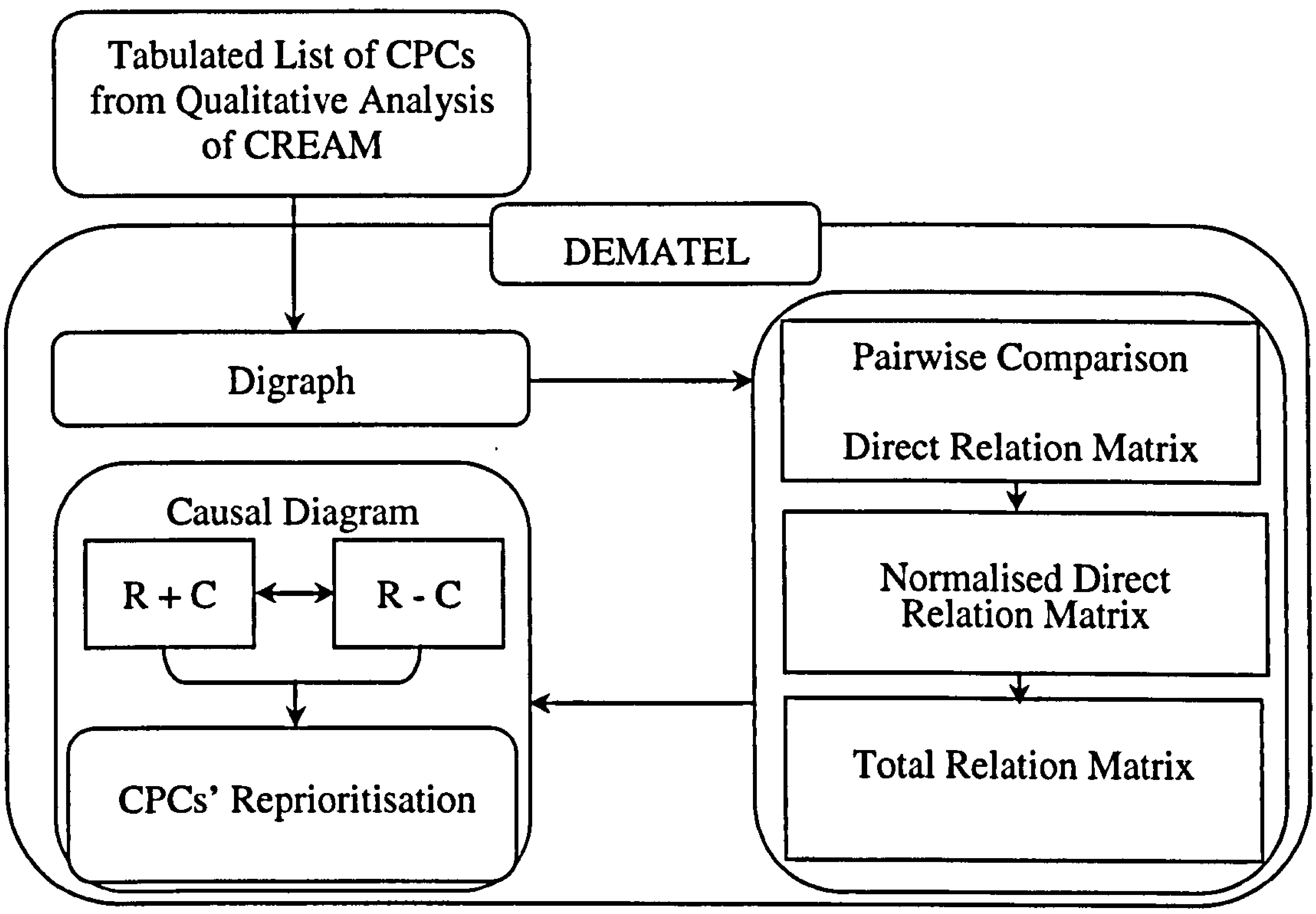

Figure 5.1 The General Framework of the Proposed DEMATEL Model

The proposed framework can be described as follows:

(a). Step 1 – Obtain a tabulated list of CPCs from detailed qualitative analysis of CREAM in an incident/accident. This table facilitates the experts' judgments whilst performing pairwise comparisons in terms of the influence among the CPCs within a designated CPC group.

(b). Step 2 – Construct a digraph to portray a contextual relationship among the CPCs within the designated CPC group.

A digraph, or directed graph, is a diagram composed of points called vertices (nodes) and arrows called arcs going from a vertex to another vertex. A digraph is drawn to illustrate the relationships among CPCs in a designated CPC group.

(c). Step 3 – Carry out pairwise comparison in terms of the influence of the CPCs to obtain a direct relation matrix. A pairwise comparison based on expert judgments in terms of the influence among the CPCs assists in determining the relative importance among the CPCs within the designated CPC group. Equation 5.1 needs to be applied to obtain an average scale to be used for pairwise comparison when more than one expert is used for the analysis (Klir and Yuan, 1995).

$$B(x) = \frac{\sum_{b=1}^{n} a_b(x)}{n} \qquad (5.1)$$

where $B(x)$ is the synthesised value of n experts' judgments, $a_b(x)$ is the value given by the b^{th} expert, $b \in n$ and n is the total number of experts.

A four point scale using Wu's (Wu, 2008) approach of scaling influence matrix measuring the relationship between criteria is adopted and illustrated in Table 5.1. This will be used as a fundamental CPCs' scale for expert judgments in terms of influence and direction among CPCs within the designated CPC groups.

Table 5.1 The Fundamental CPCs' Scale for Expert Judgments

Scale	Linguistic Influence to corresponding CPCs
0	No Influence
1	Low Influence
2	High Influence
3	Very High Influence

Decimal judgments, such as 2.9, are allowed for fine tuning, however judgments greater than 3 are recommended to be avoided if possible. A matrix A of pairwise ratios whose rows give the ratios of the scale of each CPC with respect to all others within a designated CPC group can be described as follows:

$$A = \begin{array}{c} \\ CPC_1 \\ \vdots \\ CPC_i \\ \vdots \\ CPC_g \end{array} \begin{array}{c} CPC_1 \cdots CPC_j \cdots CPC_g \\ \begin{bmatrix} 0 & \cdots & t_{1j} & \cdots & t_{1g} \\ \vdots & & \vdots & & \vdots \\ t_{i1} & \cdots & t_{ij} & \cdots & t_{ig} \\ \vdots & & \vdots & & \vdots \\ t_{g1} & \cdots & t_{gj} & \cdots & 0 \end{bmatrix} \end{array}$$

where $CPC_1, \ldots, CPC_g$ refer to the evaluation elements of CPCs in a designated CPC group, t_{ij} represents the relative influence from CPC_i to CPC_j, $i = 1, 2, \ldots, g$ and $j = 1, 2, \ldots, g$.

The result of this evaluation produces a direct relation matrix, A.

(d). Step 4 – Construct a normalised direct relation matrix.

Utilising Wu's (Wu, 2008) approach, a normalised direct relation matrix can be obtained by using Equation 5.2.

The normalised relation matrix, $X = k\,A$ (5.2) where

$$k = \frac{1}{\max\limits_{1 \leq i \leq g} \sum\limits_{j=1}^{g} CPC_{ij}} \qquad (i, j = 1, 2, \ldots, g)$$

(e). Step 5 – Obtain a total relation matrix, *T*.

A total relation matrix can be obtained by using Lin and Wu's (Lin and Wu, 2008) approach, which is illustrated in Equation 5.3.

$$T = X(I - X)^{-1} \tag{5.3}$$

where I is the identity matrix.

The detailed elaboration of deriving Equation 5.3 is provided in Appendix III.

(f). Step 6 – Construct a causal diagram and reprioritise the CPCs within the designated CPC group.

In this step, the sums of row and column of the *i*th CPC in a total relation matrix denoted by R_i and C_i respectively are required to produce a causal diagram. A causal diagram is constructed by mapping the dataset of $(R_i + C_i)$ and $(R_i - C_i)$. The R_i is the sum of the i^{th} row and C_i is the sum of the j^{th} column of the total relation matrix, i and $j \in g$ and, i and $j = 1, 2, \ldots, g$.

In the casual diagram, the horizontal axis of $(R_i + C_i)$ will show the state of the relationship among the CPCs, whereas the vertical axis of $(R_i - C_i)$ will display the state of influence among the CPCs. Similarly the horizontal axis $(R_i + C_i)$ and the vertical axis $(R_i - C_i)$ divide the CPCs into cause and effect groups. The maximum and minimum values of $(R_i + C_i)$ and $(R_i - C_i)$ are known as "Master Dispatcher", which has the most relationship with the CPCs within a designated CPC group, and "Master Receiver", which has the least relations to the remaining CPCs respectively (Seyed-Hosseini et al., 2006). Generally when the value of $(R_i - C_i)$ is positive, the CPC_i belongs to the cause group, whereas when the value of $(R_i - C_i)$ is negative, the CPC_i belongs to the effect group. All component CPCs in the designated CPC groups will be reprioritised referring to the causal diagram, which illustrates distinctly the complex causal relationships and interdependencies among the CPCs within that designated CPC group. Knowing more about the relationships of CPCs within the designated CPC groups could provide decision makers with better alternatives to take improved action to overcome and prevent a similar incident/accident from reoccurring. Subsequently, an enhanced solution is achieved to reduce human error in a management of an organisation.

5.4 Case Study of *'Prestige'*

The case study of *'Prestige'* is used to demonstrate the proposed novel approach using a DEMATEL model to reprioritise the CPCs in CREAM.

(a). Step 1 – A tabulated list of CPCs from a detailed qualitative analysis in CREAM of the *'Prestige'* incident is illustrated in Table 4.8.

(b). Step 2 – Construct a digraph to portray contextual relations among the CPCs within the designated CPC group.

A digraph to illustrate relationships among the CPCs in the CPC_{SWC}, CPC_{ASO}, CPC_{MMI}, CPC_{QAT}, CPC_{CRT}, CPC_{ASP} CPCs group in CREAM is shown in Figure 5.2.

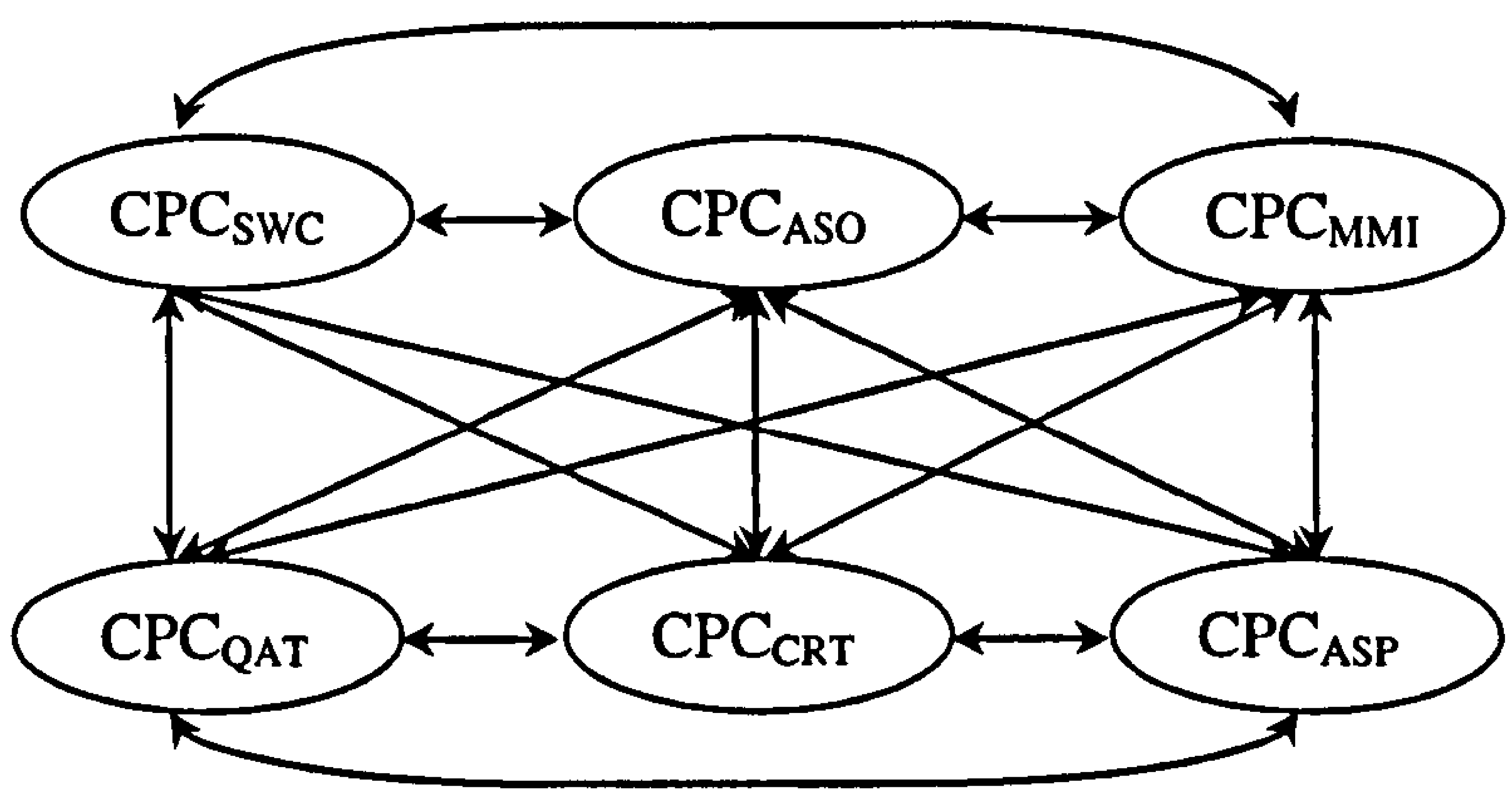

Figure 5.2 The Digraph of the CPC_{SWC}, CPC_{ASO}, CPC_{MMI}, CPC_{QAT}, CPC_{CRT} and CPC_{ASP} CPCs Group

(c). Step 3 – Carry out pairwise comparison in terms of the influence and direction among the CPCs to obtain a direct relation matrix.

A human reliability specialist from a classification society and two officials from two flag state administrations with accident investigation backgrounds, and a master mariner with more than ten years of oil tanker sailing experience were used to provide evaluation of the direct relation matrix of CPCs. The individual expert evaluations are provided in Appendix III. The average scales used for the pairwise comparison of CPCs are obtained by using Equation 5.1. Table 5.2 illustrates the results of the expert judgments pairwise comparison in terms of the influence among the CPCs.

From Equation 5.1, an example of calculation to obtain direct relation matrix value of CPC_{SWC} to CPC_{ASO} by row is shown as follows:

$$CPC_{SWC} \text{ to } CPC_{ASO} \text{ direct relation matrix value} = \frac{(a_1(x) + a_2(x) + a_3(x) + a_4(x))}{4}$$

$$= \frac{(2 + 1 + 2 + 1)}{4}$$

$$= 1.500$$

$a_1(x)$, $a_2(x)$, $a_3(x)$ and $a_4(x)$ are the values on the direct relation matrix of CPC_{SWC} to CPC_{ASO} by row obtained from expert evaluations.

Table 5.2 The Direct Relation Matrix of the CPC_{SWC}, CPC_{ASO}, CPC_{MMI}, CPC_{QAT}, CPC_{CRT} and CPC_{ASP} CPCs Group

CPCs	SWC	ASO	MMI	QAT	CRT	ASP
SWC	0.000	1.500	2.250	1.250	1.250	2.000
ASO	0.750	0.000	1.000	2.000	1.500	2.750
MMI	1.250	0.750	0.000	0.750	1.500	0.750
QAT	1.000	1.500	1.500	0.000	1.500	2.750
CRT	1.000	1.000	0.750	0.750	0.000	0.750
ASP	1.750	2.000	1.250	1.750	0.750	0.000

(d). Step 4 – Construct a normalised direct relation matrix.

A normalised direct relation matrix is obtained by using Equation 5.2. The normalised direct relation matrix of the CPC_{SWC}, CPC_{ASO}, CPC_{MMI}, CPC_{QAT}, CPC_{CRT}, CPC_{ASP} CPCs group is presented in Table 5.3.

From Equation 5.2, the sums of the rows of the direct relation matrix of CPC_{SWC}, CPC_{ASO}, CPC_{MMI}, CPC_{QAT}, CPC_{CRT}, CPC_{ASP} are 8.250, 8.000, 5.000, 8.250, 4.250 and 7.500 respectively.

Hence, $k = \dfrac{1}{8.250}$

An example of calculation to obtain normalised value of CPC_{SWC} to CPC_{ASO} by row is illustrated as follows:

$$CPC_{SWC} \text{ to } CPC_{ASO} \text{ normalised value} = \frac{1}{8.250} \times 1.500 = 0.182$$

Table 5.3 The Normalised Direct Relation Matrix of the CPC_{SWC}, ASO, MMI, QAT, CRT and ASP CPCs Group

CPCs	SWC	ASO	MMI	QAT	CRT	ASP
SWC	0.000	0.182	0.273	0.152	0.152	0.242
ASO	0.091	0.000	0.121	0.242	0.182	0.333
MMI	0.152	0.091	0.000	0.091	0.182	0.091
QAT	0.121	0.182	0.182	0.000	0.182	0.333
CRT	0.121	0.121	0.091	0.091	0.000	0.091
ASP	0.212	0.242	0.152	0.212	0.091	0.000

(e). Step 5 – Obtain a total relation matrix, T.

A total relation matrix is obtained by using Equation 5.3. From Equation 5.3, initially the normalised direct relation matrix X, is subtracted from an identity matrix I, to obtain $(I - X)$ matrix. The I is shown in Table 5.4.

Table 5.4 The *I* Matrix of the CPC_{SWC}, CPC_{ASO}, CPC_{MMI}, CPC_{QAT}, CPC_{CRT} and CPC_{ASP} CPCs Group

CPCs	SWC	ASO	MMI	QAT	CRT	ASP
SWC	1.000	0	0	0	0	0
ASO	0	1.000	0	0	0	0
MMI	0	0	1.000	0	0	0
QAT	0	0	0	1.000	0	0
CRT	0	0	0	0	1.000	0
ASP	0	0	0	0	0	1.000

An example of calculation to obtain value of CPC_{SWC} to CPC_{ASO} by row in the $(I - X)$ matrix is shown as follows:

CPC_{SWC} to CPC_{ASO} $(I - X)$ matrix value = (0 – 0.182) = -0.182

The $(I - X)$ matrix is illustrated in Table 5.5.

Table 5.5 The $(I - X)$ Matrix of the CPC_{SWC}, CPC_{ASO}, CPC_{MMI}, CPC_{QAT}, CPC_{CRT} and CPC_{ASP} CPCs Group

CPCs	SWC	ASO	MMI	QAT	CRT	ASP
SWC	1.000	-0.182	-0.273	-0.152	-0.152	-0.242
ASO	-0.091	1.000	-0.121	-0.242	-0.182	-0.333
MMI	-0.152	-0.091	1.000	-0.091	-0.182	-0.091
QAT	-0.121	-0.182	-0.182	1.000	-0.182	-0.333
CRT	-0.121	-0.121	-0.091	-0.091	1.000	-0.091
ASP	-0.212	-0.242	-0.152	-0.212	-0.091	1.000

This is followed by inversing the obtained matrix $(I - X)$. It would be tedious and involves large calculation for inversing a 6x6 matrix. Software such as Excel or MATLAB can be used for computing larger than 3x3 matrices. The inverse matrix of the $(I - X)$ matrix is presented in Table 5.6.

Table 5.6 The $(I - X)^{-1}$ Matrix of the CPC_{SWC}, CPC_{ASO}, CPC_{MMI}, CPC_{QAT}, CPC_{CRT} and CPC_{ASP} CPCs Group

CPCs	SWC	ASO	MMI	QAT	CRT	ASP
SWC	1.740	0.998	1.041	0.949	0.920	1.249
ASO	0.832	1.861	0.928	1.030	0.942	1.336
MMI	0.594	0.613	1.516	0.594	0.653	0.744
QAT	0.863	1.020	0.982	1.837	0.950	1.337
CRT	0.525	0.588	0.551	0.550	1.449	0.689
ASP	0.892	1.025	0.934	0.981	0.856	2.048

Finally, the normalised direct relation matrix X is multiplied by the inversed matrix $(I - X)^{-1}$ to obtain the total relation matrix, T. An element in the T matrix can be obtained by computing the product of multiplication of each row in the X matrix with the corresponding column in the $(I - X)^{-1}$ matrix.

An example of the calculation to obtain the value of CPC_{SWC} to CPC_{ASO} by row in the T matrix is shown as follows:

CPC_{SWC} to CPC_{ASO} T matrix value = {(0 × 0.998) + {(0.182 × 1.861) + {(0.273 × 0.613) + (0.152 × 1.020) + {(0.152 × 0.588) + {(0.242 × 1.025)}

= 0.998

The total relation matrix is presented in Table 5.7.

Table 5.7 The Total Relation Matrix of the CPC_{SWC}, CPC_{ASO}, CPC_{MMI}, CPC_{QAT}, CPC_{CRT} and CPC_{ASP} CPCs Group

CPCs	SWC	ASO	MMI	QAT	CRT	ASP
SWC	0.740	0.998	1.041	0.949	0.920	1.249
ASO	0.832	0.861	0.928	1.030	0.942	1.336
MMI	0.594	0.613	0.516	0.594	0.653	0.744
QAT	0.863	1.020	0.982	0.837	0.950	1.337
CRT	0.525	0.588	0.551	0.550	0.449	0.689
ASP	0.892	1.025	0.934	0.981	0.856	1.048

(f). Step 6 – Construct a causal diagram and reprioritise the CPCs within the designated CPC group.

The R_i and C_i values are computed for all the CPCs within the CPC_{SWC}, CPC_{ASO}, CPC_{MMI}, CPC_{QAT}, CPC_{CRT} and CPC_{ASP} CPCs group. The values of R_i, C_i, $(R_i + C_i)$ and $(R_i - C_i)$ are illustrated in Table 5.8.

An example of calculation to obtain R_i, C_i, $(R_i + C_i)$ and $(R_i - C_i)$ values of CPC_{SWC} is presented as follows:

$R_{i\ SWC} = (0.7399 + 0.9978 + 1.0408 + 0.9487 + 0.\ 9203 + 1.2489) = 5.8964$

$C_{i\ SWC} = (0.7399 + 0.8321 + 0.5943 + 0.8630 + 0.5253 + 0.8916) = 4.4462$

$(R_i + C_i)_{SWC} = (5.8964 + 4.4462) = 10.3426$

$(R_i - C_i)_{SWC} = (5.8964 - 4.4462) = 1.4502$

Table 5.8 The R_i, C_i, $(R_i + C_i)$ and $(R_i - C_i)$ values of the CPC_{SWC}, CPC_{ASO}, CPC_{MMI}, CPC_{QAT}, CPC_{CRT} and CPC_{ASP} CPCs Group

CPCs	R_i	C_i	$(R_i + C_i)$	$(R_i - C_i)$
SWC	5.896	4.446	10.343	1.450
ASO	5.929	5.105	11.034	0.824
MMI	3.714	4.951	8.665	-1.238
QAT	5.989	4.941	10.930	1.048
CRT	3.352	4.770	8.122	-1.418
ASP	5.735	6.401	12.136	-0.666

A causal diagram is constructed by mapping the dataset of $(R_i + C_i)$ and $(R_i - C_i)$ from Table 5.8. Figure 5.3 displays the causal diagram of the CPC_{SWC}, CPC_{ASO}, CPC_{MMI}, CPC_{QAT}, CPC_{CRT}, CPC_{ASP} CPCs group.

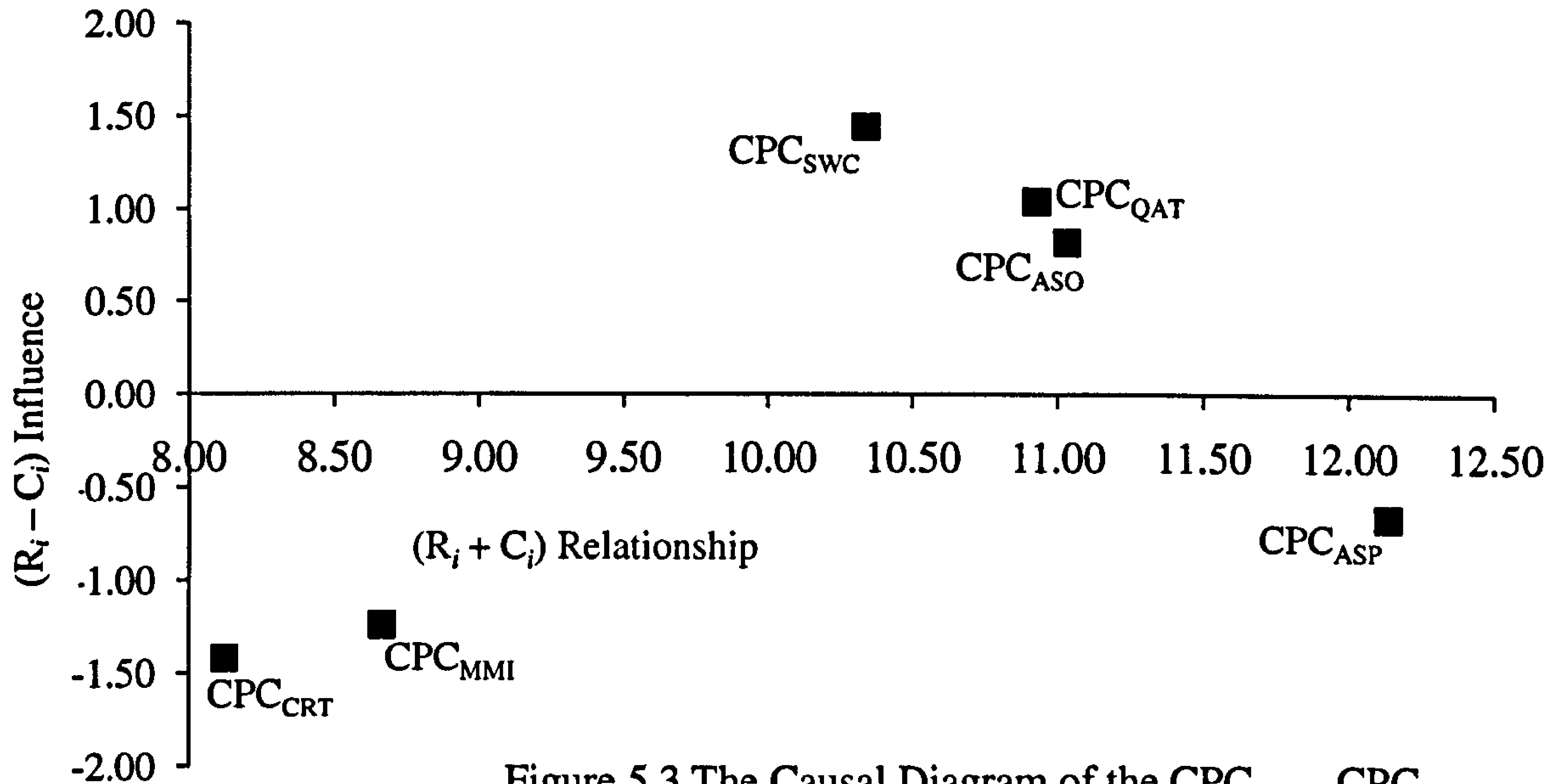

Figure 5.3 The Causal Diagram of the CPC_{SWC}, CPC_{ASO}, CPC_{MMI}, CPC_{QAT}, CPC_{CRT}, and CPC_{ASP} CPCs Group

Analysing the causal diagram, it is apparent that the CPC_{ASP} with a maximum value of $(R_i + C_i)$ is the "Master Dispatcher", while the CPC_{CRT} is the "Master Receiver", with a minimum value of $(R_i - C_i)$. The CPC_{ASP} has the most relations with the other five CPCs of CPC_{SWC}, CPC_{ASO}, CPC_{MMI}, CPC_{QAT}, and CPC_{CRT}. The CPC_{CRT} having the minimum value of $(R_i + C_i)$, is considered to have the least relations to the other five CPCs. Furthermore, the characteristics of the CPC_{ASO}, CPC_{SWC} and CPC_{QAT} CPCs belong to the cause group while the CPC_{MMI}, CPC_{CRT} and CPC_{ASP} CPCs belong to the effect group. The CPC_{ASP} experiences the most relations towards CPC_{MMI} and CPC_{CRT} CPCs within the effect group. The CPC_{ASO} and CPC_{QAT} play a significant role in determining the effect of the principal CPC of this group, CPC_{SWC}. It can be established that the proposed approach using a DEMATEL model has provided decision makers with a better understanding of the relationships of CPCs within the designated CPC group in determining an appropriate CPC, which needs to be improved to prevent similar incidents/accidents from occurring in the future.

5.5 CPCs Reprioritisation Using Sensitivity Analysis

Sensitivity analysis is a study of how systematically changing parameters in a model to determine the effects of such changes (Tarantola, 2008). It is a method for testing the degree of sensitivity of a model's variables. The sensitivity analysis is carried out by changing the effect of CPC_{CRT} to the remaining five CPCs. The original expert evaluation values associated with CPC_{CRT} in the direct relation matrix were increased from 0.1 to 0.8 at a step of 0.1. The assumption made is that the trend line of the CPC_{CRT} should increase steadily resulting in the CPC_{CRT} to shift from an effect group to a cause group. Meanwhile, the remaining CPCs, CPC_{SWC}, CPC_{ASO}, and CPC_{QAT} should remain in the cause group and the CPC_{MMI} and CPC_{ASP} should remain in the effect group. Furthermore, the gradient of the trend lines of CPC_{MMI} and CPC_{ASP} should change due to the changes of one of the member of the effect group, CPC_{CRT}. As for the gradient of the trend lines of CPC_{SWC}, CPC_{ASO} and CPC_{QAT}, there should not be apparent changes as to the CPCs in the effect group due to the characteristic of belonging to the cause group. The trend lines of resultant simulated causal diagram are illustrated in Figure 5.4.

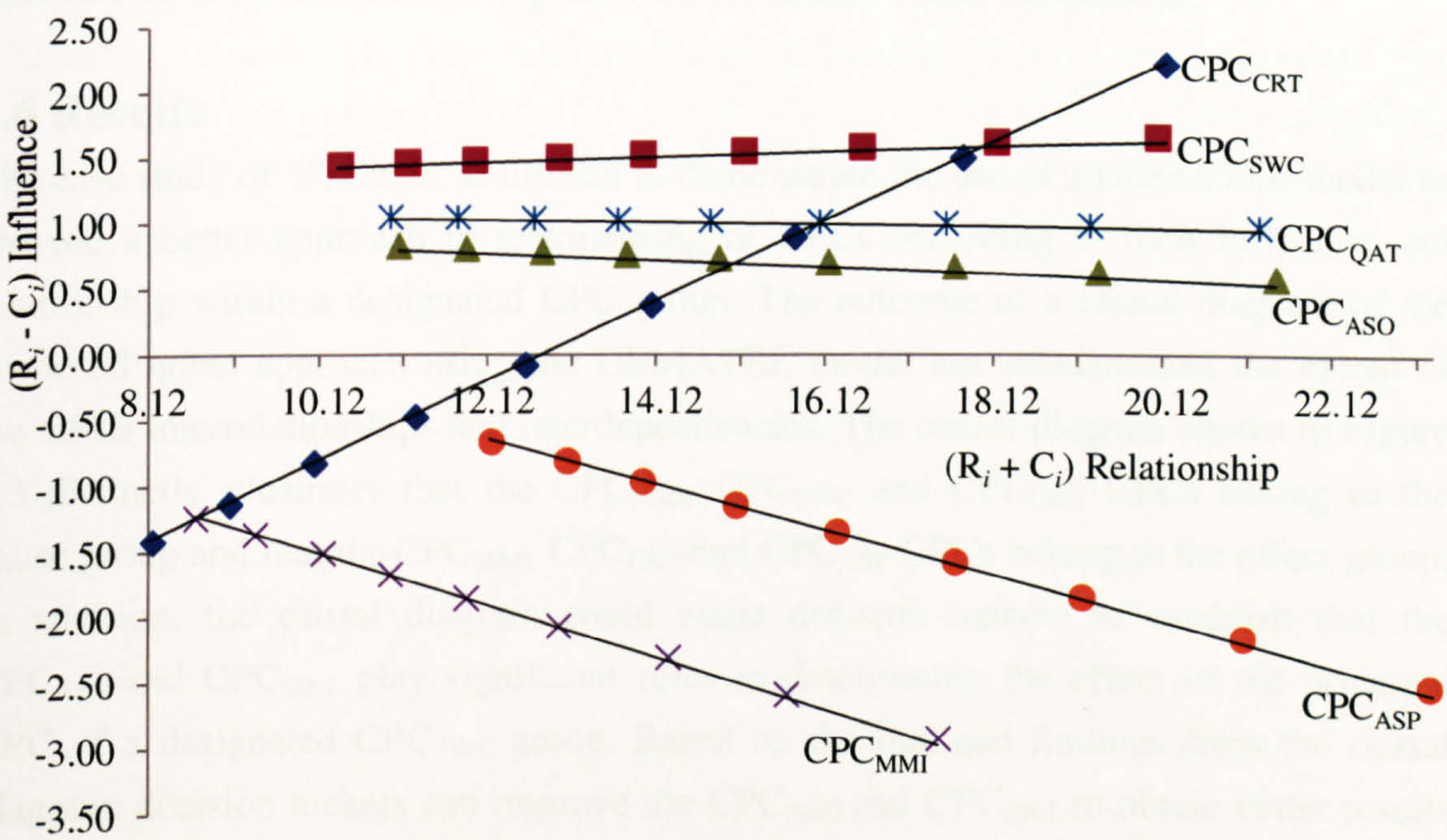

Figure 5.4 The Trend Lines of Simulated Causal Diagram of the CPC_{SWC}, CPC_{ASO}, CPC_{MMI}, CPC_{QAT}, CPC_{CRT}, CPC_{ASP} CPCs Group

A similar proposed approach using the DEMATEL model is applied to determine if small changes of the input variables would induce small changes in the output results of the causal diagram. It can be observed from the trend lines of the simulated causal diagram in Figure 5.4 that the relationship among the other five CPCs of CPC_{SWC}, CPC_{ASO}, CPC_{MMI}, CPC_{QAT}, and CPC_{ASP} has increased correspondingly with increment of evaluation values of relationship and influence of CPC_{CRT}. Furthermore, the characteristics of the CPC_{ASO}, CPC_{SWC} and CPC_{QAT} CPCs have remained in the cause group. Meanwhile the other remaining CPC_{MMI} and CPC_{ASP} CPCs have also remained within their respective effect group. The CPC_{CRT} has moved from an effect group to the cause group. On analysing the trend lines result of the simulated causal diagram in Figure 5.4, it has demonstrated that a small increment of scale of the relationship and influence among the CPCs within the CPC group can be displayed sufficiently on the causal diagram. Additionally, no abrupt large changes of relationship and influence of CPCs were generated in the sensitivity analysis. Therefore, the model is able to illustrate the differences and has passed the sensibility check adequately.

5.6 Results

The case study of '*Prestige*' is utilised to demonstrate the use of a DEMATEL model to provide a better approach in restructuring of CPCs according to their influence and relationship within a designated CPC group. The outcome of a causal diagram of the proposed novel approach using the DEMATEL model has substantiated the extent of the CPCs interrelationships and interdependencies. The causal diagram shown in Figure 5.3 distinctly illustrates that the CPC_{ASO}, CPC_{SWC} and CPC_{QAT} CPCs belong to the cause group and that the CPC_{MMI}, CPC_{CRT} and CPC_{ASP} CPCs belong to the effect group. In addition, the causal diagram could assist decision makers to establish that the CPC_{ASO} and CPC_{QAT} play significant roles in determining the effect of the principal CPC of a designated CPC_{SWC} group. Based on the outlined findings from the causal diagram, decision makers can improve the CPC_{ASO} and CPC_{QAT} to obtain better results in the outcome of CPC_{SWC} leading to improved shipboard management to prevent the reoccurrence of a similar incident. In a similar way, an understanding of the relationships and interdependencies among CPCs within other designated CPC groups in CREAM could be established, allowing for improvement of shipboard management in reducing human error.

5.7 Discussions

The existing generic CREAM framework employs a qualitative analysis approach to determine the state of linguistic terms of CPCs. The nine CPCs within the CREAM are assembled into four groups of multiple CPCs. Each group consists of a principal CPC and its component CPCs to model their interdependencies. The state of the principal CPC of the designated CPC group is determined on the basis of the effects of the component CPCs within the designated group. There is no research related to the description of relationships among the CPCs in CREAM. Hence the present CREAM leaves a significant gap in illustrating the relationships among the CPCs. The proposed novel approach using a DEMATEL model plays an important role by providing a better understanding of the relationships and interdependencies among the CPCs within the designated CPC groups. In addition, the proposed approach also assists HRA analysts in determining whether a CPC belongs to a cause group or an effect group. Furthermore, the model also establishes the strength of relationships and interdependencies among the CPCs within the designated CPC group. An original aspect of the proposed approach using a DEMATEL technique is that the approach has carried out an empirical work that has not been done before. Additionally, the proposed approach has looked into relationships among the CPCs that researchers in the discipline have not looked at before. The presented case study has focused on a maritime incident, however a similar approach can be adapted for other industries with some modifications in CREAM classification schemes. The proposed model can provide an alternative approach in determining relationships and interdependencies within variables of any human performance factor groups, leading to a reduction in human errors in various industrial environments.

5.8 Conclusion

Since the CREAM was developed, few studies have come forward with an efficient model to provide a better understanding of the relationships among the CPCs in CREAM. The proposed approach using a DEMATEL model addresses this aspect and can be applied along with the developed and advanced CREAM framework to assist HRA analysts in performing better qualitative analysis. The scrutinising and comprehension of relationships among CPCs could improve the utilisation of CREAM in carrying out a good qualitative analysis in determining linguistic terms of CPCs. Furthermore, the proposed approach using the DEMATEL model also allows reprioritisation of CPCs within the designated CPC groups. The significance of the proposed model is that it can assist decision makers in determining an appropriate CPC that needs to be improved to overcome the root cause of an incident/accident. As a result, actions can be taken to minimise the human errors in the management of an organisation effectively reducing the risk of a similar incident/accident occurring in the future. The limitation of this model is that it requires experts to provide a scaled judgment of the importance and influence of CPCs. It is addressed in this research by using experts from classification society and flag state administrations. Furthermore, the developed approach using the DEMATEL model can be used to appreciate and assimilate the relationships and interdependencies among human factor variables involved in other transportation systems and industrial fields, such as the chemical, gas and oil industries. A better understanding of the relationships among the human factor variables involved in causing an incident/accident can facilitate a reduction of human errors in the future. Finally, the innovative approach using the DEMATEL model can be developed as computer software to allow for commercial appreciation leading to a reduction of human errors in various industries.

Chapter 6

Combined AHP and Fuzzy Approach to Facilitating the Quantification Analysis of CREAM in Oil Tanker Operations

Summary

On addressing the relationships and interdependencies among CPCs of CREAM in Chapter 5, this chapter is focused on quantitative analysis of human reliabilities. A novel human reliability quantification model using a combined AHP and fuzzy logic approach is established. This methodology is found to be particularly useful in dealing with the limited availability of data in the maritime domain and the uncertainty and complexity that exist in the quantitative analysis of human reliabilities. The proposed model is demonstrated with a case study and validated using a sensitivity analysis. The result of HPFP in the case study is within the parameters of CREAM's COCOM. Thus, this research can facilitate the quantification development of HRA in the maritime field.

6.1 Introduction

HRA is a collection of methods used to predict the occurrence of human errors and to assess and reduce human error potential in management and safety systems (Hollnagel, 2005). Most of the HRA research was conducted in the nuclear, chemical, oil, gas and aviation industries. Comparatively, limited research of HRA has been carried out in the maritime industry. The complexity of the human behaviour involved in human operations results in difficulties in quantifying human reliabilities in maritime operations. In addition, methodological limitations related to the subjectivity of analysts and expert judgments along with inadequate data hinder quantification of HRA. The methods that have been developed by engineers and psychologists to analyse human errors and human reliabilities often use expert judgment, simulation proofs and statistical data (Konstandinidou et al., 2006).

Maritime accident data, especially that related to HRA, may be imprecise and insufficient. Apart from the uncertainty due to data or information, deficiencies in the definition of the system while analysing its environment and deficiencies associated with the prediction of accident escalation could also be present, which may result in difficulties in carrying out HRA successfully (Wang and Trbojevic, 2007). Some relevant research efforts have been made in improving HRA quantification using a fuzzy approach (Konstandinidou et al., 2006; Marseguerra et al., 2007), using probabilistic techniques (Fujita and Hollnagel, 2004) and the quantitative developments in CREAM (Marseguerra et al., 2006). The proposed model of a combined AHP and fuzzy logic approach produces a HPFP value. The developed methodology of quantifying each CPC value to obtain a final HRA value is comprehensive compared to the past practices using the methodology of assigning a probability of occurrence to each human error event. The detailed qualitative CREAM analysis identifies root causes of human errors in an incident. The outcome of the qualitative analysis includes the descriptions of nine CPCs. The quantification of the nine CPCs is carried out by converting CPCs into fuzzy probabilities. In addition, the weight influence of each CPC is incorporated into the computation of a final human failure probability. The proposed model scrutinises in detail each component that played a significant role in an incident. Human error probability is none other than the probability of human failure that is assigned based on the characteristics of the task that a human has to perform (Kim et al., 2006). Therefore, using the CPC which deals with human performance makes it judicious to derive a HPFP value. In addition the use of AHP to determine proper weighting among the CPCs allows this model to be more human decision-making prone. The proposed model could further assist the present HRA to increase technical data in maritime human reliabilities.

6.2 Literature Review

6.2.1 Quantification Analysis of CREAM

There has been limited research carried out in quantification analysis of CREAM. Among the research on this aspect are CREAM quantification using a fuzzy approach (Konstandinidou et al., 2006), HRA by fuzzy CREAM (Marseguerra et al., 2007) and CREAM prospective quantification (He et al., 2008). The recent quantification analysis of CREAM by Konstandinidou et al. (2006) had a common fallacy of making an assumption that all the CPCs had an equal weight of influence in causing an incident. Meanwhile, Marseguerra et al. (2007) had disintegrated the nine CPCs into three attributes and He et al. (2008) had simplified the weighting factors to one common performance index for four cognitive functions, to carry out quantification of human error probabilities. The proposed methodology in this chapter overcomes the shortcomings of the previous studies by introducing an AHP approach to obtain weights of influence of each CPC and by carrying out pairwise comparison among the CPCs as a whole, taking into consideration the incident investigated. This approach is reliable and sensible, understanding that in real life the CPCs are not of an equal influence and importance but are interrelated with reference to the incident. However, the newly developed methodology would rely on the comprehensiveness of the task analysis carried out in the qualitative analysis of CREAM.

6.2.2 Overview on the Fuzzy Logic Approach

One of the feasible ways to deal with uncertainty and numerical analysis of ambiguity is to use fuzzy logic theory (Sii et al., 2001). Fuzzy logic theory assists in addressing qualitative information considering human decision making. Another aspect of fuzzy logic theory is that it can accommodate the ambiguities that are present in the maritime human decision factors while investigating maritime incidents/accidents. The theoretical foundation for modelling imprecise information is the well-known fuzzy set theory initially developed by Zadeh (Zadeh, 1965). Fuzzy logic theory is useful for modelling a complex process involving qualitative uncertain information. The concept of membership functions used by fuzzy logic theory is adequate for depicting this knowledge. However, Saaty is against the idea of applying fuzzy logic to the AHP's fundamental criteria scale. The fundamental criteria scale for the expert judgment used in the AHP was already in the fuzzy form from Weber-Fechner observations. Furthermore, he has proven that fuzzification of the fundamental scale does not improve the outcome of the AHP analysis (Saaty, 2008). A fuzzy rule-based approach has been adopted to carry out HRA quantification of CREAM to obtain HPFP. The fact that the influence of the contextual conditions in which the task is performed is greater than the characteristics of the task itself was found in the studies of human performance in accidents (Marseguerra et al., 2007). It can be concluded that the context is the significant aspect that affects human performance failure. Therefore, CREAM, which was developed based on this principle, emphasising the important influence of the context on human performance, could provide a good path to quantify human reliabilities. In a maritime context, an assessment of the CPCs could provide an overall prediction of how a ship's crew and the related shipboard management systems might behave towards an incident.

6.2.2.1 Fuzzy Logic

Fuzzy logic is a precise logic of imprecision and approximate reasoning (Zadeh, 2008). It is a superset of conventional Boolean logic that has been extended to handle the concept of partial truth-values between completely true and completely false. It has many features; however, basic mathematical features are the logical and fuzzy-set-theoretic aspects. Relational features play an important role in all applications of fuzzy logic. Fuzzy classification systems have had many applications and fuzzy logic theory has emerged as a useful tool for the modelling processes (Konstandinidou et al., 2006). The most significant factor of fuzzy logic theory is that it assists in addressing qualitative information considering human decision making. The fundamental difference of fuzzy logic compared to conventional modelling techniques is in relation to the definition of sets. Traditional set theory is based on a binary logic where a number or an object is either a member of a set or not. Fuzzy logic on the contrary allows a number or an object to be a member of more than one set. It introduces the concept of partial membership (Klir and Yuan, 1995). A degree of membership in a set is based on a scale from 0 to 1 with 1 corresponding to complete membership and 0 referring to no membership. A membership of 0.5 on the scale will reflect that it belongs with a half degree. The fuzzy logic approach often addresses qualitative information ideally as it resembles the manner in which humans make assumptions and decisions. The basic structure of fuzzy logic consists of fuzzy sets, linguistic variables, possibility distributions and fuzzy if-then rules (Kim and Bishu, 2006).

6.2.2.2 Fuzzy Set

Fuzzy set is a class of objects with a continuum of membership grades. A membership function, which assigns to each object a grade of membership, is associated with each fuzzy set (Pedrycz, 1993).

Let's assume K to be a set of elements denoted by x, K = $\{x\}$. A fuzzy set L in K is characterised by a set of ordered pairs L = $\{(x), m_L(x)\}$, $x \in K$ where m_L is the membership degree of x in L. Membership degree $m_L(x)$ assumes its value in [0, 1]. In fuzzy set theory, a fuzzy set L in K is defined by a membership degree $m_L(x)$ between 0 and 1.

$$m_L: L \rightarrow [0, 1]$$

For an element x of L, $m_L(x)$ is the degree to which x is an element of L

$m_L(x) = 1$	x is totally in L
$0 < m_L(x) < 1$	x is partially in L
$m_L(x) = 0$	x is not in L

In fuzzy logic, the transition from set to set is gradual whereas an object can have partial membership in multiple sets. Some of the basic concepts of fuzzy sets are as follows (Pedrycz, 1993):

a). Label implies a descriptive name used to identify a membership function.

b). Degree of membership refers to how much a crisp value is compatible with a membership function.

c). Membership function defines a fuzzy set by mapping crisp values from its domain to degrees of membership.

d). Scope is the width of the membership function (fuzzy set).

e). Universe of discourse denotes the range of all possible values applicable to a system variable.

Figure 6.1 illustrates the basic concepts of fuzzy sets.

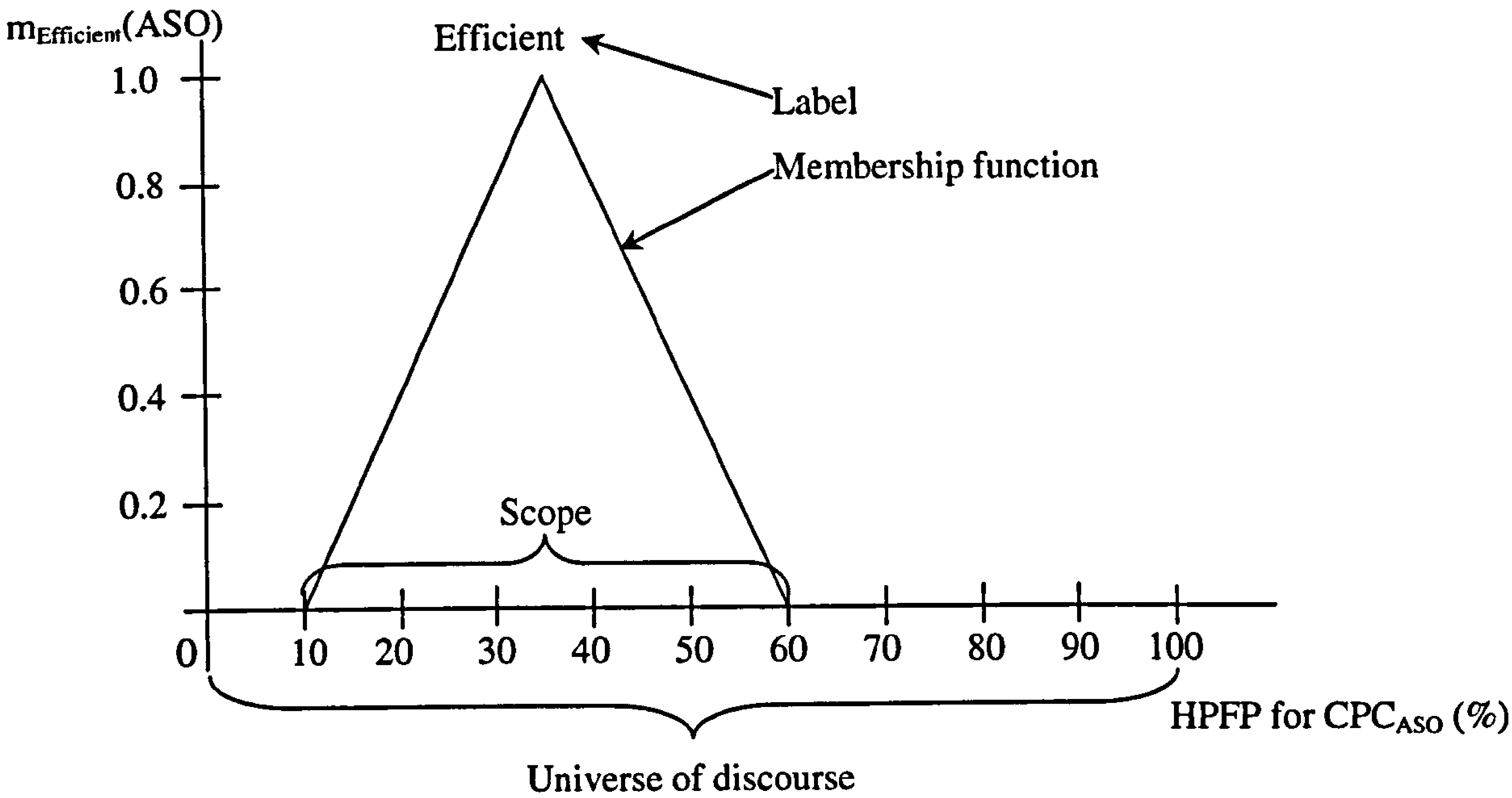

Figure 6.1 Basic Concepts of Fuzzy Sets

6.3 Methodology

The general framework of the proposed model is illustrated in Figure 6.2. The figure shows the research methodology of a combined AHP and fuzzy logic approach which is used to obtain the CPCs' weights and to convert CPC linguistic terms into crisp values respectively. Each step of the framework is elaborated in detail in the following subsections.

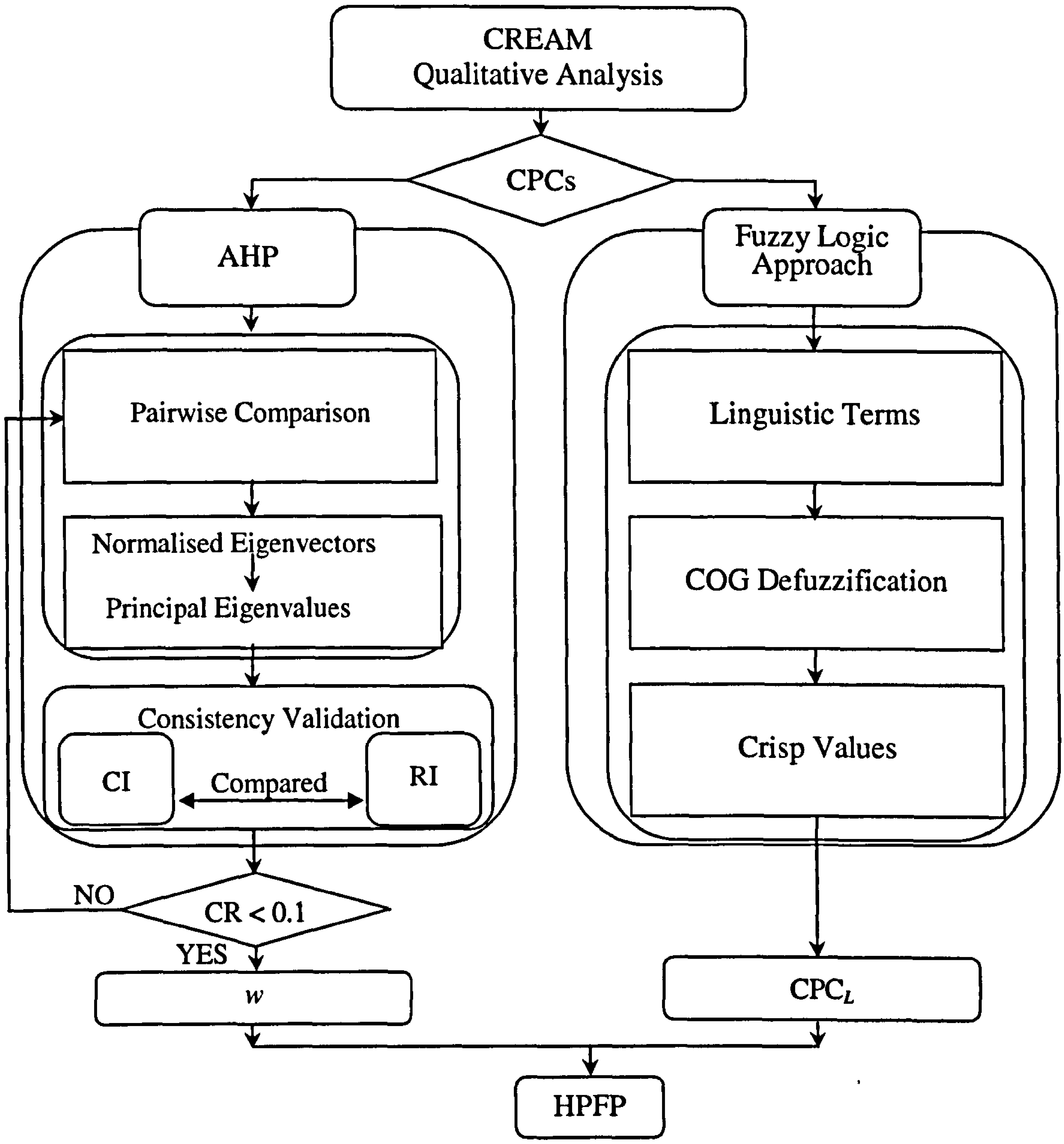

Figure 6.2 The General Framework of the Proposed Model

The proposed methodology is described as follows:

(a). Step 1 – Obtain tabulated CPCs from a detailed qualitative CREAM analysis of an incident.

(b). Step 2 – Carry out pairwise comparison of nine CPCs to determine their relative importance using AHP by expert judgments.

Personnel used for expert judgments are apparently better selected by decision makers because eventually it is the decision makers that will determine the actions to take to overcome the human error in their shipboard management. Furthermore, it is important to consider that reducing the number of factors negatively affecting cognition could lead to a better-quality expert judgment (Meyer and Booker, 2001). However, if more than one expert is used for analysis, then the following formula needs to be applied to obtain an average scale to be used for pairwise comparison (Klir and Yuan, 1995).

$$B(x) = \frac{\sum_{b=1}^{n} a_b(x)}{n} \qquad (6.1)$$

where $B(x)$ is the synthesised value of n expert judgments, $a_b(x)$ is the value given by the b^{th} expert, $b = 1, 2, \ldots, n$ and n is the total number of experts.

An expert judgment of the relative importance among the CPCs needs to be carried out by pairwise comparisons using a nine-point scale suggested by Saaty (Saaty, 1996). The scale used in this methodology to indicate the intensity of importance among CPCs is illustrated in Table 6.1.

Table 6.1 The Fundamental CPC Scale for Expert Judgment

Scale	Linguistic Influence to corresponding CPC	Description
1	Equal	Both of the compared CPCs contribute equally to the incident
2	Between Equal and Moderate	Both of the compared CPCs contribute between scale 1 and 3 to the incident
3	Moderate	Experience and judgment favour one CPC over another
4	Between Moderate and Strong	Both of the compared CPCs contribute between scale 3 and 5 to the incident
5	Strong	Experience and judgment strongly favour

		one CPC over another
6	Between Strong and Very Strong	Both of the compared CPCs contribute between scale 5 and 7 to the incident
7	Very Strong	A CPC is favoured and dominates very strongly over another
8	Between Very Strong and Extreme	Both of the compared CPCs contribute between scale 7 and 9 to the incident
9	Extreme	Evidence of one CPC favouring at the highest order to another CPC appears

Decimal judgments, such as 2.9, are allowed for fine tuning; however, judgments greater than 9 are recommended to be avoided if possible. Suppose that a matrix A of pairwise ratios is formed whose rows give the ratios of the scale of each CPC with respect to all others as follows (Saaty, 2008):

$$A = \begin{array}{c} \\ CPC_1 \\ \vdots \\ CPC_i \\ \vdots \\ CPC_s \end{array} \begin{array}{c} CPC_1 \cdots \; CPC_j \cdots \; CPC_s \\ \begin{bmatrix} 1 & \cdots & w_{1s} \\ . & . & . \\ . & w_{ij} & . \\ . & . & . \\ w_{s1} & \cdots & 1 \end{bmatrix} \end{array}$$

where $CPC_1,\ldots,CPC_s$ refer to the evaluation CPCs, w_{ij} represents the relative importance of CPC_i against CPC_j, $i = 1, 2,\ldots, s$ and $j = 1, 2,\ldots, s$.

(c). Step 3 – Compute the weights of the nine CPCs.

The eigenvectors can be computed with normalisation of the pairwise comparison CPC matrix. It is carried out by dividing each element by its column sum. This will produce a normalised relative weight matrix for the nine CPCs. The normalised principal eigenvector is also known as the priority vector. It is illustrated in Equation 6.2 (Saaty, 2008).

$$\mu_{ij} = \frac{w_{ij}}{\sum_{i=1}^{s} w_{ij}} \tag{6.2}$$

where μ_{ij} is the eigenvector of each CPC of normalised pairwise comparison matrix, w_{ij} represents the relative importance between CPC_i and CPC_j, i and j = 1, 2,..., s in the pairwise comparison matrix.

Upon having a normalised comparison CPC matrix, nine priority eigenvectors representing each CPC will be computed. The arithmetic mean (average) of the values of each row is an element of the eigenvector that produces a principal eigenvector for each CPC. The priority vectors show relative weights among the compared CPCs. The mathematical expression of this step can be illustrated using Equation 6.3 (Saaty, 2008).

$$w_i = \frac{1}{s} \sum_{j=1}^{s} \mu_{ij} \tag{6.3}$$

where w_i is the weight of ith CPC and i and j = 1, 2,..., s.

(d). Step 4 – Consistency validation.

A principal eigenvalue (λ_{max}) of a CPC matrix of pairwise comparison is required to compute a Consistency Index (CI). The principal eigenvalue is the maximum eigenvalue of the $s \times s$ pairwise comparison matrix A, which is computed using Equation 6.4 (Saaty, 2008).

$$\lambda_{max} = \frac{\sum_{j=1}^{s} \frac{\sum_{k=1}^{s} w_k w_{jk}}{w_j}}{s} \tag{6.4}$$

where w_k is the weight of the kth CPC.

The CI value can be obtained using Equation 6.5.

$$CI = \frac{1}{(s-1)} (\lambda_{max} - s) \tag{6.5}$$

This is followed by computing a Consistency Ratio (CR), which is a ratio of the CI to the corresponding Random Index (RI). The AHP methodology provides a measure of the consistency for pairwise comparisons by introducing a CR. The CR of a pairwise comparison matrix is the ratio of its CI to the corresponding RI value. The average RI values are presented in Table 6.2, where the size of the pairwise comparison matrix is referred to as *s*.

Table 6.2 The Average RI values (Saaty, 2008)

s	1	2	3	4	5	6	7	8	9	10	11	12	13
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.52	1.54	1.56

The CR value can be obtained using Equation 6.6.

$$CR = \frac{CI}{RI} \tag{6.6}$$

On computing the CR, verification needs to be conducted to determine if the CR value is less than 0.1. The inconsistency is acceptable if the value of the CR is equal to or less than 0.1 (Saaty, 2008). The re-evaluation of ratios is to be performed if the CR value obtained is greater than 0.1. The value 0.1 is adopted because it has been proven by Saaty and Tran (2007) that improving the CR value to less than 0.1 will not improve the accuracy of the outcome in an AHP analysis.

(e). Step 5 – Fuzzy model operations.

When the fuzzy model is applied to a set of input parameter values, the information flows through the fuzzification, fuzzy inference and defuzzification process.

i). Fuzzification is performed by assigning fuzzy labels in the universe of discourse to each of the crisp inputs. The crisp inputs could be of multiple labels whereas the number of labels of each CPC in CREAM is fixed. Marseguerra et al. (2007) approach in scaling the CPCs' universe of discourse is adopted with some modifications. The details of CPC labels and effects with their parameters of universe of discourse are illustrated in Table 6.3.

Table 6.3 The Membership Labels, Effects and Parameters of CPCs

CPC	Membership Labels, Effects and Parameters (%)			
ASO	Very Efficient [Improved]	Efficient [Not Significant]	Inefficient [Reduced]	Deficient [Reduced]
	(0, 0, 25)	(10, 35, 60)	(40, 65, 90)	(75, 100, 100)
SWC	Advantages [Improved]	Compatible [Not Significant]	Incompatible [Reduced]	
	(0, 0, 30)	(20, 50, 80)	(70, 100, 100)	
MMI	Supportive [Improved]	Adequate [Not Significant]	Tolerable [Not Significant]	Inappropriate [Reduced]
	(0, 0, 25)	(10, 35, 60)	(40, 65, 90)	(75, 100, 100)
APP	Appropriate [Improved]	Acceptable [Not Significant]	Inappropriate [Reduced]	
	(0, 0, 30)	(20, 50, 80)	(70, 100, 100)	
NSG	Less than actual capacity [Not Significant]	Matching current capacity[Not Significant]	More than actual capacity [Reduced]	
	(0, 0, 30)	(20, 50, 80)	(70, 100, 100)	
QAT	Adequate [Improved]	Temporarily inadequate [Not Significant]	Continuously inadequate [Reduced]	
	(0, 0, 30)	(20, 50, 80)	(70, 100, 100)	
CRT	Night-time (unadjusted) [Reduced]	Daytime (adjusted) [Not Significant]	Night-time (adjusted) [Reduced]	
	(0, 0, 30)	(20, 50, 80)	(70, 100, 100)	
ASP	Adequate with vast experience [Improved]	Adequate with limited experience [Not Significant]	Inadequate experience [Reduced]	
	(0, 0, 30)	(20, 50, 80)	(70, 100, 100)	
SCQ	Very Efficient [Improved]	Efficient [Not Significant]	Inefficient [Not Significant]	Deficient [Reduced]
	(0, 0, 25)	(10, 35, 60)	(40, 65, 90)	(75, 100, 100)

The parameters of the universe of discourse for nine CPCs – CPC_{ASO}, CPC_{SWC}, CPC_{MMI}, CPC_{APP}, CPC_{NSG}, CPC_{QAT}, CPC_{CRT}, CPC_{ASP} and CPC_{SCQ} are between 0% and 100% corresponding to the HPFPs. 0% of HPFP corresponds to the better linguistic terms compared to 100% HPFP that corresponds to poor linguistic terms. For example, Very Efficient for CPC_{SCQ} is described by a triangular membership function (0, 0, 25) as shown in Figure 6.3, which is extracted from Appendix IV. According to the generic CREAM, a selection of the CPCs' linguistic terms can provide an estimation of the control mode that the shipboard management is acting with relevance to COCOM (Konstandinidou et al., 2006).

ii). Fuzzy Inference

A fuzzy rule base is developed using the CPC's linguistic terms as an input parameters based on the features of the generic CREAM. An example of the fuzzy rule for the '*Carina*' case study is as follows:

IF the CPC_{ASO} has been analysed as **Inefficient** AND the CPC_{SWC} is **Incompatible** AND the CPC_{MMI} is **Tolerable** AND the CPC_{APP} is **Inappropriate** AND the CPC_{NSG} is **More than actual capacity** AND the CPC_{QAT} is **Continuously inadequate** AND the CPC_{CRT} is **Daytime (adjusted)** AND the CPC_{ASP} is **Inadequate experience** AND the CPC_{SCQ} is **Inefficient** THEN the shipboard crew would act in a 'Scrambled' manner with reference to the COCOM.

iii). Defuzzification

Similar to Konstandinidou et al. (2006) approach, a triangular membership function is adopted to simplify the defuzzification of each of the nine CPCs. The membership function for each linguistic term of a CPC is evaluated within its limits on an arbitrary scale of 0 to 1. Finally, the fuzzy input is derived by combining the crisp input with membership functions. The defuzzified crisp value of a CPC is determined by expert judgment evaluation described by membership degrees associated with two linguistic terms of a CPC. The structure of a generic CREAM contains three CPCs with four linguistic terms and six CPCs with three linguistic terms causes the need to adopt the scheme of using two linguistic terms. Two linguistic terms are used to reduce the level of uncertainty in determining the estimation of linguistic terms of CPCs. Additionally the use of two linguistic terms allows for more coverage of CPCs, providing increased precision in determining the linguistic terms of CPCs. Since two linguistic terms are used for describing a CPC, then the CPC's linguistic label would follow the one with the greatest membership degree. Defuzzification is a process of combining all fuzzy outputs in a specific crisp output of the system. It maps a fuzzy set, which is the output of the core of the fuzzy system, into a crisp value (Leekwijck and Kerre, 1999). One of the best-known defuzzification operators is the centre of gravity (COG) defuzzification method. It computes the centre of gravity of the area under the specific membership functions and is easier to compute. The COG equation is presented in Equation 6.7.

$$\text{COG formula} = \frac{\int_g^h m(x)\ x\,dx}{\int_g^h m(x)\ dx} \tag{6.7}$$

where $m(x)$ is the aggregated resultant membership functions of the linguistic term of a CPC, x is the universe of discourse and, g and h are the cardinality of a fuzzy set of a CPC's linguistic label.

Finally, a list consisting of defuzzified crisp values of the nine CPCs will be produced. An example of the whole fuzzification, inference and defuzzification process of the CPC_{ASO} fuzzy membership function to a single crisp value is presented in Figure 6.3 along with detailed elaboration.

With reference to Figure 6.3 extracted from Appendix IV, based on an expert judgment, the CPC_{ASO} has been evaluated 0.70 **Inefficient** and 0.30 **Efficient**. The defuzzification computation using Equation 6.7 is illustrated as follows:

$$CPC_{L(ASO)} = \frac{(0.7 \text{ x } 65\%) + (0.3 \text{ x } 35\%)}{(0.7 + 0.3)}$$

$$= 0.560$$

where $CPC_{L(ASO)}$ is the defuzzified crisp value of the ASO CPC. Similar means of computation can be performed on the remaining eight CPCs to obtain their defuzzified crisp values.

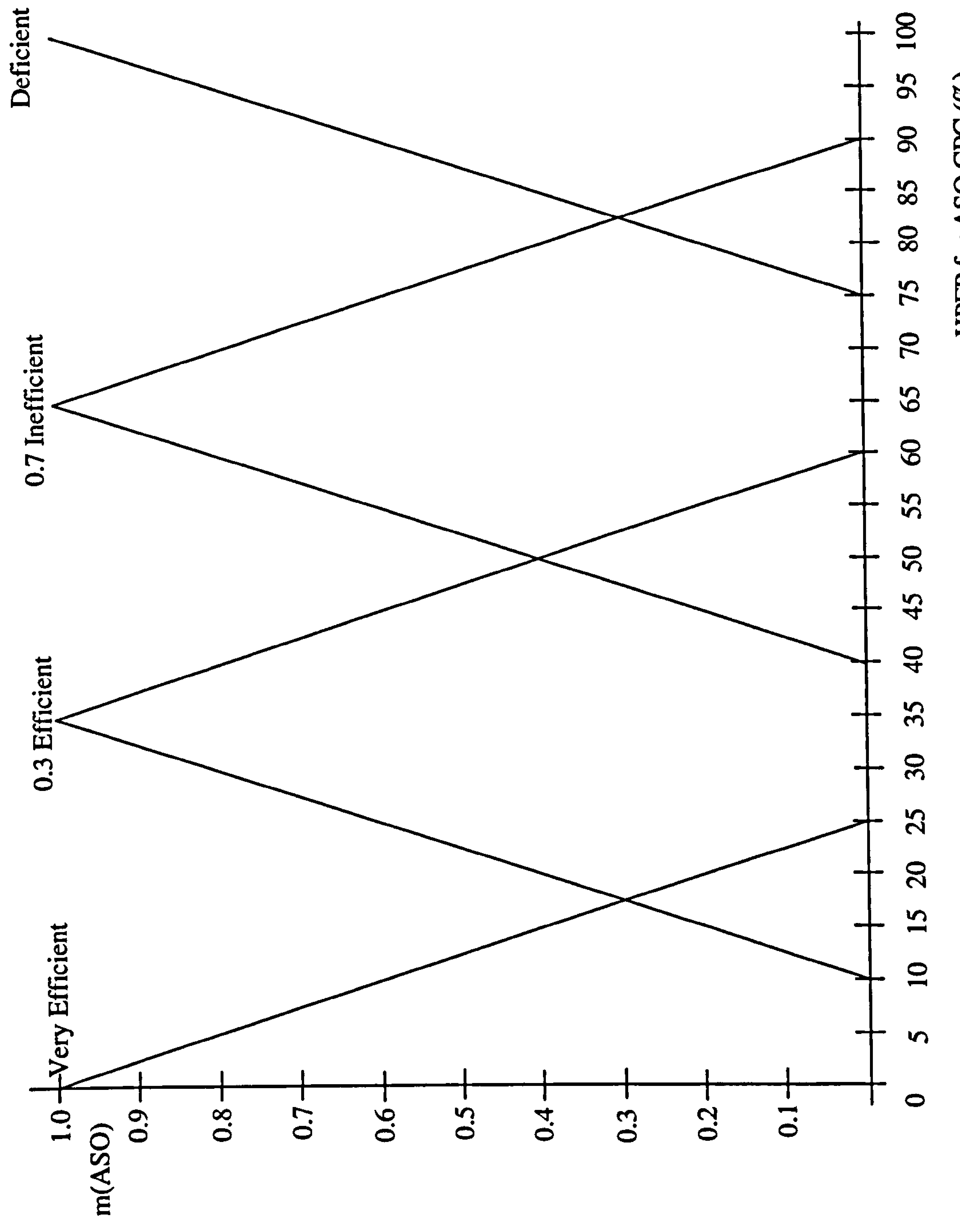

Figure 6.3 Fuzzy Sets Representation of the HPFP for ASO Input Variables

(f). Step 6 – Compute a HPFP value for the investigated incident.

A HPFP value for an investigated incident/accident is obtained from the summation of products of each CPC's defuzzified crisp value and weight. The relationship is produced in Equation 6.8 as follows:

$$\text{HPFP} = \sum_{i=1}^{s} (w * \text{CPC}_L)_i \tag{6.8}$$

where w and CPC_L are the product of the weight and the defuzzified crisp value of the ith CPC in the pairwise comparison matrix.

6.4 Case Study of '*Prestige*'

The case study of '*Prestige*' is used to demonstrate the proposed human reliability quantification model using the combined AHP and fuzzy logic approach.

(a). Step 1 – Tabulated CPCs from a detailed qualitative CREAM analysis of the '*Prestige*' incident are obtained. A human-reliability specialist from classification society, two officials from two flag state administrations with accident investigation backgrounds, and a master mariner with more than ten years of oil tanker sailing experience were used to provide expert judgment of pairwise comparison of criteria. The average scales used for the pairwise comparison of criteria are obtained by using Equation 6.1. Table 6.4 illustrates the expert judgment evaluation of CPCs for the '*Prestige*' incident.

Table 6.4 The CPCs for the '*Prestige*' Incident

CPCs	Description of Evaluation	CPC Linguistic Terms by Expert Judgment
ASO	Failure of getting the vessel to a safe haven reflects reasonable level of inefficiency in management	0.70 **Inefficient** / 0.30 Efficient
SWC	Rough weather does not provide reasonably good conditions to deal with the incident	0.67 **Incompatible** / 0.33 Compatible

MMI	Shipboard operation was reasonably carried out to overcome the emergency listing of the vessel	0.80 **Tolerable** / 0.20 Adequate
APP	Vessel had the standard contingency plan for quick action to alleviate the flooding	0.64 **Inappropriate** / 0.36 Acceptable
NSG	It is the case for any emergency situation in general	0.72 **More than actual capacity** / 0.28 Matching current capacity
QAT	Quick action to get the vessel to safe haven is vital due to the encountered rough weather	0.38 Temporarily inadequate / 0.62 **Continuously inadequate**
CRT	Time of the day is not relevant for the case	Not relevant
ASP	Crew members onboard are qualified and had received standard training as required by STCW 1995	0.47 Adequate, limited experience / 0.53 **Inadequate, experience**
SCQ	Crew had not responded well under stress	**0.62 Inefficient** / 0.38 Efficient

(b). Step 2 – Pairwise comparisons of the nine CPCs to determine the relative importance among the CPCs using AHP by expert judgment were carried out using the CPC scale shown in Table 6.1. Table 6.5 illustrates the result of expert judgment pairwise comparison of the CPCs.

Table 6.5 Judgment Matrix for Pairwise Comparison of CPCs

CPC	ASO	SWC	MMI	APP	NSG	QAT	CRT	ASP	SCQ
ASO	1	4	4	2	2	3	6	5	4
SWC	1/4	1	2	1	1	1	3	3	2
MMI	1/4	1/2	1	1	2	1	3	3	2
APP	1/2	1	1	1	2	1	5	3	2
NSG	1/2	1	1/2	1/2	1	2	6	4	3
QAT	1/3	1	1	1	1/2	1	5	4	3
CRT	1/6	1/3	1/3	1/5	1/6	1/5	1	2	1
ASP	1/5	1/3	1/3	1/3	1/4	1/4	1/2	1	1
SCQ	1/4	1/2	1/2	1/2	1/3	1/3	1	1	1

(c). Step 3 – Compute the weights of the nine CPCs.

The sums of each column of the reciprocal matrix of CPCs of ASO, SWC, MMI, APP, NSG, QAT, CRT, ASP and SCQ are 3.450, 9.667, 10.667, 7.533, 9.250, 9.783, 30.500, 26.000 and 19.000 respectively. The normalised relative weights of the CPC matrix for the nine CPCs are produced by dividing each element in Table 6.5 by its column sum. The normalised relative weight of each element in the pairwise comparison judgment of the CPCs is shown in Table 6.6.

Table 6.6 Judgment Matrix for Normalised Relative Weight of CPCs

CPC	ASO	SWC	MMI	APP	NSG	QAT	CRT	ASP	SCQ
ASO	0.290	0.414	0.375	0.265	0.216	0.307	0.197	0.192	0.211
SWC	0.072	0.103	0.188	0.133	0.108	0.102	0.098	0.115	0.105
MMI	0.072	0.052	0.094	0.133	0.216	0.102	0.098	0.115	0.105
APP	0.145	0.103	0.094	0.133	0.216	0.102	0.164	0.115	0.105
NSG	0.145	0.103	0.047	0.066	0.108	0.204	0.197	0.154	0.158
QAT	0.097	0.103	0.094	0.133	0.054	0.102	0.164	0.154	0.158
CRT	0.048	0.034	0.031	0.027	0.018	0.020	0.033	0.077	0.053
ASP	0.058	0.034	0.031	0.044	0.027	0.026	0.016	0.038	0.053
SCQ	0.072	0.052	0.047	0.066	0.036	0.034	0.033	0.038	0.053

From the normalised comparison CPC matrix, nine priority eigenvectors representing each CPC are computed using Equation 6.3. The relative weights of ASO, SWC, MMI, APP, NSG, QAT, CRT, ASP and SCQ CPCs are 0.274, 0.114, 0.110, 0.131, 0.131, 0.118, 0.038, 0.036 and 0.048 respectively.

(d). Step 4 – Consistency validation.

A principal eigenvalue is obtained using Equation 6.4.

Principal eigenvalue, $\lambda_{max} = (1 / 9) \times$

$$\left\{\left[\frac{\begin{pmatrix}(0.274 \times 1.000) + (0.114 \times 4.000) + (0.110 \times 4.000) + (0.131 \times 2.000) + (0.131 \times 2.000) + \\ (0.118 \times 3.000) + (0.038 \times 6.000) + (0.036 \times 5.000) + (0.048 \times 4.000)\end{pmatrix}}{0.274}\right] + \right.$$

$$\left[\frac{\begin{pmatrix}(0.274 \times 0.250) + (0.114 \times 1.000) + (0.110 \times 2.000) + (0.131 \times 1.000) + (131 \times 1.000) + \\ (0.118 \times 1.000) + (0.038 \times 3.000) + (0.036 \times 3.000) + (0.048 \times 2.000)\end{pmatrix}}{0.114}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.274 \times 0.250) + (0.114 \times 0.500) + (0.110 \times 1.000) + (0.131 \times 1.000) + (0.131 \times 2.000) + \\ (0.118 \times 1.000) + (0.038 \times 3.000) + (0.036 \times 3.000) + (0.048 \times 2.000)\end{pmatrix}}{0.110}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.274 \times 0.500) + (0.114 \times 1.000) + (0.110 \times 1.000) + (0.131 \times 1.000) + (0.131 \times 2.000) + \\ (0.118 \times 1.000) + (0.038 \times 5.000) + (0.036 \times 3.000) + (0.048 \times 2.000)\end{pmatrix}}{0.131}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.274 \times 0.500) + (0.114 \times 1.000) + (0.110 \times 0.500) + (0.131 \times 0.500) + (0.131 \times 1.000) + \\ (0.118 \times 2.000) + (0.038 \times 6.000) + (0.036 \times 4.000) + (0.048 \times 3.000)\end{pmatrix}}{0.131}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.274 \times 0.333) + (0.114 \times 1.000) + (0.110 \times 1.000) + (0.131 \times 1.000) + (0.131 \times 0.500) + \\ (0.118 \times 1.000) + (0.038 \times 5.000) + (0.036 \times 4.000) + (0.048 \times 3.000)\end{pmatrix}}{0.118}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.274 \times 0.167) + (0.333 \times 0.200) + (0.333 \times 0.333) + (0.200 \times 0.333) + (0.167 \times 0.333) + \\ (0.118 \times 0.200) + (0.038 \times 1.000) + (0.036 \times 2.000) + (0.048 \times 1.000)\end{pmatrix}}{0.038}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.274 \times 0.200) + (0.114 \times 0.333) + (0.110 \times 0.333) + (0.131 \times 0.333) + (0.131 \times 0.250) + \\ (0.118 \times 0.250) + (0.038 \times 0.500) + (0.036 \times 1.000) + (0.048 \times 1.000)\end{pmatrix}}{0.036}\right] +$$

$$\left.\left[\frac{\begin{pmatrix}(0.274 \times 0.250) + (0.114 \times 0.500) + (0.110 \times 0.500) + (0.131 \times 0.500) + (0.131 \times 0.333) + \\ (0.118 \times 0.333) + (0.038 \times 1.000) + (0.036 \times 1.000) + (0.048 \times 1.000)\end{pmatrix}}{0.048}\right]\right\}$$

$$= 9.515$$

From Equation 6.5, the CI is computed and illustrated as follows:

$$\mathrm{CI} = \left[\frac{1}{(9-1)}(9.515 - 9)\right]$$

$$= 0.064$$

From Equation 6.6 with RI value taken from Table 6.2, the CR is computed and shown as follows:

$$CR = \left(\frac{0.064}{1.45}\right)$$

$$= 0.044$$

The CR value obtained is less than 0.1. Therefore the subjective expert judgment on CPCs is consistent.

(e). Step 5 – Fuzzy model operations.

With reference to Table 6.4, a fuzzy rule base is established as IF the CPC_{ASO} has been analysed as **Inefficient** AND the CPC_{SWC} is **Incompatible** AND the CPC_{MMI} is **Tolerable** AND the CPC_{APP} is **Inappropriate** AND the CPC_{NSG} is **More than actual capacity** AND the CPC_{QAT} is **Continuously inadequate** AND the CPC_{CRT} is **not relevant** AND the CPC_{ASP} is **Inadequate experience** AND the CPC_{SCQ} is **Inefficient** THEN the shipboard crew would act in a 'Scrambled' manner with reference to the COCOM. "The shipboard crew would act in a 'Scrambled' manner indicates that the probability of performing an erroneous action onboard is between 1.0×10^{-1} and 1.0×10^{0}. Fuzzification is carried out referring to the fuzzy set representation of the HPFP for the ASO input variable graph as shown in Figure 6.3. A full set of graphs for the remaining eight CPCs is provided in Appendix IV. In a similar way, the remaining eight defuzzified crisp values of CPCs are obtained. Finally, a list consisting of nine defuzzified crisp values of CPCs is produced and presented in Table 6.7.

Table 6.7 Defuzzified Crisp Values of CPCs

CPCs	CPC Evaluation	CPC_L
ASO	Inefficient	0.560
SWC	Incompatible	0.735
MMI	Tolerable	0.590
APP	Inappropriate	0.724
NSG	More than actual capacity	0.752
QAT	Continuously inadequate	0.717
CRT	Not relevant	0.000
ASP	Inadequate experience	0.686
SCQ	Inefficient	0.536

(f). Step 6 – Compute a HPFP value for the investigated incident.

From Equation 6.8, the computation of HPFP is illustrated as follows:

$$
\begin{aligned}
HPFP &= [(w \times CPC_L)_{ASO} + (w \times CPC_L)_{SWC} + (w \times CPC_L)_{MMI} + (w \times CPC_L)_{APP} + \\
&\quad (w \times CPC_L)_{NSG} + (w \times CPC_L)_{QAT} + (w \times CPC_L)_{CRT} + (w \times CPC_L)_{ASP} + \\
&\quad (w \times CPC_L)_{SCQ}] \\
&= [(0.274 \times 0.560) + (0.114 \times 0.735) + (0.110 \times 0.590) + (0.131 \times 0.724) + \\
&\quad (0.131 \times 0.752) + (0.118 \times 0.717) + (0.038 \times 0.000) + (0.036 \times 0.686) + \\
&\quad (0.048 \times 0.536)] \\
&= 0.631
\end{aligned}
$$

The HPFP value is validated and found to be within the 'Scrambled' COCOM parameter as shown in Table 4.2.

Sensitivity analysis is a study of how the uncertainty in the output of a model can be apportioned to different sources of uncertainty in the model input (Tarantola, 2008). It is a method for testing the degree of sensitivity of a model's variables. Simulated defuzzified crisp values of CPCs are given to nine CPCs, while retaining the weights of the CPCs. The initial defuzzified crisp value of a CPC from the '*Prestige*' case study was reduced from 10% to 90% at an interval step of 10%, while retaining the remaining eight CPCs defuzzified crisp values to obtain a new set of HPFP values. A similar method is applied to the remaining eight CPCs. The same quantification method of the proposed combined AHP and fuzzy quantification model is applied to determine if small changes of the input variables would induce small changes in the output results of HPFP values. If the model is reliable, then the sensitivity analysis must at least comply with two axioms that a reduction of each CPC's relative importance will result in the fall of the HPFP values, and the gradient of the HPFP values should be proportionate to each CPC's weight. Lesser weight CPCs should register lesser gradient compared to the greater weight CPCs. The simulated HPFP values are plotted for each CPC except CPC_{CRT} for being not relevant to the case study, and are illustrated in Figure 6.4.

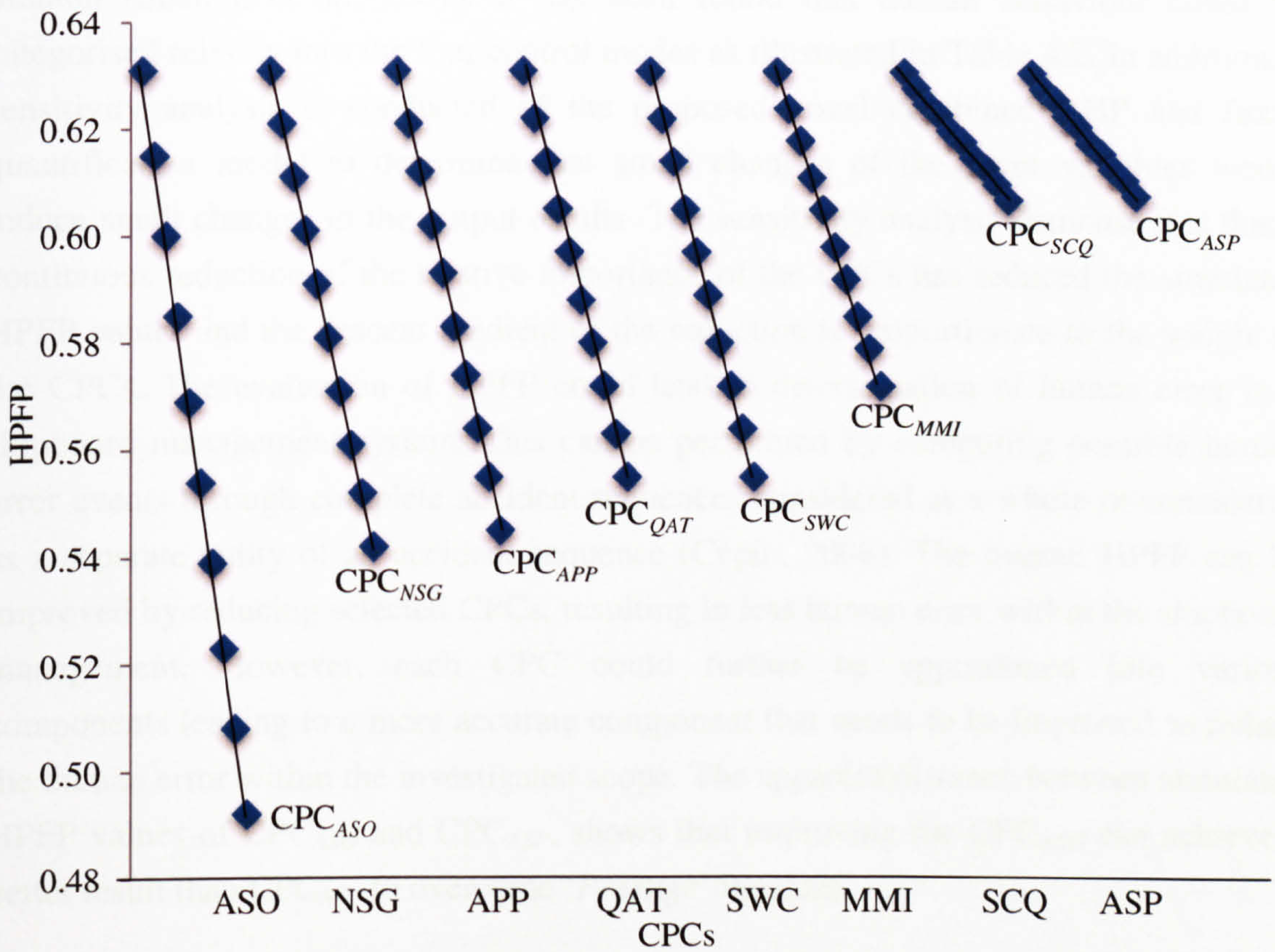

Figure 6.4 The Trend Lines of Simulated HPFP values

On analysing Figure 6.4, it can be illustrated that a small change in the relative importance of the CPCs has apparently changed the simulated HPFP values gradually as anticipated. Furthermore, continuous reduction of the relative importance of the CPCs has reduced the simulated HPFP values and the descent gradient of the reduction is proportionate to the weight of the CPCs. Additionally, no abrupt large changes of simulated HPFP values were generated in the sensitivity analysis.

6.5 Results

The reliability of the output of the proposed combined AHP and fuzzy quantification model is tested and the results are compared to the COCOM HPFP interval values provided in CREAM. The final HPFP value of the case study is established to be within a COCOM parameter. The COCOM has been tested and found to be satisfactory by

Stanton (Stanton et al., 2001). It has been found that human behaviour could be categorised reliably into the four control modes as illustrated in Table 4.2. In addition, a sensitivity analysis is conducted of the proposed novel combined AHP and fuzzy quantification model to determine that small changes of the input variables would induce small changes in the output results. The sensitivity analysis demonstrates that a continuous reduction of the relative importance of the CPCs has reduced the simulated HPFP values and the descent gradient of the reduction is proportionate to the weight of the CPCs. The evaluation of HPFP could lead to determination of human error in a shipboard management system. This can be performed by computing possible human error events through complete accident sequences considered as a whole or considered as a separate entity of an accident sequence (Cepin, 2008). The overall HPFP can be improved by reducing selected CPCs, resulting in less human error within the shipboard management. However, each CPC could further be apportioned into various components leading to a more accurate component that needs to be improved to reduce the human error within the investigated scope. The apparent distance between simulated HPFP values of CPC_{ASO} and CPC_{ASP}, shows that improving the CPC_{ASO} can achieve a better result than CPC_{ASP} to overcome '*Prestige*' incident.

6.6 Discussions

The proposed combined AHP and fuzzy quantification model has provided a novel HRA quantification in CREAM. The proposed model assists in the quantification of human performance within the shipboard management. The examples provided in this research are of use in maritime operations. However, the model could be applied to other industries with appropriate modification in the classifications of the CPCs. The significance of this model is that it could assist HRA analysts to determine in numerical values the status of human performance within the shipboard management in an investigated incident. As a result, actions can be taken to reduce human errors within the management system, systematically reducing the risk of a similar incident reoccurring in the future. Another aspect is that the newly developed model caters for the real-life case of CPCs considering that some of the CPCs could be performing a major role compared to other CPCs. This model is practical and still reliable for use in the present generic CREAM, which treats CPCs within groups. The limitation of this model is that a good qualitative analysis is required to obtain a detailed tabulated CPC along with its linguistic terms. However, this was overcome by creating comprehensive classification tables dealing with maritime operations in Chapter 4. For future research, the introduced combined AHP and fuzzy quantification model can be created as computer software to produce quick results for HRA quantification values. The outcomes from this model can be used in other fields, such as quantification of undesired events in a fault tree or an event tree analysis.

6.7 Conclusion

A novel combined AHP and fuzzy quantification model is developed to estimate the HPFP based on the combined AHP and fuzzy logic approach of CREAM in maritime operations. The proposed model is found to be suitable for application to HRA due to the limited availability of data in the maritime domain and the uncertainty and complexity that exists in dealing with human reliability quantifications. The model has been tested and partially validated using a sensitivity analysis through the presented case study of '*Prestige*'. The case study has established that the results of HPFP values are within the parameters of COCOM of CREAM. The proposed model has also demonstrated that CREAM can be used successfully to determine the root causes of an incident along with quantifying the HPFP values within the event. Conclusions can be made that the proposed model can assist in HRAs, resulting in quantifying and reducing human errors in maritime operations. Finally, the developed novel combined AHP and fuzzy quantification model can further be used to compute the human performance failure probabilities in other transportation systems and industrial fields, such as chemical, gas and oil industries, resulting in a reduction in human errors.

Chapter 7
RCO Selection in CREAM Using an Integrated AHP and Fuzzy TOPSIS Model

Summary
This chapter presents a novel integrated AHP and fuzzy TOPSIS model, to determine the selection of an optimal RCO by taking subjective judgment of decision makers into consideration in CREAM. This facilitates use of the advanced CREAM proposed in Chapter 4. The AHP method is used to determine the relative importance weights of the established criteria in CBA of the identified RCOs. This is followed by ranking of the selected RCOs using a fuzzy TOPSIS. The proposed model has been demonstrated through a case study and validated using a sensitivity analysis. The integrated model can be used along with the advanced CREAM, for identifying root causes of human error and for providing definitive appropriate RCOs that solve the root cause identified.

7.1 Introduction
This chapter emphasises the newly introduced element of RCOs in the extended CREAM in Chapter 4. An appropriate list of RCOs can be identified and obtained on completion of detailed qualitative performance prediction in CREAM. The newly incorporated RCO in the generic CREAM model can assist in determining regulatory measures and actions required to be carried out based on the outcome of detailed qualitative performance analysis, taking into consideration elimination of the hazards, mitigation of the consequences and prevention of the occurrence of similar incident/accidents. In addition, all the intolerable risks from detailed qualitative analysis need to be reduced to an ALARP level. It can be carried out from various aspects, including management, operational and engineering issues, as described in detail in Chapter 3. An equitable and fair RCO can be selected by scrutinising the available RCOs. It would be prudent to develop a model that could assist decision makers to determine the appropriate RCO that needs to be selected. An integrated AHP and fuzzy TOPSIS model is developed to select an appropriate RCO by taking subjective

judgment of decision makers into consideration. Such decision making involves the identification and selection of alternatives based on the values and preferences of decision makers.

7.2 Literature Review

7.2.1 Overview on TOPSIS

TOPSIS is a MCDM technique to identify solutions from a finite set of alternatives, based on simultaneous minimisation of distance from a Positive Ideal Solution (PIS) and maximisation of distance from a Negative Ideal Solution (NIS). It was developed by Hwang and Yoon (Hwang and Yoon, 1981). TOPSIS applies a Euclidean norm to obtain PIS and NIS values (Olson, 2004). The TOPSIS method begins with the construction of a normalised decision matrix in order to transform the various attribute dimensions into non-dimensional attributes and to allow for comparison across the attributes. This is followed by constructing a weighted normalised decision matrix. Then, the PIS and NIS values are determined, followed by computation of separation measures of ideal and negative ideal separations. Finally, relative closeness to the ideal solution is obtained, which allows for preferred order ranking among the alternatives. TOPSIS has been used extensively and its applications have been established including those in maritime operations (Celik et al., 2009a), computer operating systems (Ball and Korukoglu, 2009), finance (Mahmoodzadeh et al., 2007; Salehi, 2009), business (Tsou, 2007; Percin, 2008; Sun and Lin, 2009), military operations (Wang and Chang, 2007; Dagdeviren, 2009), manufacturing (Li and Huang, 2009; Zeydan and Colpan, 2009) and in complex decision making (Lotfi et al., 2007). However, some of the criticisms of TOPSIS are its inability to adequately handle the ambiguity associated with mapping of the decision maker's perception to crisp values (Dagdeviren, 2009) and its inability to provide weight elicitation of various compared attributes (Celik et al., 2009b). The synopsis of TOPSIS development begins with the basic generic TOPSIS (Hwang and Yoon, 1981), followed by fuzzy TOPSIS (Chen, 2000) and TOPSIS under fuzzy environment to improve the existing ambiguity in the decision maker's judgment. Recently, an interval arithmetic-based fuzzy TOPSIS (Chu and Lin, 2009) was introduced by using an interval arithmetic approach for the normalisation of fuzzy weights to overcome the present fuzzy TOPSIS approach of using approximate membership functions.

7.2.2 Overview on Integrated AHP and Fuzzy TOPSIS

The application of fuzzy set theory was introduced by Zadeh to express the linguistic terms used in the decision making process in order to determine the ambiguity and subjectivity of human judgment (Zadeh, 1965). This facilitates the introduction of fuzzy modelling into TOPSIS to address the existing ambiguity of human judgment. The fuzzy TOPSIS has been preferred to assist in the selection of an appropriate RCO because the fuzzy approach allows for the ambiguity of expert judgment to be taken into consideration. The fundamental criteria scale for the expert judgment used in the AHP was already in the fuzzy form from Weber-Fechner observations (Saaty, 2008). Hence, the fuzzy approach was not used in the AHP but in TOPSIS of the proposed model. Using a combination of both subjective approaches of utilising expert judgment to select an appropriate RCO could reduce the effects of ambiguity that arose from using information from human judgment and preferences. Compared to the AHP, the simplicity of fuzzy TOPSIS, which only requires limited subjective input from decision makers and its ability to identify the best alternative quickly, encourage the use of it to determine an appropriate RCO (Dagdeviren, 2009).

7.2.3 Overview on Application of Fuzzy Modelling into TOPSIS

Wang and Chang's (Wang and Chang, 2007) and Wang and Lee's (Wang and Lee, 2009) approaches of TOPSIS under fuzzy environment have been adopted to improve human judgment analysis used in the basic generic TOPSIS. In this study, the alternative of RCOs is provided with seven levels of linguistic terms' ratings of importance. A membership function is established to each linguistic term to the rating of each alternative of the listed RCOs. The concept of membership functions used in fuzzy logic theory allows complex modelling, involving qualitative vague information of the expert judgment, to be illustrated. A triangular membership function is adopted with each linguistic term of the RCOs' rating being evaluated within its limits on an arbitrary scale of 0 to 1. Furthermore, modelling using triangular fuzzy numbers has been proven to be an effective way to address the subjectivity and ambiguity that exists in decision making problems (Chang and Yeh, 2002; Kahraman et al., 2004; Chang et al., 2007). A triangular fuzzy number can be presented as (a_1, a_2, a_3), where the membership function (μ) of the fuzzy number $\tilde{N}$ can be defined as follows:

$$\mu_{\tilde{N}}(x) = \begin{cases} 0, x < a_1, \\ (x - a_1) / (a_2 - a_1), a_1 \leq x \leq a_2, \\ (a_3 - x) / (a_3 - a_2), a_2 \leq x \leq a_3, \\ 0, x > a_3 \end{cases}$$

The following are the operational laws of triangular fuzzy numbers used in the fuzzy TOPSIS. Assume $\tilde{N}$ and $\tilde{U}$ as two triangular fuzzy numbers expressed as (a_1, a_2, a_3) and (b_1, b_2, b_3) respectively. Then,

$$\tilde{N} (+) \tilde{U} = (a_1, a_2, a_3) (+) (b_1, b_2, b_3) = (a_1 + b_1, a_2 + b_2, a_3 + b_3) \quad (7.1)$$

$$\tilde{N} (-) \tilde{U} = (a_1, a_2, a_3) (-) (b_1, b_2, b_3) = (a_1 - b_3, a_2 - b_2, a_3 - b_1) \quad (7.2)$$

$$\tilde{N} (\times) \tilde{U} = (a_1, a_2, a_3) (\times) (b_1, b_2, b_3) = (a_1 b_1, a_2 b_2, a_3 b_3) \quad (7.3)$$

$$\tilde{N} (/) \tilde{U} = (a_1, a_2, a_3) (/) (b_1, b_2, b_3) = \left(\frac{a_1}{b_3}, \frac{a_2}{b_2}, \frac{a_3}{b_1}\right) \quad (7.4)$$

$$k \tilde{N} = (k a_1, k a_2, k a_3) \quad (7.5)$$

$$(\tilde{N})^{-1} = \left(\frac{1}{a_3}, \frac{1}{a_2}, \frac{1}{a_1}\right) \quad (7.6)$$

7.3 Technique of Transforming Quantitative to Qualitative Data

Procedures to collect and analyse quantitative and qualitative data in the context of a single study are known as mixed methods research (Tashakkori and Teddlie, 2003). The use of both quantitative and qualitative data could facilitate in expanding the scope of a research. It can provide means to offset weakness that might appear if either one approach was performed in the research (Driscoll et al., 2007). Recent studies, which integrates quantitative and qualitative data include those in health studies (Sandelowski, 2000; Adamson et al., 2004), in social science (Onwuegbuzie and Teddlie, 2003), in childhood study (Weisner, 2005; Driscoll et al., 2007), in tourism (MacKay et al, 2004) and in business (Bazeley, 2004).

If a decision maker has decided to use quantitative RCOs to be considered in selecting an appropriate RCO, a simple linear utility location algorithm method (Yang et al., 2001) can be employed to facilitate the proposed methodology. The method can be illustrated as follows:

Assume the costs of four RCOs are £50, £100, £200 and £350. In case, there are seven linguistic terms in the model, hence the following computation is performed to obtain the cost for each linguistic term.

$$\text{Cost for each linguistic term} = \frac{£\,(350\text{-}50)}{6}$$

$$= £50$$

The costs of seven linguistic terms for RCOs will be £350, £300, £250, £200, £150, £100 and £50 for Very Poor (VP), Poor (P), Medium Poor (MP), Fair (F), Medium Good (MG), Good (G), and Very Good (VG) respectively. Hence, the costs of four RCOs £50, £100, £200 and £350 can be categorised as VG, G, F and VP respectively. Meanwhile, if the RCO cost falls between the two linguistic terms for the RCOs, the linguistic term for that RCO cost could be computed using a belief degree method obtaining proportion values of the RCO cost belonging to the corresponding linguistic terms, which is illustrated as follows:
Assume the cost of RCO as £70, which would be in between VG and G linguistic terms for the RCOs.

$$\text{Belief degree of VG linguistic term} = \frac{(100\text{-}70)}{(100\text{-}50)}$$

$$= \frac{(30)}{(50)}$$

$$= 0.600$$

$$\text{Belief degree of G linguistic term} = \frac{(70\text{-}50)}{(100\text{-}50)}$$

$$= \frac{(20)}{(50)}$$

$$= 0.400$$

The cost of RCO £70 could be categorised as VG with 0.6 belief degree and G with 0.4 belief degree.

7.4 Methodology

The decision hierarchy of RCO selection and a generic framework of the proposed model are illustrated in Figures 7.1 and 7.2 respectively. Figure 7.1 displays the decision hierarchy structured with the established alternative RCOs and criteria of CBA elements. There are three levels in the decision hierarchy structured for the RCO selection problem. The base of the three-level decision hierarchy is formed by the alternative RCOs identified. This is followed by the criteria of CBA elements at the second level. Finally, the decision hierarchy is concluded with the selection of the RCO at the uppermost level of the hierarchy. Meanwhile, Figure 7.2 illustrates the research methodology, which consists of an AHP application to obtain weighting vectors for each of the listed criteria and the fuzzy TOPSIS application to select an appropriate RCO. Each step of the framework is elaborated in detail in the following subsections.

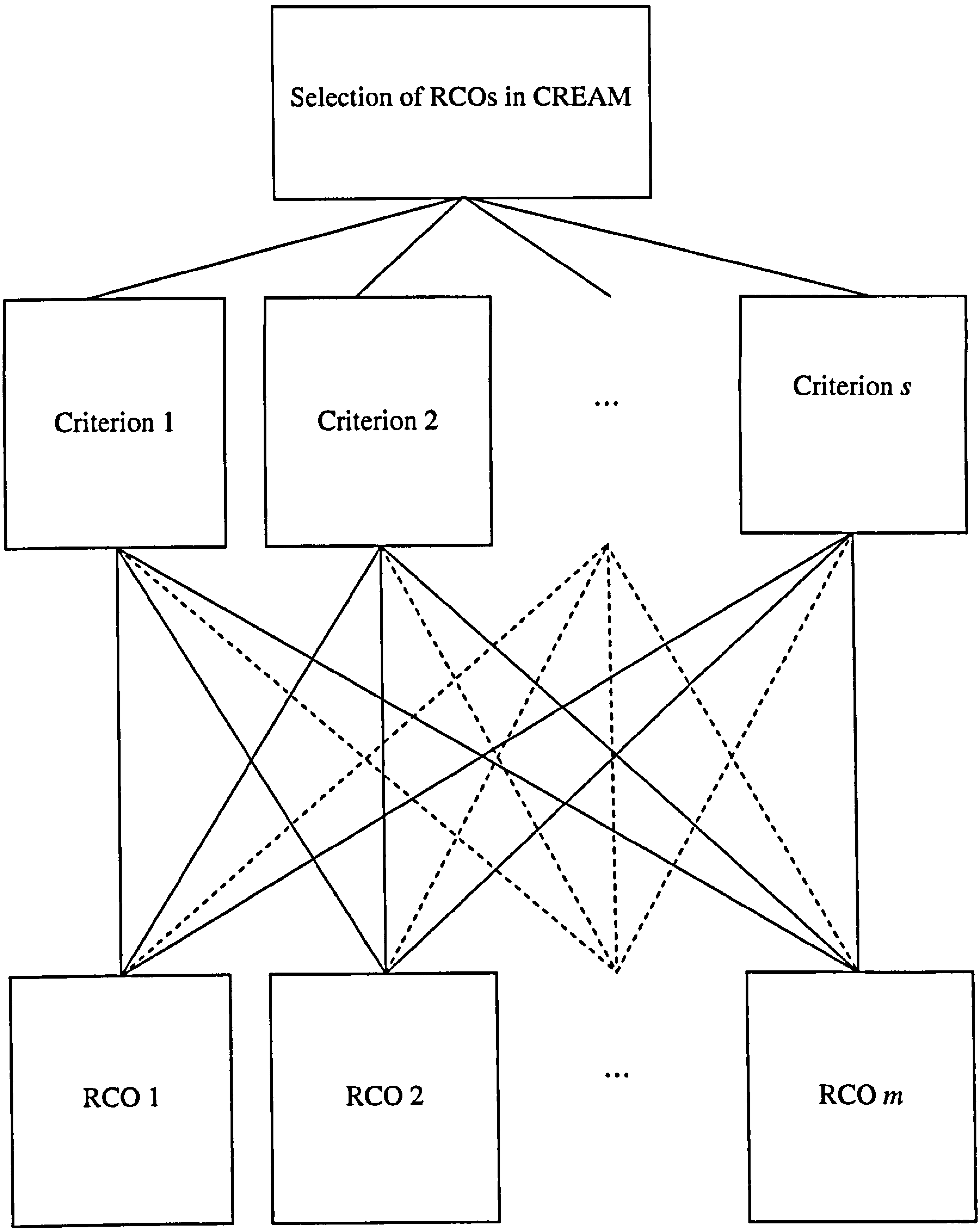

Figure 7.1 The Generic Decision Hierarchy of RCO Selection in CREAM

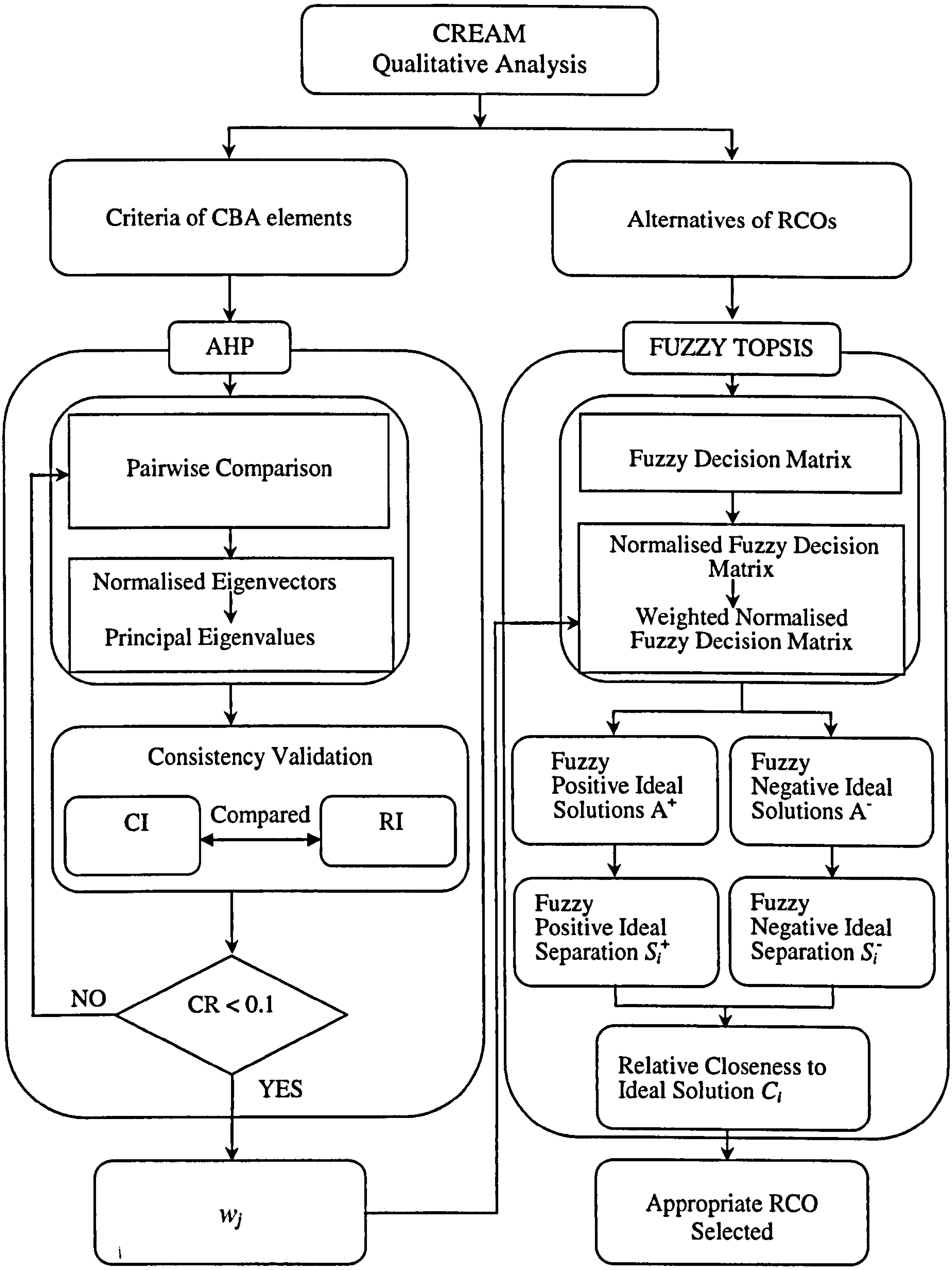

Figure 7.2 The General Framework of the Proposed Integrated AHP and Fuzzy TOPSIS Model

The description of the proposed methodology framework is as follows:

(a). Step 1 – Obtain a list of the established criteria of CBA elements from the listed RCOs provided by decision makers.

Such a list of the criteria can be obtained from expert judgment of a detailed qualitative CREAM analysis of an incident/accident.

(b). Step 2 – Carry out pairwise comparisons of the listed criteria to determine the relative importance weights among the criteria using an AHP by expert judgment.

Equation 6.1 can be applied to obtain an average scale used for pairwise comparisons when more than one expert is involved for analysis.

(c). Step 3 – Compute the weights of the established criteria.

The weights of the established criteria values are computed using Equations 6.2 to 6.6 from Chapter 6.

(d). Step 4 – Evaluation of RCOs with respect to each criterion.

Adopting Dagdeviren's approach (Dagdeviren, 2009), the alternative RCO ratings are determined by the expert judgment' evaluation using linguistic fuzzy values. The membership functions of linguistic variables for the alternative RCO ratings, and details of the fuzzy linguistic terms and their correspondent fuzzy numbers for the alternative RCO ratings are illustrated in Figure 7.3 and Table 7.1 respectively.

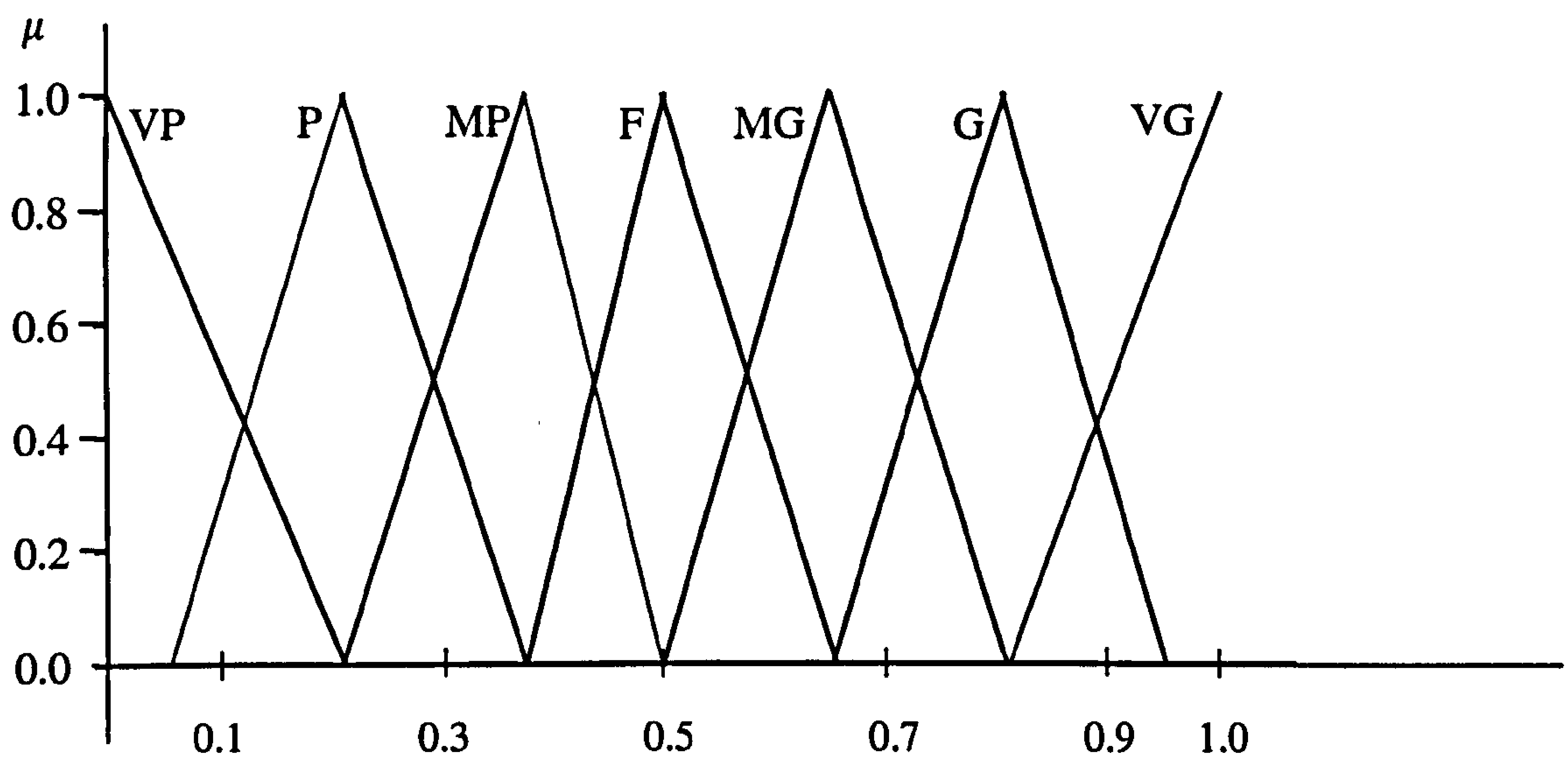

Figure 7.3 The Membership Functions of Linguistic Variables for RCOs

Table 7.1 The Fuzzy Linguistic Terms and Correspondent Fuzzy Numbers for RCOs

Linguistic terms	Abbreviation	Fuzzy Numbers
Very Poor	VP	(0, 0, 0.20)
Poor	P	(0.05, 0.20, 0.35)
Medium Poor	MP	(0.20, 0.35, 0.50)
Fair	F	(0.35, 0.50, 0.65)
Medium Good	MG	(0.50, 0.65, 0.80)
Good	G	(0.65, 0.80, 0.95)
Very Good	VG	(0.80, 1.00, 1.00)

Using a combined AHP and fuzzy logic approach model as elaborated in Chapter 6, the HPFP for an incident is calculated. Using a similar approach, the HPFP values after applying each RCO to the incident can be obtained. Finally, a list of RCOs HPFP reduction values is determined by subtracting the HPFP of each RCO from the initial HPFP of the incident. The quantitative RCOs estimation can be transformed into qualitative ones using the technique described in Section 7.3.

(e). Step 5 – Construct a fuzzy decision matrix for the listed RCOs compared with each established criterion of the CBA elements.

When more than one expert is used for an analysis, Equation 6.1 needs to be applied to obtain an average value used in the fuzzy decision matrix. A typical fuzzy decision matrix K can be expressed as follows:

$$\tilde{K} = \begin{array}{c} \\ RCO_1 \\ \vdots \\ RCO_i \\ \vdots \\ RCO_m \end{array} \begin{array}{c} \begin{matrix} Cri_1 \cdots & Cri_j & \cdots & Cri_s \end{matrix} \\ \begin{bmatrix} \tilde{p}_{11} & \cdots & \tilde{p}_{12} & \cdots & \tilde{p}_{1s} \\ \vdots & & \vdots & & \vdots \\ \tilde{p}_{i1} & \cdots & \tilde{p}_{ij} & \cdots & \tilde{p}_{is} \\ \vdots & & \vdots & & \vdots \\ \tilde{p}_{m1} & \cdots & \tilde{p}_{mj} & \cdots & \tilde{p}_{ms} \end{bmatrix} \end{array}$$

where RCO_1, RCO_2,..., RCO_m are the alternative RCOs, Cri_1, Cri_2,..., Cri_s referring to the evaluation criteria of the CBA elements, $\tilde{p}_{ij}$ represents the rating of alternative RCO_i with respect to criterion Cri_j, $i = 1, 2,..., m$ and $j = 1, 2,..., s$.

(f). Step 6 – Construct a normalised fuzzy decision matrix.

The normalised fuzzy decision matrix $\tilde{R}$ is developed by using Equation 7.7.

$$\tilde{R} = [\tilde{r}_{ij}]_{ms}, \; i = 1, 2, \ldots, m \text{ and } j = 1, 2, \ldots, s. \tag{7.7}$$

where for the benefit criteria,

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^+}, \frac{b_{ij}}{c_j^+}, \frac{c_{ij}}{c_j^+} \right), \quad c_j^+ = \max_i c_{ij} \text{ and,}$$

where for the cost criteria,

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}} \right), \quad a_j^- = \min_i a_{ij}$$

where $\tilde{p}_{ij} = (a_{ij}, b_{ij}, c_{ij})$ is the evaluated RCOs' performance to each criterion and $\max_i c_{ij}$ and $\min_i a_{ij}$ are the maximum and minimum values of RCO_i with respect to criterion Cri_j for each criterion in the fuzzy decision matrix respectively.

(g). Step 7 – Construct a weighted normalised fuzzy decision matrix for the RCOs.

The weighted normalised fuzzy decision matrix is constructed by multiplying the normalised fuzzy decision matrix by the importance weights of the criteria obtained from Equation 6.3. The relationship is illustrated in Equation 7.8.

$$\tilde{V} = [\tilde{v}_{ij}]_{ms}, \; i = 1, 2, \ldots, m \text{ and } j = 1, 2, \ldots, s. \tag{7.8}$$

where

$$\tilde{v}_{ij} = \tilde{r}_{ij} \times w_j$$

where w_j is the importance weight of criterion Cri_j.

(h). Step 8 – Determine the Fuzzy Positive Ideal Solution (FPIS) and Fuzzy Negative Ideal Solution (FNIS).

The $\tilde{v}_{ij}$ elements are normalised positive triangular fuzzy numbers and include ranges to the closed interval [0, 1]. Thus, the FPIS A^+ and FNIS A^- can be illustrated as in Equations 7.9 and 7.10 respectively.

$$A^+ = \{\tilde{v}_1^+, \tilde{v}_2^+, \tilde{v}_j^+, \ldots, \tilde{v}_s^+\} \tag{7.9}$$

$$A^- = \{\tilde{v}_1^-, \tilde{v}_2^-, \tilde{v}_j^-, \ldots, \tilde{v}_s^-\} \quad (7.10)$$

where $\tilde{v}_j^+ = (1, 1, 1)$ and $\tilde{v}_j^- = (0, 0, 0)$, $j = 1, 2, \ldots, s$.

(i). Step 9 – Computation of separation measures using the m-dimensional Euclidean distance.

The separation of each alternative RCO from the FPIS (S_i^+) and FNIS (S_i^-) is computed using Equations 7.11 and 7.12 respectively. Equation 7.13 is used to compute the distance between two triangular fuzzy numbers using the vertex method (Chen, 2000).

$$S_i^+ = \sum_{j=1}^{s} (\tilde{v}_{ij} - \tilde{v}_j^+) \quad \text{where } i = 1, 2, \ldots, m \text{ and } j = 1, 2, \ldots, s. \quad (7.11)$$

$$S_i^- = \sum_{j=1}^{s} (\tilde{v}_{ij} - \tilde{v}_j^-) \quad \text{where } i = 1, 2, \ldots, m \text{ and } j = 1, 2, \ldots, s. \quad (7.12)$$

where S_i^+ is the separation of the ith RCO from FPIS, S_i^- is the separation of the ith RCO from FNIS, and $\tilde{v}_{ij}$, $\tilde{v}_j^+$ and $\tilde{v}_j^-$ denote triangular fuzzy numbers from the weighted normalised fuzzy decision matrix.

$$d(\tilde{N},\tilde{U}) = \sqrt{\frac{1}{3}\left[(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2\right]} \quad (7.13)$$

where, $\tilde{N}$ and $\tilde{U}$ as two triangular fuzzy numbers expressed as (a_1, a_2, a_3) and (b_1, b_2, b_3) respectively and d is the distance between $\tilde{N}$ and $\tilde{U}$.

(j). Step 10 – Computation of the relative closeness (C_i) to the ideal solution and ranking of each alternative RCO.

The C_i values are obtained by using Equation 7.14.

$$C_i = \frac{S_i^-}{(S_i^+ + S_i^-)} \quad \text{where } i = 1, 2, \ldots, m \quad (7.14)$$

Finally, the ranking of RCOs is determined by comparing the obtained C_i values and the preference order ranked according to the descending values of C_i. The performance of a RCO is better as the value of its C_i increases.

7.5 Case Study of '*Carina*'

The case study of '*Carina*' is used to demonstrate the proposed integrated AHP and fuzzy TOPSIS model to determine an appropriate selection of RCO in CREAM. The case study can be presented as a MCDM problem in which the alternatives are the RCOs and the criteria are those attributes which relate to the CBA elements from the listed RCOs.

(a). Step 1 – A tabulated list of the established criteria of CBA elements from the listed RCOs provided by decision makers. Such a list of criteria and RCOs is obtained from expert judgment of a detailed qualitative analysis of CREAM on the '*Carina*' incident elaborated in Chapter 4 and is presented in Table 7.2. Additionally, a decision hierarchy of RCO selection in CREAM of the '*Carina*' incident is illustrated in Figure 7.4.

Table 7.2 The Criteria of CBA Elements for the RCO Selection of the '*Carina*' Incident

Criteria	Description
C_F	Cost to implement the selected RCO
T_E	Time taken to complete the selected RCO
E_C	Efforts required to implement the selected RCO
L_F	Lifespan of the selected RCO
$HPFP_R$	Human Performance Failure Probability reduction

With reference to Table 7.2, criterion C_F, T_E and E_C are categorised as cost criteria, whereas criterion L_F and $HPFP_R$ are categorised as benefit criteria.

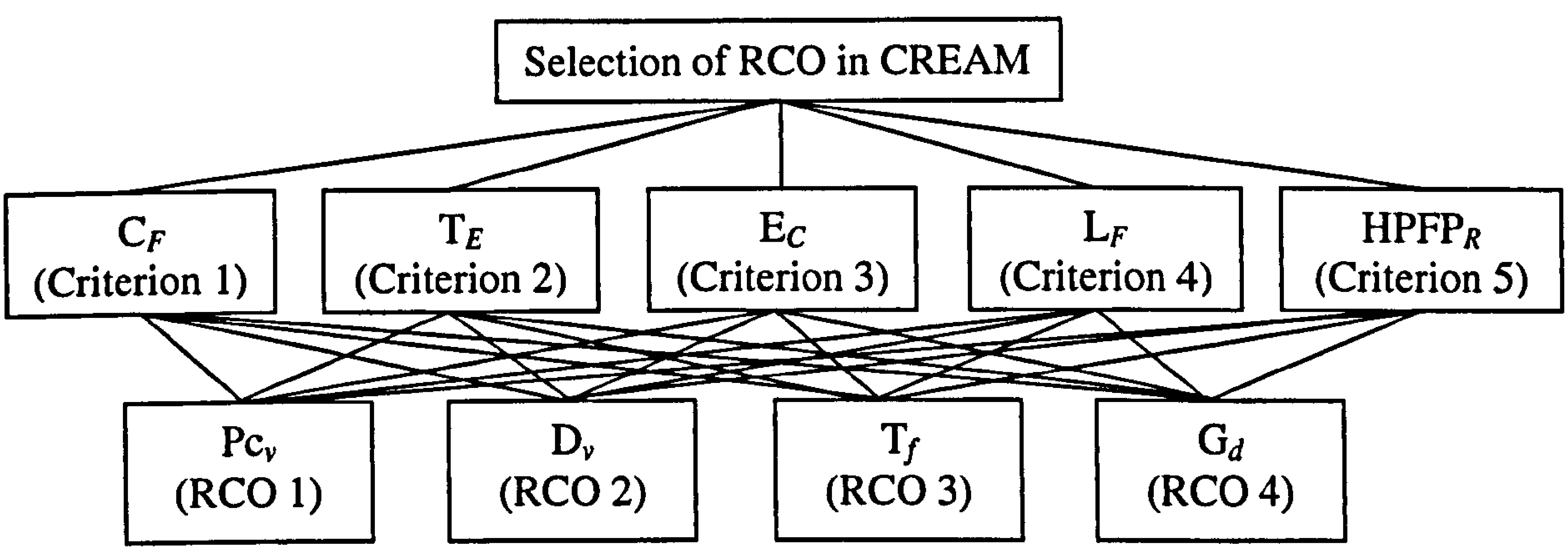

Figure 7.4 The Decision Hierarchy of RCO Selection in CREAM

The abbreviations used in Figure 7.4 are as follows:

i). C_F – Cost to implement the selected RCO.

ii). T_E – Time taken to complete the selected RCO.

iii). E_C – Efforts required to implement the selected RCO.

iv). L_F – Lifespan of the selected RCO.

v). $HPFP_R$ - Human Performance Failure Probability reduction.

vi). Pc_v – Periodical checking of the cargo tanks' inert gas branch valves.

vii). D_v – Dismantling of cargo tanks' inert gas branch valves during vessel's drydocking.

viii). T_f – Continuous training and familiarisation of crew onboard oil tankers to be conducted to emphasise the significance of proper use of cargo tanks' inert gas branch valves.

ix). G_d – A good structural design at shipbuilding phase, along with a reliable locking arrangement of cargo tanks' inert gas branch valves and an appropriate warning system such as an audible alarm, visual light warning signals, or a combination of the two, which could be provided in the cargo control room to show the status of the cargo tanks' inert gas branch valves.

(b). Step 2 – Carry out pairwise comparisons of the listed criteria to determine the relative importance weights among the criteria using an AHP by expert judgment.

A human-reliability specialist from a classification society, two officials from two flag state administrations with accident investigation backgrounds, and a master mariner with more than ten years of oil tanker sailing experience were used to provide expert judgment of pairwise comparison of criteria. The individual expert evaluations are provided in Appendix V. The average scales used for the pairwise comparison of criteria are obtained by using Equation 6.1. Table 7.3 illustrates the result of expert judgment pairwise comparison of the criteria.

From Equation 6.1, an example of calculation to obtain judgment matrix for pairwise comparison of criteria value of T_E to E_C by row is shown as follows:

The pairwise comparison of criterion T_E to E_C value,

$$= \left[\frac{(a_1(x) + a_2(x) + a_3(x) + a_4(x))}{4}\right]$$

$$= \left[\frac{(1.000 + 2.000 + 2.000 + 2.000)}{4}\right]$$

$$= 1.750$$

where, $a_1(x)$, $a_2(x)$, $a_3(x)$ and $a_4(x)$ are the values on the pairwise comparison of criteria T_E to E_C by row obtained from expert evaluations.

Table 7.3 Judgment Matrix for Pairwise Comparison of Criteria

Criteria	C_F	T_E	E_C	L_F	$HPFP_R$
C_F	1.000	0.778	1.028	1.028	1.000
T_E	1.285	1.000	1.750	2.625	1.000
E_C	0.973	0.571	1.000	2.583	1.000
L_F	0.973	0.381	0.387	1.000	1.000
$HPFP_R$	1.000	1.000	1.000	1.000	1.000

(c). Step 3 – Compute the weights of the established criteria.

The computation of weights of the established criteria is carried out using an AHP method similar to the computation of CPCs' relative importance weights for '*Prestige*' using Equations 6.2 to 6.6 from Chapter 6.

The sums of each column of the reciprocal matrix of criteria of C_F, T_E, E_C L_F and $HPFP_R$ are 5.231, 3.730, 5.165, 8.236 and 5.000 respectively. The normalised relative importance of each criterion is computed using Equation 6.2 and shown in Table 7.4.

From Equation 6.2, an example of calculation to obtain the normalised relative importance of T_E to E_C by row is illustrated as follows:

Normalised relative importance value of T_E to E_C = $\left[\left(\frac{1}{5.165}\right) \times 1.750\right]$

$= 0.339$

Table 7.4 Judgment Matrix for Normalised Relative Importance of Criteria

Criteria	C_F	T_E	E_C	L_F	$HPFP_R$
C_F	0.191	0.209	0.199	0.125	0.200
T_E	0.246	0.268	0.339	0.319	0.200
E_C	0.186	0.153	0.194	0.314	0.200
L_F	0.186	0.102	0.075	0.121	0.200
$HPFP_R$	0.191	0.268	0.194	0.121	0.200

Upon having a normalised comparison criteria matrix, five priority eigenvectors representing each criterion importance are computed using Equation 6.3. The priority vectors show relative weights among the criteria compared.

From Equation 6.3, an example of calculation to obtain relative weight of criterion T_E is illustrated as follows:

Relative weight of criterion T_E = $\left[\frac{(0.246 + 0.268 + 0.339 + 0.319 + 0.200)}{5}\right]$

$= 0.274$

Using a similar method, the relative weights of the remaining criteria are computed. The relative weights of criteria C_F, T_E, E_C, L_F and $HPFP_R$ are computed as 0.185, 0.274, 0.209, 0.137 and 0.195 respectively.

A principal eigenvalue, λ_{max} is obtained using Equation 6.4.

$$\lambda_{max} = \frac{1}{5} \times$$

$$\left\{\left[\frac{(0.185 \times 1.000) + (0.274 \times 0.778) + (0.209 \times 1.028) + (0.137 \times 1.028) + (0.195 \times 1.000)}{0.185}\right] +\right.$$

$$\left[\frac{(0.185 \times 1.285) + (0.274 \times 1.000) + (0.209 \times 1.750) + (0.137 \times 2.625) + (0.195 \times 1.000)}{0.274}\right] +$$

$$\left[\frac{(0.185 \times 0.973) + (0.274 \times 0.571) + (0.209 \times 1.000) + (0.137 \times 2.583) + (0.195 \times 1.000)}{0.209}\right] +$$

$$\left[\frac{(0.185 \times 0.973) + (0.274 \times 0.381) + (0.209 \times 0.387) + (0.137 \times 1.000) + (0.195 \times 1.000)}{0.137}\right] +$$

$$\left[\frac{(0.185 \times 1.000) + (0.274 \times 1.000) + (0.209 \times 1.000) + (0.137 \times 1.000) + (0.195 \times 1.000)}{0.195}\right]\}$$

$$= 5.162$$

From Equation 6.5 with $s = 5$, $CI = \left[\frac{(5.162 - 5)}{(5 - 1)}\right]$

$$= 0.040$$

From Equation 6.6 and RI value taken from Table 6.2, $CR = \left[\frac{(0.040)}{(1.110)}\right]$

$$= 0.036$$

The CR value obtained is less than 0.1. Thus, the expert judgment on the criteria is consistent.

(d). Step 4 – Evaluation of RCOs with respect to each criterion.

With reference to the HPFP computation for '*Prestige*' in Chapter 6, the HPFP value for the '*Carina*' incident is computed using Equations 6.2 to 6.8 from Chapter 6. Detailed computation of obtaining the $HPFP_{Carina}$ is provided in Appendix VI. In a similar method, the HPFPs on implementation of RCOs can be obtained and are provided in Appendix VI and listed as follows:

$HPFP_{Carina} = 0.623$, $HPFP\ D_v = 0.603$, $HPFP\ Pc_v = 0.607$, $HPFP\ T_f = 0.612$, and $HPFP\ G_d = 0.484$

The following are the HPFP reduction for each RCO:

$HPFP_R\ D_v = (0.623 - 0.603) = 0.020$

$HPFP_R\ Pc_v = (0.623 - 0.607) = 0.016$

$HPFP_R\ T_f = (0.623 - 0.612) = 0.011$

$HPFP_R\ G_d = (0.623 - 0.484) = 0.139$

The $HPFP_R$ of each RCO is converted to the linguistic variables using a similar method as described in Section 7.3.

The $HPFP_R$ T_f and $HPFP_R$ G_d of 0.011 and 0.139 would be the VP and VG RCO linguistic variables respectively due to its minimum and maximum $HPFP_R$ values. The interpolations to obtain the linguistic variables for the $HPFP_R$ Pc_v and $HPFP_R$ T_f are provided as follows:

$$\text{Distance between two neighbouring } HPFP_R \text{ linguistic variables} = \left[\frac{(0.139 - 0.011)}{6}\right]$$

$$= 0.021$$

Since the VP rating was 0.011 hence, the next RCO rating of P will be,

$$= (0.011 + 0.021)$$

$$= 0.032$$

The $HPFP_R$ Pc_v and $HPFP_R$ D_v ratings fall between VP and P. The interpolation to obtain the $HPFP_R$ Pc_v and $HPFP_R$ D_v ratings are illustrated as follows:

$$HPFP_R\,Pc_v = \left[\frac{(0.032 - 0.016)}{(0.032 - 0.011)}\right] \text{VP}, \left[\frac{(0.016 - 0.011)}{(0.032 - 0.011)}\right] \text{P}$$

$$= 0.8 \text{ VP and } 0.2 \text{ P}$$

Using the fuzzy numbers for the linguistic terms VP and P in Table 7.1, the final $HPFP_R$ Pc_v is obtained as follows:

$$HPFP_R\,Pc_v = [(0.8 \times (0, 0, 0.2)) + (0.2 \times (0.05, 0.20, 0.35))]$$

$$= [(0, 0, 0.16) + (0.01, 0.04, 0.07)]$$

$$= (0.01, 0.04, 0.23)$$

$$HPFP_R\,D_v = \left[\frac{(0.032 - 0.020)}{(0.032 - 0.011)}\right] \text{VP}, \left[\frac{(0.020 - 0.011)}{(0.032 - 0.011)}\right] \text{P}$$

$$= 0.6 \text{ VP and } 0.4 \text{ P}$$

Using Table 7.1, the final $HPFP_R D_v$ is obtained as follows:

$$HPFP_R D_v = [(0.6 \times (0, 0, 0.2)) + (0.4 \times (0.05, 0.20, 0.35))]$$
$$= [(0.00, 0.00, 0.12) + (0.02, 0.08, 0.14)]$$
$$= (0.02, 0.08, 0.26)$$

(e). Step 5 – Construct a fuzzy decision matrix for the listed RCOs with respect to each established criterion of the CBA elements.

Similar method of averaging four experts evaluation values using Equation 6.1 as mentioned in Step 2 and Table 7.1 were used to obtain the final judgment matrix for fuzzy decision matrix of RCOs/criteria. The individual expert evaluations are provided in Appendix V. The fuzzy decision matrix for the listed RCOs compared with each established criterion of the CBA elements is illustrated in Table 7.5.

From Equation 6.1, an example of calculation to obtain the fuzzy decision matrix is illustrated as follows:

The value of RCO D_v with respect to E_C of the fuzzy decision matrix of RCOs/criteria,

$$= \left[\frac{(a_1(x) + a_2(x) + a_3(x) + a_4(x))}{4}\right]$$

$$= \left[\frac{(G + G + G + F)}{4}\right]$$

$$= \left\{\frac{[(0.65, 0.80, 0.95) + (0.65, 0.80, 0.95) + (0.65, 0.80, 0.95) + (0.35, 0.50, 0.65)]}{4}\right\}$$

$$= \left[\frac{(2.30, 2.90, 3.50)}{4}\right]$$

$$= (0.58, 0.73, 0.88)$$

where $a_1(x)$, $a_2(x)$, $a_3(x)$ and $a_4(x)$ are the values of RCO D_v with respect to E_C obtained from expert evaluations.

Table 7.5 The Judgment Matrix for Fuzzy Decision Matrix of RCOs/Criteria

Criteria / RCOs	C_F	T_E	E_C	L_F	$HPFP_R$
Pc_v	(0.54, 0.70, 0.81)	(0.20, 0.35, 0.50)	(0.28, 0.43, 0.58)	(0.20, 0.35, 0.50)	(0.01, 0.04, 0.23)
D_v	(0.13, 0.28, 0.43)	(0.65, 0.80, 0.95)	(0.58, 0.73, 0.88)	(0.14, 0.21, 0.39)	(0.02, 0.08, 0.26)
T_f	(0.39, 0.54, 0.69)	(0.20, 0.35, 0.50)	(0.13, 0.28, 0.43)	(0.13, 0.28, 0.43)	(0, 0, 0.20)
G_d	(0.16, 0.31, 0.46)	(0.39, 0.55, 0.66)	(0.65, 0.84, 0.88)	(0.80, 1.00, 1.00)	(0.80, 1.00, 1.00)

(f). Step 6 – Construct a normalised fuzzy decision matrix.

All the criteria have been converted into benefit element and therefore, only Equation 7.7 for the benefit criteria is used in this case study. The normalised fuzzy decision matrix is constructed by using Equation 7.7 and is presented in Table 7.6. From Equation 7.7, an example of calculation to obtain the normalised relative performance value of RCO D_v with respect to E_C is illustrated as follows:

$$\text{The normalised value of } D_v \text{ to } E_C = \left[\left(\frac{0.58}{0.88}\right), \left(\frac{0.73}{0.88}\right), \left(\frac{0.88}{0.88}\right)\right]$$
$$= (0.66, 0.83, 1.00)$$

Table 7.6 The Judgment Matrix for Normalised Fuzzy Decision Matrix of RCOs/Criteria

Criteria / RCOs	C_F	T_E	E_C	L_F	$HPFP_R$
Pc_v	(0.66, 0.86, 1.00)	(0.21, 0.37, 0.53)	(0.31, 0.49, 0.66)	(0.20, 0.35, 0.50)	(0.01, 0.04, 0.23)
D_v	(0.15, 0.34, 0.52)	(0.68, 0.84, 1.00)	(0.66, 0.83, 1.00)	(0.14, 0.21, 0.39)	(0.02, 0.08, 0.26)
T_f	(0.48, 0.66, 0.85)	(0.21, 0.37, 0.53)	(0.14, 0.31, 0.49)	(0.13, 0.28, 0.43)	(0, 0, 0.20)
G_d	(0.20, 0.38, 0.57)	(0.41, 0.58, 0.70)	(0.74, 0.96, 1.00)	(0.80, 1.00, 1.00)	(0.80, 1.00, 1.00)

(g). Step 7 – Construct a weighted normalised fuzzy decision matrix for the RCOs compared with the criteria of the CBA elements.

Equation 7.8 is used to develop the weighted normalised fuzzy decision matrix. The relative weight of each criterion obtained through AHP is multiplied by the triangular fuzzy numbers of the evaluated judgment matrix of the fuzzy decision matrix of RCOs/criteria. The weighted normalised fuzzy decision matrix for the RCOs compared with the criteria of the CBA elements is shown in Table 7.7.

From Equation 7.8, an example of calculation to obtain the weighted normalised fuzzy decision matrix value of RCO D_v to E_C by row is illustrated as follows:

$$\text{The weighted normalised value of } D_v \text{ to } E_C = (0.66, 0.83, 1.00) \times 0.209$$
$$= (0.138, 0.173, 0.209)$$

Table 7.7 The Judgment Matrix for Weighted Normalised Fuzzy Decision Matrix of RCOs

Criteria / RCOs	C_F	T_E	E_C	L_F	$HPFP_R$
Pc_v	(0.122, 0.159, 0.185)	(0.058, 0.101, 0.144)	(0.066, 0.102, 0.138)	(0.027, 0.048, 0.068)	(0.002, 0.008, 0.045)
D_v	(0.028, 0.063, 0.097)	(0.188, 0.231, 0.274)	(0.138, 0.173, 0.209)	(0.019, 0.029, 0.053)	(0.004, 0.016, 0.051)
T_f	(0.088, 0.122, 0.156)	(0.058, 0.101, 0.144)	(0.030, 0.066, 0.102)	(0.017, 0.038, 0.058)	(0, 0, 0.039)
G_d	(0.037, 0.071, 0.105)	(0.112, 0.159, 0.191)	(0.155, 0.200, 0.209)	(0.110, 0.137, 0.137)	(0.156, 0.195, 0.195)

(h). Step 8 – Determine the FPIS and FNIS.

The FPIS values of Pc_v, D_v, T_f and G_d are determined with reference to Equation 7.9, and are as follows:

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

Meanwhile, the FNIS values of Pc_v, D_v, T_f and G_d are established with reference to Equation 7.10, and are as follows:

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

(i). Step 9 – Computation of separation measures using the m-dimensional Euclidean distance.

The separation of each alternative of Pc_v, D_v, T_f, and G_d from the FPIS and FNIS are obtained by using Equations 7.11 and 7.12 respectively along with Equation 7.13, and are as follows:

$$S_i^+ = 4.578, 4.478, 4.662, 4.279$$

$$S_i^- = 0.447, 0.545, 0.368, 0.735$$

An example of calculation to obtain the S_i^+ value of RCO D_v is illustrated as follows:

$$S_i^+ \text{ of } D_v \text{ value} = \{\sqrt{\frac{1}{3} \times [(0.028 - 1.000)^2 + (0.063 - 1.000)^2 + (0.097 - 1.000)^2]} +$$

$$\sqrt{\frac{1}{3} \times [(0.188 - 1.000)^2 + (0.231 - 1.000)^2 + (0.274 - 1.000)^2]} +$$

$$\sqrt{\frac{1}{3} \times [(0.138 - 1.000)^2 + (0.173 - 1.000)^2 + (0.209 - 1.000)^2]} +$$

$$\sqrt{\frac{1}{3} \times [(0.019 - 1.000)^2 + (0.029 - 1.000)^2 + (0.053 - 1.000)^2]} +$$

$$\sqrt{\frac{1}{3} \times [(0.004 - 1.000)^2 + (0.016 - 1.000)^2 + (0.051 - 1.000)^2]}\}$$

$$= 4.478$$

(j). Step 10 – Computation of the C_i to the ideal solution and ranking of RCOs.
The C_i values of Pc_v, D_v, T_f, and G_d are obtained by using Equation 7.14 and the preference order ranked according to the descending values is illustrated in Table 7.8.

Table 7.8 The Preference Order of C_i

Sequence	RCOs	C_i
1	G_d	0.147
2	D_v	0.109
3	Pc_v	0.089
4	T_f	0.073

From Equation 7.14, an example of calculation to obtain the C_i value of D_v is illustrated as follows:

$$\text{The } C_i \text{ value of } D_v = \left[\frac{0.545}{(4.478 + 0.545)}\right]$$

$$= 0.109$$

7.6 Sensitivity Analysis of RCO Selection in CREAM

Sensitivity analysis is a study of how the uncertainty in the output of a model can be apportioned to different sources of uncertainty in the model input (Saltelli et al., 2008). It is a method for testing the degree of sensitivity of a model's variables and considered by some as prerequisite for model building in diagnostic or prognostic setting (Saltelli, 2002). The results of a sensitivity analysis can be used to validate a model, warn of unrealistic model behaviour, help formulate model structure, suggest new experiments, guide future data collection efforts, suggest accuracy for calculating parameters and detect critical criteria. A sensitivity analysis tells which parameters are the most important and most likely to affect predictions of the model (Smith et al., 2008). A sensitivity analysis was performed by changing the expert judgment evaluation associated with the performance of RCO. The performance of D_v to the criterion T_E was changed from G to MP reducing at an interval step of one level of linguistic term. The simulated preference order of C_i was plotted for each linguistic level. If the model is reliable, then the sensitivity analysis must at least comply with an axiom that a reduction of D_v performance will result in the fall of its preferences. Small changes of the input variables would induce small changes in the output results of C_i values. The final trend lines of resultant simulated C_i values of Pc_v, D_v, T_f, and G_d are illustrated in Figure 7.5.

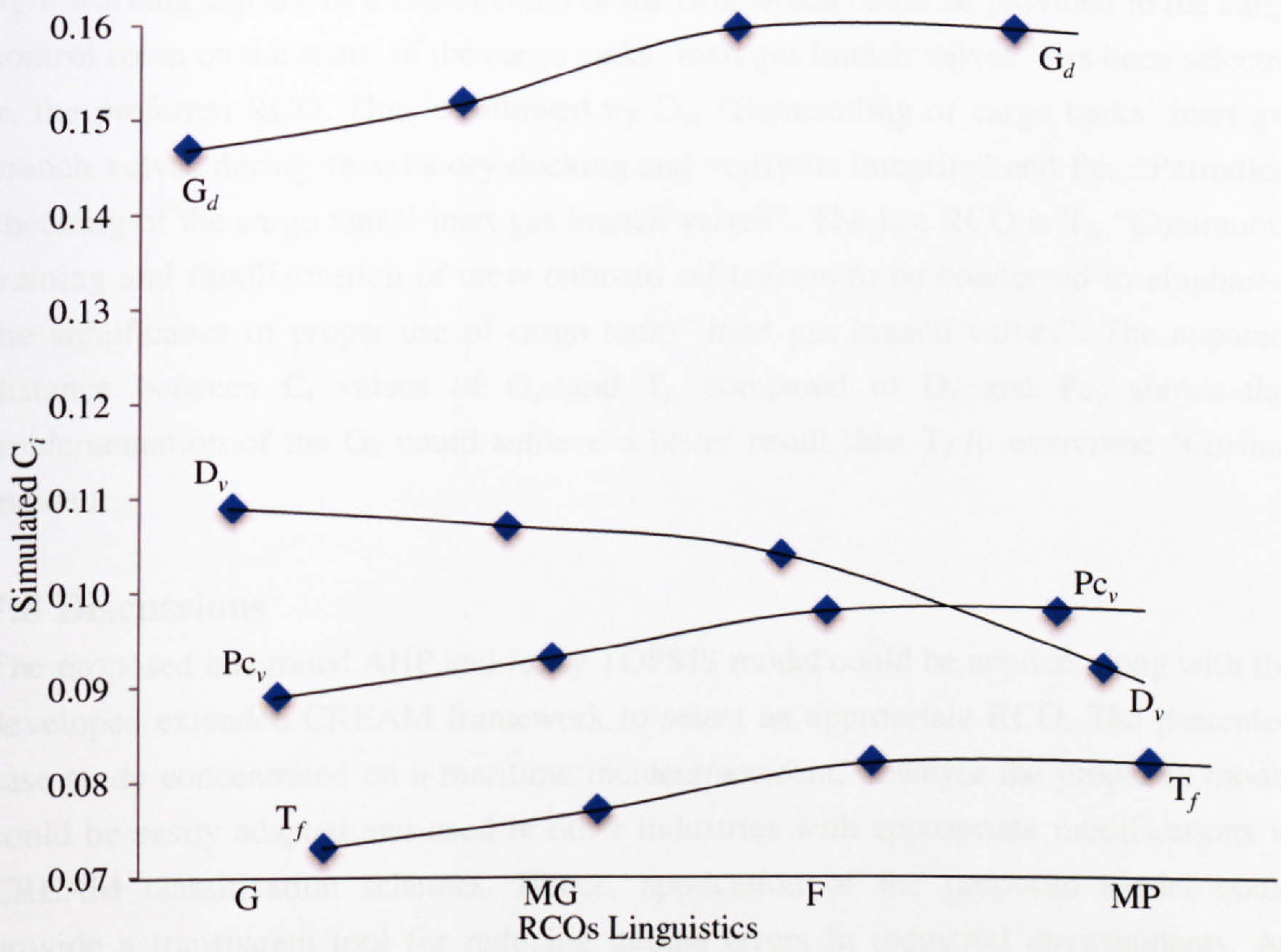

Figure 7.5 The Trend Lines of Simulated Preference Order of C_i

On analysing Figure 7.5, it can be illustrated that a small change in the expert judgment scale performance of D_v with regards to the criterion T_E has apparently changed the simulated C_i values of D_v gradually as anticipated. Furthermore, continuous reduction of D_v performance has reduced the simulated C_i values and resulted in the fall of D_v ranking from second to third. Additionally, no abrupt large changes of simulated C_i values were generated in the sensitivity analysis.

7.7 Results

The case study of '*Carina*' has demonstrated that G_d, "a good structural design at shipbuilding phase, along with a reliable locking arrangement of the cargo tanks' inert gas branch valves and an appropriate warning system such as an audible alarm, visual light warning signals, or a combination of the two, which could be provided in the cargo control room on the status of the cargo tanks' inert gas branch valves" has been selected as the preferred RCO. This is followed by D_v, "Dismantling of cargo tanks' inert gas branch valves during vessel's dry-docking and verify its integrity" and Pc_v, "Periodical checking of the cargo tanks' inert gas branch valves". The last RCO is T_f, "Continuous training and familiarisation of crew onboard oil tankers to be conducted to emphasise the significance of proper use of cargo tanks' inert gas branch valves". The apparent distance between C_i values of G_d and T_f, compared to D_v and Pc_v shows that implementation of the G_d could achieve a better result than T_f to overcome '*Carina*' incident.

7.8 Discussions

The proposed integrated AHP and fuzzy TOPSIS model could be applied along with the developed extended CREAM framework to select an appropriate RCO. The presented case study concentrated on a maritime incident/accident, however the proposed model could be easily adapted and used in other industries with appropriate modifications in CREAM classification schemes. Hence, application of the proposed model could provide a transparent tool for reducing human errors in industrial environments. An AHP approach of expert judgment is applied to obtain relative weights of importance of criteria of the CBA elements. Given the advantages of both, AHP and fuzzy TOPSIS, the proposed model provides a reliable means of determining an appropriate selection of RCOs. Additionally, the innovative proposed model has been demonstrated by a case study and partially validated using a sensitivity analysis. The full validation of this model is possible provided more time is given for the model to be used and tested rigorously by various stakeholders in the maritime industry and other industries. The significance of the proposed model is that it could assist decision makers to determine an ideal RCO in terms of overcoming the root cause of an incident/accident effectively.

As a result, actions can be taken to reduce human errors within a management system, efficiently preventing the risk of a similar incident/accident occurring in the future.

7.9 Conclusion

A novel integrated AHP and fuzzy TOPSIS model to determine an appropriate selection of RCO in CREAM is proposed in this chapter. An AHP method is used to determine the weight of each criterion of the CBA element derived from a comprehensive qualitative analysis of CREAM. Then a fuzzy TOPSIS method is used to determine the ranking of the RCOs. The integration of AHP and fuzzy TOPSIS approaches can assist decision makers to select an appropriate RCO when an incident/accident investigation is carried out. The proposed model can work together with the developed extended CREAM framework to select an appropriate RCO, which can be adapted and used in other transportation systems and industrial fields such as the chemical, gas and oil industries. Finally, this approach of using an integrated AHP and fuzzy TOPSIS in CREAM and in selecting an RCO can assist in HRA, resulting in the reduction of human errors in industrial environments.

Chapter 8

Conclusions and Further Research

Summary

This chapter summarises the results of the research. The themes for which further efforts are required in order to improve the developed subject matter in the research are outlined. The limitations of the research are elicited.

8.1 Conclusions

In the preceding chapters, the various technical models involved in the development of the CREAM have been outlined in detail. As a whole, the research has provided a comprehensive HRA framework supplemented with tools to support it. This chapter provides the main conclusions of this research study, which can be summarised as follows:

i). A generic oil tanker, to provide means of risk factors to be taken into account while performing risk assessment for an oil tanker, is produced in Chapter 3. A similar generic framework can be further expanded emphasising the navigation bridge and cargo control room.

ii). A newly developed HRA to facilitate a FSA framework will provide comprehensive fundamental information and development of the application of HRA in an incident/accident investigation. The innovative framework addresses the human factors, which are known to be the most important contributors to the causation and avoidance of an incident/accident. The proposed framework can be applied by principal stakeholders in the shipping industry in general and in the management of oil tankers in particular, to continuously improve the shipboard operation to prevent oil spills. In addition, continuous application of this approach would further refine it and, subsequently, would improve the decisions made by the tanker owners, leading to a safer oil tanker shipping community. One of the ideal ways of preventing oil spills by oil tankers is by immolating the system approach, by anticipating the worst and equipping a ship's crew members to deal with it at all levels of the organisation within a shipboard management. This can be further accentuated by implementing a safety culture within the organisation in which the crewmembers' pursuit of safety is not so much about preventing isolated human failures or technical failures, but more towards making the organisation as robust as practicable in order to manage and minimise its human operational hazards.

iii). The proposed innovative advanced CREAM framework provides a complete solution to HRA. It is significant for the need to find ways to analyse human error and to provide a good solution in order to prevent reoccurrence of an investigated incident/accident. This research would change the perspective of an incident/accident investigation from merely finding the root causes of an incident/accident to providing a complete solution to the investigation to prevent reoccurrence of a similar incident/accident in the future. The advanced CREAM can be easily assimilated into a simulator to be used as a third generation HRA method. Hence, the new advanced CREAM framework, which caters to the need to find the root causes of an incident/accident along with providing a solution to overcome the accident/incident, subsequently providing quantification of HRA, can be established as adding to the frontier of knowledge in a way that has not been done before.

iv). The developed pioneer approach of using a DEMATEL model, which illustrates and allows for a comprehensive comprehension of relationships and interdependencies of CPCs, will reduce the existing gap left in CREAM research studies in terms of understanding of the CPCs. Furthermore, the proposed model can be tailored to recognise and incorporate the relationships and interdependencies among human factor variables involved in other transportation systems and industrial fields, such as the chemical, gas and oil industries. A better understanding of the relationships among the human factor variables involved in causing an incident/accident can facilitate a reduction in human error.

v). The research has also introduced a new approach to compute human reliability, using a combined AHP and fuzzy logic approach, which is very much lacking in the maritime industry, and at the same time overcomes the existing fallacy of making the assumption that the CPCs are all of equal importance which is not in fact the case. Additionally, the proposed model also facilitates in dealing with limitation of availability of data in the maritime domain and, the uncertainty and complexity that exist in the quantitative analysis of human reliabilities. Moreover, the proposed model can easily be modified to other transportation systems and industrial fields, and enhance HRA data in the related fields.

vi). Finally, this research has proposed an innovative integrated AHP and fuzzy TOPSIS model to select an appropriate RCO to supplement the advanced CREAM framework to facilitate an incident/accident investigation. Additionally, with minor modifications, the proposed model can also be used in the generic FSA framework to determine an ideal RCO.

vii). The contribution of this research from the practical aspect of the maritime industry is that it would facilitate the effective investigation of an oil tanker incident/accident. Additionally, a similar advanced CREAM framework can be utilised for other industries by modifying classification schemes in the CREAM to suit the industry concerned.

Most of the HRA research had been carried out in the nuclear, chemical, oil, gas and aviation industries. The research has added to the frontier of knowledge in a way that has not been done before by concentrating on the maritime domain to overcome the present limited nature of similar research in the maritime industry. The prime audience of this research is obviously maritime accident investigators however the research findings and conclusions are of interest to a wider audience, including maritime researchers, other maritime safety policy makers and regulators, and other stakeholders in the shipping industry at large. The entire research has made a reasonable contribution to pushing forward the frontier of knowledge and has provided a sensible contribution to the practical aspect of the maritime industry. Nevertheless, with a judicious number of modifications, the outcome of this research can be assimilated for use in other transportation systems and industrial fields, such as the chemical, gas and oil industries.

8.2 Limitations of the Research

The research is focused on one of the second generation HRA methods, CREAM, to ensure an extensive detailed coverage. The whole research is solely focused on maritime operations, which results in changes made in classification tables of CREAM that are limited to maritime use only. The characteristic of the proposed human reliability quantification model using a combined AHP and fuzzy logic approach requires a good qualitative analysis to obtain a detailed tabulated CPC along with the model's utilisation of linguistic terms, which will result in the need for experienced HRA analysts. The integrated AHP and fuzzy TOPSIS model to determine the selection of an appropriate RCO by taking subjective judgments of decision makers into consideration in CREAM involves a complex quantification method using fuzzy TOPSIS. An additional feature of decision support is that all the proposed models require expert judgment and evaluation of data, meaning that personnel who are well experienced in the related field are needed. Furthermore, qualitative and quantitative assessment approaches were utilised in this research to attain larger means of input data for the technical models. The use of both quantitative and qualitative data could facilitate in expanding the scope of a research. In addition, it can provide means to offset weakness that might appear if either one approach was performed in the research.

8.3 Further Research

The areas that can be further developed are as follows:

i). The advancement of shipping management resulted in an increased number of maritime base training and research simulators. Simulator based studies can be conducted to perform qualitative and quantitative analyses of HRA. Structured research studies specifically devised for collecting data available for use in HRA can be carried out. The proposed advanced CREAM framework can be designed as computer software and used in maritime simulators for HRA purposes, which can contribute to an increase in maritime failure data focusing on human error.

ii). More research studies can be carried out to develop the present classification schemes of CREAM to cater specifically for the maritime domain, especially for the navigation bridge, cargo control room and engine room. Additionally, more work can be carried out to develop comprehensive classification schemes of CREAM for various types of vessels, including containerships, gas carriers, bulk carriers, car carriers and reefers.

iii). All the proposed models were partially validated hence the HRA validation exercises in this research need to undergo rigorous testing and can be further developed. The validation practices will further refine the methods and increase the credibility and applicability of HRA overall.

iv). Further attempts to develop the proposed approach using a DEMATEL model can be made by incorporating an AHP technique. An AHP can be used to determine weights of importance of the CPCs and be applied to the DEMATEL model to ascertain constructively the CPCs that play important roles in causing an incident/accident.

v). Fuzzy logic theory can facilitate addressing qualitative information in investigating a maritime incident/accident. Hence, the fuzzy approach can be utilised to perform a pairwise comparison in terms of the influence and direction among the CPCs in the proposed DEMATEL model, allowing for the ambiguity of expert judgment to be taken into consideration rationally.

8.4 Applicability of Research to Other Industries.

This research as a pioneer work in developing and applying advanced techniques to improve the generic CREAM in oil tanker operations establishes a foundation for future effort to improve the use of CREAM in other industries. All the proposed models in the research can be modified to be used for other industries. An example of the utilisation of the proposed DEMATEL model in business environment can be described as follows. The relationships and interdependencies among the departments in a company can be studied using the DEMATEL model to raise the productivity of the human resources. This can be performed by illustrating the causal diagram using the individuals in each department instead of the CPCs. Recommendations can be made on the selected individuals that are required to be sent for further management trainings based on the outcome of the causal diagram.

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Appendix I

Elicitation of Expert Judgment (General)

I.1 Description of Common Performance Conditions (CPCs)

Detailed descriptions of the nine CPC functions are as follows:

i). Adequacy of Shipboard Organisation (ASO)

This CPC describes the characteristic and responsibilities of crew onboard ships, additional support, communication systems, Safety Management Systems (SMS), instructions and guidelines in carrying out the activities resulting in initiating events of an incident.

ii). Shipboard Working Condition (SWC)

This CPC includes the nature of the physical working conditions onboard ships including ambient lighting, glare on screens, noise from alarms and any interruption from carrying out relevant tasks, etc.

iii). Adequacy of Man Machine Interface and Shipboard Operational Support (MMI)

This CPC consists of the information available on control panels, navigation bridge, cargo control room, engine control room and shipboard operational support provided by specifically designed decision aids such as marine navigation equipments, cargo operation and engine room instruments. Furthermore, these CPC requires thorough analysis to be conducted due to the increased automation in shipboard operations.

iv). Availability of Plans/Procedures (APP)

This CPC is used to match the existing operating and emergency instructions and procedures in carrying out ship operations.

v). Number of Simultaneous Goals (NSG)

This CPC describes the number of tasks a crew is required to carry out at the same time.

vi). Available Time (QAT)

This CPC refers to the time available to carry out a task competently resulting in a reasonable outcome.

vii). Time of day (Circadian Rhythm) (CRT)

This CPC relates to the time of the day or night when the task is carried out. Emphasis lies in how the crew can get well adapted to the current time. Examples are the nature of four hourly of navigation bridge and engine room watch keeping sequence.

viii). Adequacy of Shipboard Training and Preparation (ASP)

This CPC describes the quality of training provided to the crew in carrying out their routine tasks onboard ship. It includes familiarisation training and refreshers' courses to new joiners and experienced crew respectively within the shipboard management.

ix). Shipboard Crew Collaboration Quality (SCQ)

This CPC relates to the efficient manner in which crew works among them to complete a task efficiently onboard ship.

I.2 Chronicle of 'Prestige'

On November 13, 2002, *'Prestige'*, a 26 years old Bahamian registered and American Bureau of Shipping (ABS) classed single hull tanker, carrying 77 000 tonnes of heavy oil developed a substantial starboard list. She was underway in heavy seas and high winds in the region of Cape Finisterre, between 25 to 30 nautical miles, off the coast of Galicia in the northwest of Spain (ABS, 2003). A large crack was found in the starboard side of the hull. Vessel lost her main propulsion due to list and began to drift. Twenty four out of twenty seven crewmembers were evacuated by helicopter from the Spanish authority. The remaining onboard, Master, Chief Engineer and Chief Officer managed to counter flood port side ballast tanks and reduced the list to about 3 degrees starboard list. The vessel, however, was still adrift. On November 14, 2003, SMIT, a Dutch salvage company, took control of the vessel upon a request from *'Prestige'* owner and insurer. Two of the SMIT's tugs, the Rio De Vigo and Sertosa 32 with difficulty managed to secure towlines onboard *'Prestige'*. The ship was towed out to sea into heavy weather away from Spanish coast. Meanwhile, discussions were going on to find a safe haven for the vessel to lighter its cargo to another vessel, the condition however, deteriorated onboard. Consequently, *'Prestige'* structure gave away and collapsed; subsequently the vessel broke into two and sank about 133 nautical miles off the coast of Spain on November 19, 2002.

I.3 Case Study of *'Prestige'*

I.3.1

Based on the *'Prestige'* incident, please fill the blank columns in Table I.1 with a scale within one (1) to nine (9) with reference to Table I.2. A pairwise comparison should be made by row. An example of ASO compared to SWC is 5, followed by ASO compared to MMI as 3, etc. Please ensure the consistency check results in less than 0.1. On the Excel spreadsheet, protected cells with formula that shows the consistency value was provided.

Table I.1 Judgment Matrix for Pairwise Comparison of CPCs

CPC	ASO	SWC	MMI	APP	NSG	QAT	CRT	ASP	SCQ
ASO	1								
SWC	-	1							
MMI	-	-	1						
APP	-	-	-	1					
NSG	-	-	-	-	1				
QAT	-	-	-	-	-	1			
CRT	-	-	-	-	-	-	1		
ASP	-	-	-	-	-	-	-	1	
SCQ	-	-	-	-	-	-	-	-	1

Table I.2 The Fundamental CPC Scale for Expert Judgment

Scale	Linguistic Influence to corresponding CPC	Description
1	Equal	Both of the compared CPCs contribute equally to the incident
2	Between Equal and Moderate	Both of the compared CPCs contribute between scale 1 and 3 to the incident
3	Moderate	Experience and judgment favor more towards one of the CPC over another
4	Between Moderate and	Both of the compared CPCs contribute

	Strong	between scale 3 and 5 to the incident
5	Strong	Experience and judgment strongly favor one CPC over another
6	Between Strong and Very Strong	Both of the compared CPCs contribute between scale 5 and 7 to the incident
7	Very Strong	A CPC is favored and dominates very strongly over another
8	Between Very Strong and Extreme	Both of the compared CPCs contribute between scale 7 and 9 to the incident
9	Extreme	An evidence of one CPC favoring at the highest order to another CPC appears

I.3.2

Based on the 'Prestige' incident, please fill the blank columns in Table I.3 with TWO linguistic terms AND the corresponding scales of membership degree with reference to the Table I.4. A triangular membership function is adopted to simplify the defuzzification of each linguistic term of the nine CPCs. The membership function for each linguistic term of a CPC is evaluated within its limits on an arbitrary scale of 0 to 1. Description of evaluation section was provided to assist you to recall the incident. An example of CPC linguistic term for an ASO can be evaluated as 0.8 Inefficient and 0.2 Efficient.

Table I.3 The CPCs for '*Prestige*' Incident

CPC	Description of Evaluation	CPC Linguistic Terms by Expert Judgment
ASO	Failure of getting the vessel to a safe haven do reflects reasonable level of inefficiency in management	
SWC	Rough weather does not provide reasonably well condition to deal with the incident	
MMI	Shipboard operation was reasonably carried out to overcome the emergency listing of the vessel	
APP	Vessel had the standard contingency plan for quick action to alleviate the flooding	
NSG	It is the case for any emergency situation in general	

QAT	Quick action to get the vessel to safe haven is vital due to the encountered rough weather	
CRT	Time of the day is not relevant for the case	
ASP	Crew onboard are qualified and had received standard training as required by STCW 1995	
SCQ	Crew had not responded well under stress	

Table I.4 The Parameters and Scopes of Linguistic Terms of CPCs

CPC	Linguistic Terms Membership Labels and Its Scopes (%)			
ASO	Very Efficient	Efficient	Inefficient	Deficient
	0 - 25	10 - 60	40 - 90	70 - 100
SWC	Advantages	Compatible	Incompatible	
	0 - 30	20 - 80	70 - 100	
MMI	Supportive	Adequate	Tolerable	Inappropriate
	0 - 25	10 - 60	40 - 90	75 - 100
APP	Appropriate	Acceptable	Inappropriate	
	0 - 30	20 - 80	70 - 100	
NSG	Less than actual capacity	Matching current capacity	More than actual capacity	
	0 - 30	20 - 80	70 - 100	
QAT	Adequate	Temporarily inadequate	Continuously inadequate	
	0 - 30	20 - 80	70 - 100	
CRT	Night time(unadjusted)	Day time(adjusted)	Night time(adjusted)	
	0 - 30	20 - 80	70 - 100	
ASP	Adequate with vast experience	Adequate with limited experience	Inadequate experience	
	0 - 30	20 - 80	70 - 100	
SCQ	Very Efficient	Efficient	Inefficient	Deficient
	0 - 25	10 - 60	40 - 90	70 - 100

I.3.3

Based on the 'Prestige' incident, please fill the blank columns in Table I.5 with your expert judgment of the relative importance and influence among the CPCs' values with reference to the fundamental CPC scale provided in Table I.6. Similarly to *I.3.1*, pairwise comparison should be made by row.

Table I.5 Judgment Matrix for Pairwise Comparison for Importance and Influence of CPCs

CPCs	SWC	ASO	MMI	QAT	CRT	ASP
SWC	0					
ASO		0				
MMI			0			
QAT				0		
CRT					0	
ASP						0

Table 1.6 The Fundamental CPCs' Scale for Expert Judgment

Scale	Linguistic Influence to corresponding CPCs
0	No Influence
1	Low Influence
2	High Influence
3	Very High Influence

I.4 Chronicle of 'Carina'

M.T. CARINA, an American Bureau of Shipping (ABS) classed double hull tanker of 16 years old was discharging crude oil at one of the US Gulf of Mexico oil terminal. While the vessel was discharging in daytime, it was found that two branches of cargo tanks inert gas valves were in a closed position. The presence of inert gas inside the cargo tank ensures that the cargo tank atmosphere is retained at a lesser percentage of oxygen content to prevent any combustion that could lead to tank explosion. Therefore, discharging crude oil without having a positive supply of inert gas could result in cargo tank to collapse and subsequently results with an explosion. It was found during routine deck cargo watch that both inert gas valves of four wing cargo tanks were in a closed position. Upon seeing the status, the deck cargo watch keepers, immediately, opened the valves.

I.5 Case Study of 'Carina'

I.5.1

Based on the *'Carina'* incident, please fill the blank columns in Table I.7 with a linguistic scale within one (1) to nine (9) with reference to Table I.8. Please ensure the consistency check results in less than 0.1. Extra blanks columns are provided for you to add new criterion. On the Excel spreadsheet, protected cells with formula that shows the consistency value was provided along with abbreviation definitions which can be accessed by bringing the cursor towards the terms.

Table I.7 The Judgment Matrix for Pairwise Comparison for Importance among the Criteria

Criteria	C_F	T_E	E_C	L_F		
C_F	1					
T_E	-	1				
E_C	-	-	1			
L_F	-	-	-	1		
	-	-	-	-	1	

The abbreviations used on Table 1.7 are listed as follows:

a). C_F – Cost to implement the selected RCO.

b). T_E – Time taken to complete the selected RCO.

c). E_C – Efforts required to implement the selected RCO.

d). L_F – Life span of the selected RCO.

Table I.8 The Fundamental Criteria Scale for Expert Judgment

Scale	Linguistic influence to corresponding criteria	Description
1	Equal	Both of the compared criteria are equally important
2	Between Equal and Moderate	Both of the compared criteria contribute between scale 1 and 3 to the objective
3	Moderate	Experience and judgment favor more towards one of the criterion over another
4	Between Moderate and Strong	Both of the compared criteria contribute between scale 3 and 5 to the objective
5	Strong	Experience and judgment strongly favor one criteria over another
6	Between Strong and Very Strong	Both of the compared criteria contribute between scale 5 and 7 to the objective
7	Very Strong	A criterion is favored and dominates very strongly over another
8	Between Very Strong and Extreme	Both of the compared criteria contribute between scale 7 and 9 to the objective
9	Extreme	An evidence of one criterion favoring at the highest order to another criterion appears

I.5.2

Based on the '*Carina*' incident, please fill the blank columns in Table I.9 with your expert judgment of the relative importance among the criteria and the RCOs with reference to Table I.10. Extra blank columns are provided to allow you to add new criterion.

Table I.9 The Judgment Matrix for Decision Matrix of RCOs/Criteria

Criteria / RCOs	C_F	T_E	E_C	L_F		
Pc_v						
D_v						
T_f						
G_d						

The abbreviations used on Table I.9 are listed as follows:

a). Pc_v – Periodical checking of the cargo tanks' inert gas branch valves.

b). D_v – Dismantling of cargo tanks' inert gas branch valves during vessels drydocking.

c). T_f – Continuous training and familiarization of crew onboard oil tankers to be conducted to emphasize the significance of proper use of cargo tanks' inert gas branch valves.

d). G_d - A good structural design at shipbuilding phase along with reliable locking arrangement of cargo tanks' inert gas branch valves and an appropriate means of a warning system such as an audible alarm, visual light warning signals, or the combination of the two could be provided in the cargo control room on the status of the cargo tanks' inert gas branch valves.

Table I.10 The Linguistic Terms to Determine Relative Importance of Criteria and RCOS

Linguistic terms	Abbreviation
Very Poor	VP
Poor	P
Medium Poor	MP
Fair	F
Medium Good	MG
Good	G
Very Good	VG

Appendix II
CREAM Classification Scheme

The tables in Appendix II represent the non-hierarchical CREAM classification scheme organised in causes (genotypes) and symptoms (phenotypes). The purpose of presenting these tables is to provide an account of how erroneous action can occur by constructing a path of probable antecedent-consequent link, as part of an event analysis or a performance prediction. These tables are reproduced from CREAM (Hollnagel, 1998), however many of the contents are modified and added including some which have been newly developed to suit the characteristic of the maritime domain.

Table AII.1 Categories for Action at Wrong Time

General effects	Specific effects	Definition/Explanation
Timing	Too early	An action started too early, before a signal was given or the required conditions had been established. (Premature action)
	Too late	An action started too late. (Delayed action)
	Omission	An action that was not done at all. (Within the time interval allowed)
Duration	Too long	An action that continued beyond the point when it should have stopped.
	Too short	An action that was stopped before it should have been.

Table AII.2 Categories for Action of Wrong Type

General effect	Specific effects	Definition/Explanation
Force	Too little	Insufficient force.
	Too much	Surplus force, too much effort.
Distance/ Magnitude	Too far	A movement taken too far.
	Too short	A movement not taken far enough.

Speed	Too fast	Action performed too quickly, with too much speed or finished too early.
	Too slow	Action performed too slowly, with too little speed or finished too late.
Direction	Wrong direction	Movement in the wrong direction e.g. forward instead of backward or left instead of right.
	Wrong movement type	The wrong kind of movement, such as pulling a knob instead of turning it.

Table AII.3 Categories for Action at Wrong Object

General effect	Specific effect	Definition/Explanation
Wrong object	Neighbour	An object that is in physical proximity to the object that should have been used.
	Similar object	An object that is similar in appearance to the object that should have been used.
	Unrelated object	An object that is used by mistake, even though it had no obvious relation to the object that should have been used.

Table AII.4 Categories for Action in Wrong Place

General effect	Specific effect	Definition/Explanation
Sequence	Omission	An action that was not carried out. This includes in particular the omission of the last action(s) of a series.
	Jump forward	One or more actions in a sequence were skipped.

General effect	Specific effect	Definition/Explanation
	Jump backward	One or more earlier actions that have been carried out are carried out again.
	Repetition	The previous action was repeated.
	Reversal	The order of two neighbouring actions is reversed.
	Wrong action	An extraneous or irrelevant action is carried out.

Table AII.5 Categories for Observation

General consequent	Specific consequent	Definition/Explanation
Observation missed	Overlook cue/signal	A signal or an event that should have been the start of an action (sequence) is missed.
	Overlook measurement	A measurement or some information is missed, usually during a sequence of actions.
False observation	False reaction	A response is given to an incorrect stimulus or event, e.g. starting to drive when the light changes to red.
	False recognition	An event or some information is incorrectly recognised or mistaken for something else.
Wrong identification	Mistaken cue	A signal or a cue is misunderstood as something else.
	Partial identification	The identification of an event or some information is incomplete.
	Incorrect identification	The identification of an event or some information is incorrect.

Table AII.6 Categories for Interpretation

General consequent	Specific consequent	Definition/Explanation
Faulty diagnosis	Wrong diagnosis	The diagnosis of the situation or system state is incorrect.
	Incomplete diagnosis	The diagnosis of the situation or system state is incomplete.
Wrong reasoning	Induction error	Faulty reasoning involving inferences or generalisation (going from specific to general) leading to invalid results.
	Deduction error	Faulty reasoning involving deduction (going from general to specific) leading to invalid results.
	Wrong priorities	The selection among alternatives (hypotheses, explanations, interpretations) using incorrect criteria, hence leading to invalid results.
Decision error	Decision paralysis	Inability to make decision in a situation.
	Wrong decision	Making the wrong decision (typically about action alternatives).
	Partial decision	Making a decision that does not completely specify what to do, hence creating a need for further decisions to complete the course of action.
Delayed interpretation	No identification	Identification is not made in time (for appropriate action to be taken).
	Increased time pressure	Identification is not made fast enough, e.g. because the reasoning involved is difficult, leading to a time pressure.
Incorrect prediction	Unexpected state change	A state change occurred which had not been anticipated.
	Unexpected side effects	The event developed in the main as anticipated but some side effects had been overlooked.
	Process speed misjudged	The speed of development (of the system) has been misjudged so things happen either too slowly or too fast.

Table AII.7 Categories for Planning

General consequent	Specific consequent	Definition/Explanation
Inadequate plan	Incomplete plan	The plan is not complete, i.e., it does not contain all the details needed when it is carried out. This can have serious consequences later in time.
	Wrong plan	The plan is wrong, in the sense that it will not achieve its purpose.
Priority error	Wrong goal selected	The goal has been wrongly selected resulting in a non-effective plan.

Table AII.8 Categories for Temporary Person Related Functions

General Consequent	Specific Consequent	Definition/Explanation
Memory failure	Forgotten	An item or some information cannot be recalled when needed.
	Incorrect recall	Information is incorrectly recalled.
	Incomplete recall	Information is only recalled partially.
Fear	Random actions	Actions do not seem to follow any plan or principle, but rather look like trial and error.
	Action freeze	The person is paralysed.
Distraction	Task suspended	The performance of a task is suspended because the person's attention was caught by something else.
	Task not completed	The performance of a task is not completed because of a shift in attention.
	Goal forgotten	The person cannot remember why something is being done. This may cause a repetition of previous steps.
	Loss of orientation	The person cannot remember or think of what to do next or what happened before.
Fatigue	Delayed response	The person's response speed (physically or mentally) is reduced due to fatigue.
Performance variability	Lack of precision	Reduced precision of actions, e.g. in reaching a target value.
	Increasing	An increasing number of actions fail to achieve

	misses	their purpose.
Inattention	Signal missed	A signal or an event was missed due to inattention. This is similar to observation missed, the difference being whether it is seen as a random event or something that can be explained by a cognitive function.
Physiological stress	Many specific effects	A general condition caused by physiological stress.
Psychological stress	Many specific effects	A general condition caused by psychological stress.

Table AII.9 Categories of Permanent Person Related Functions

General consequent	Specific consequent	Definition/Explanation
Functional impairment	Deafness	Caused due to working environment i.e. noises in engine machinery room.
	Bad eyesight	Caused by ignorance of spectacle wearers whom failed to carry out continuous eye sight test to verify changes of power required on the spectacle lenses.
	Colour blindness	Results in failure of mariners to identify navigation lights correctly.
	Dyslexia/aphasia	
	Other disability	Specific physiological disabilities may be added to this group if required by the analysis.
Cognitive style	Simultaneous scanning	Search for data and information is accomplished by looking for several things at the same time such as radar observation during arrival and departure ports.
	Successive scanning	Search for data and information is accomplished by looking for one thing at a time.
	Conservative focusing	Search for data and information starts from an assumption of which the various aspects are examined one by one.
Cognitive bias	Focus gambling	Search for data or information changes in an opportunistic way rather than systematically.

Cognitive bias	Incorrect revision of probabilities	New information does not lead to a proper adjustment of probabilities – either a conservative or a too radical effect.
	Hindsight bias	Interpretation of past events is influenced by knowledge of the outcome.
	Attribution error	Events are (mistakenly) seen as being caused by specific phenomena or factors.
	Illusion of control	Person mistakenly believes that the chosen actions control the developments in the systems.
	Confirmation of bias	Search for data or information is restricted to that which will confirm current assumptions.
	Hypothesis fixation	Search for information and action alternatives is constrained by a strong hypothesis about what the current problem is.

Table AII.10 Categories of Equipment Failure

General consequent	Specific consequent	Definition of explanation.
Equipment failure Navigation bridge	Radar joystick	A radar joystick stuck and not functioning.
	Rudder indicator light	Rudder indicator light failure.
Cargo control room	Cargo valves indicator	Cargo valves open/shut indicator failure.
	Ullage indicator	Cargo ullage monitoring indicator failure.
Engine room	Speed up/slow down	The speed of the process changes significantly.
	Release	Uncontrolled release or matter or energy that causes other equipment to fail.
Software fault	Performance slow down	The performance of the system slows down. This can in particular be critical for command and control.

Software fault	Information delays	There are delays in the transmission of information, hence in the efficiency of communication, both within and between systems.
	Command queues	Commands or actions are not being carried out because the system is unstable, but are (presumably) stacked.
	Information not available	Information is not available due to software or other problems.

Table AII.11 Categories for Procedures

General consequent	Specific consequent	Definition/Explanation
Inadequate procedure	Ambiguous text	The text of the procedure is ambiguous and open to interpretation. The logic of the procedure may be unclear.
	Incomplete text	The descriptions given by the procedure are incomplete, and assume that the user has specific additional knowledge.
	Incorrect text	The descriptions of the procedure are factually incorrect.
	Mismatch to actual equipment	The procedure text does not match the physical reality, for example due to equipment upgrades.

Table AII.12 Categories for Temporary Interface Problems

General consequent	Specific consequent	Definition/Explanation
Access limitations	Item cannot be reached	An item is permanently out of reach, e.g. too high, too low or too far away from the operators working position.
	Item cannot be found	An item is permanently difficult to find. Infrequently used items that are inappropriately labelled fall into this category.
Ambiguous information	Position mismatch	There is a mismatch between the indicated positions of an item and the actual positions, e.g. controls have unusual movements.

	Coding mismatch	There is a mismatch in coding, e.g. in the use of colour or shape. This may lead to difficulties in the use of equipment.
Incomplete information	Poor continuity	The information provided by the interface is incomplete, e.g. error messages, directions, warnings, etc.

Table AII.13 Categories for Permanent Interface Problems

General consequent	Specific consequent	Definition/Explanation
Access problems	Item cannot be reached	An item, e.g. a control, cannot be reached, for instance because it is hidden by something or due to a change in the operator's working position.
	Item cannot be found	An item, information or control cannot be located when it is needed or it is temporarily unavailable.
Mislabelling	Incorrect information	The labelling or identification of an item is not correct.
	Ambiguous identification	The labelling or identification of an item is open to interpretation.
	Language error	The labelling or identification of an item is incorrectly formulated, or is written in an unfamiliar foreign language.

Table AII.14 Categories for Communication

General consequent	Specific consequent	Definition/Explanation
Communication failure	Message not received	The message or the transmission of information did not reach the receiver. This could be due to incorrect address or failure of communication channels.
	Message misunderstood	The message was received but it was misunderstood. The misunderstanding was, however, not deliberate.
Missing information	No information	Information is not being given when it was needed or requested, e.g. missing feedback.
	Incorrect information	Incorrect or incomplete information was given.
	Misunderstanding	There is misunderstanding between sender and receiver about the purpose, form or structure of the communication.

Table AII.15 Categories for Organisation

General consequent	Specific consequent	Definition/Explanation
Maintenance failure	Equipment not operational	Equipment (controls, resources) does not function or is not available due to missing or inappropriate management.
	Indicators not working	Indications (lights, signals) do not work properly due to inappropriate maintenance.

Inadequate quality control	Inadequate procedures	Equipment/function is not adequate due to insufficient quality control.
	Inadequate reserves	Lack of resources or supplies (e.g. inventory, back up equipment, etc.)
Management problems	Unclear roles	People in organisation are not clear about their roles and duties.
	Dilution of responsibility	There is not clear distribution of responsibility; this is particularly important in abnormal situations.
	Unclear line of command	The line of command is not well defined and control of the situation may be lost.
Design failure	Anthropometric mismatch	The working environment is inadequate, and the cause is clearly a design failure.
	Inadequate MMI	The interface is inadequate, and the cause is clearly a design failure.
Inadequate task allocation	Inadequate managerial rule	The organisation of work is deficient due to the lack of clear rules or principles.
	Inadequate task planning	Task planning/scheduling is deficient.
	Inadequate work procedures	Procedures for how work should be carried out are inadequate.
Social pressure	Group thinking	The individual's situation understanding is guided or controlled by the group.
	Peer pressure	Social pressure from one's peer to behave in a similar manner to peers in order to be accepted as part of a group.

Table AII.16 Categories for Training

General consequent	Specific consequent	Definition/Explanation
Insufficient skills	Performance failure	Lack of skills (practical experience) means that a task cannot be accomplished.

Insufficient skills	Equipment mishandling	Lack of skills (practical experience) means that equipment is incorrectly used.
Insufficient knowledge	Confusion	The person is not quite certain about what to do, due to lack of knowledge.
	Loss of situation awareness	The person has lost general situation awareness (understanding) due to lack of knowledge.

Table AII.17 Categories for Ambient Conditions

General consequent	Specific consequent	Definition/Explanation
Temperature	Too hot	Uncomfortably warm.
	Too cold	Uncomfortably cold.
Sound	Too loud	Noise level is too high.
	Too soft	Noise level is too low.
Humidity	Too dry	Uncomfortably dry.
	Too humid	Uncomfortably humid.
Illumination	Too bright	High luminosity, glare and reflection.
	Too dark	Low luminosity, reduced colour and contrast.
Adverse ambient conditions	Heavy ship movement	High context dependent, may coincide with some of the CPC.
Others	Vibration	Vibration dampers not in operation. Main engine running within the barred engine rpm.

Table AII.18 Categories for Working Conditions

General consequent	Specific consequent	Definition/Explanation
Excessive demand	None defined	Excessive task demands on insufficient time/resources.
Inadequate work place layout	Narrow work space	Available work space is not large enough for the required activities. This is often the case for maintenance work.
	Dangerous space	Work must be carried out in dangerous conditions, e.g. high voltage line work, radiation, unstable mass or energy storage, etc.
	Elevated work space	Work must be carried out where there is a risk of falling down.
Inadequate team support	Unclear job description	The roles within the team are not well defined or well understood.
	Inadequate communication	The distribution of work/ responsibilities within the team is not mutually agreed.
	Lack of team cohesiveness	There is little cohesiveness in the team, hence little collaboration.
Irregular working hours	Circadian rhythm effects	Shift work leading to disturbances of physiological and psychological functions (jet lag, lack of sleep, etc).

Table AII.19 General and Specific Antecedents for Error Modes

General consequent	Specific consequent		Specific antecedent
Timing/ Duration	Communication failure Faulty diagnosis Inadequate plan	Inadequate procedure Inattention Observation missed	Earlier omission Trapping error
Sequence	Access limitations	Inadequate procedure	Trapping error

	Communication failure Faulty diagnosis Inadequate plan	Inattention Memory failure Wrong identification	
Force	Communication failure Equipment failure Faulty diagnosis	Inadequate plan Inadequate procedure Observation missed	Ambiguous label Convention conflict Incorrect label
Distance/ Magnitude	Communication failure Equipment failure Faulty diagnosis	Inadequate plan Inadequate procedure Observation missed	Ambiguous label Convention conflict Incorrect label
Speed	Communication failure Distraction Equipment failure Faulty diagnosis	Inadequate plan Inadequate plan Observation missed Performance variability	None defined
Direction	Communication failure Faulty diagnosis Inadequate plan	Inadequate procedure Inattention Observation missed	Ambiguous label Convention conflict Incorrect label
Wrong object	Access problems Communication failure Wrong identification Inadequate plan	Inadequate procedure Inattention Performance variability Observation missed	Ambiguous label Incorrect label

Table AII.20 General and Specific Antecedents for Observation

General consequent	General antecedent	Specific antecedent	
Observation missed	Equipment failure Faulty diagnosis Inadequate plan Functional impairment Inattention	Information overload Multiple signals Lack of system knowledge	Noise Parallax Complacency
False observation	Fatigue Distraction	Lack of interest	
Wrong identification	Distraction Missing information Faulty diagnosis Mislabelling	Ambiguous symbol set Ambiguous signal Erroneous information	Habit, expectancy Information overload

Table AII.21 General and Specific Antecedents for Interpretation

General consequent	General antecedent	Specific antecedent	
Faulty diagnosis	Cognitive bias Wrong identification Inadequate procedure	Confusing symptoms Error in mental mode Misleading symptoms	Multiple disturbances New situation Erroneous analogy
Wrong reasoning	Cognitive bias Cognitive style	Too short planning horizon	False analogy Overgeneralization Mode error
Decision error	Fear Cognitive bias Distraction Social pressure	Lack of knowledge Mode error Shock	Stimulus overload Workload
Delayed interpretation	Inadequate procedure Equipment failure Fatigue	Indicator failure Lack of theoretical knowledge Multitasking	Slow response
Incorrect prediction	Cognitive bias Ambiguous information Incomplete information	Misinterpretation results of reading instruments wrongly due to wrong perception	

Table AII.22 General and Specific Antecedents for Planning

General consequent	General antecedent	Specific antecedent	
Inadequate plan	Distraction Memory failure Wrong reasoning Excessive demand Insufficient knowledge	Error in goal Inadequate training Model error Overlook precondition	Overlook side consequent Violation Too short planning horizon
Priority error	Faulty diagnosis Communication failure	Justifiable higher priority	Conflicting criteria

Table AII.23 General and Specific Antecedents for Temporary Person Related Functions

General consequent	General antecedent	Specific antecedent
Memory failure	Excessive demand	Day dreaming Temporary incapacitation Long time since learning Other priority
Fear	Haunting thoughts due to past failures	Earlier error Uncertainty Possible consequences
Distraction	Equipment failure Communication failure	Superior/Crew Competing task Comfort call Telephone Commotion
Fatigue	Adverse ambient conditions Irregular working hours	Exhaustion
Performance variability	Equipment failure Excessive demand Insufficient skills	Change of system character Lack of training Over enthusiasm Illness
Inattention	Adverse ambient conditions	Temporary incapacitation
Physiological stress	Adverse ambient conditions Irregular working hours	Boredom Heavy weather
Psychological stress	Mind effecting environment	Boredom Heavy weather Family problems Peer conflicts

Table AII.24 General and Specific Antecedents for Permanent Person Related Functions

General consequent	General antecedent	Specific antecedent
Functional impairment	Due to individual misperception on a matter	None defined
Cognitive style	Due to individual misperception on a matter	None defined
Cognitive bias	Due to individual misperception on a matter	Bias thoughts due to misperception

Table AII.25 General and Specific Antecedents for Equipment

General consequent	General antecedent	Specific antecedent
Equipment failure	Maintenance failure	Power failure tremor Fire external event Flooding impact/projectile
Software fault	Inadequate quality control	Poor maintenance

Table AII.26 General and Specific Antecedents for Procedures

General consequent	General antecedent	Specific antecedent
Inadequate procedure	Inadequate quality control Design failure	SMS failure

Table AII.27 General and Specific Antecedents for Temporary Interface Problems

General consequent	General antecedent	Specific antecedent
Access limitations	Equipment failure Design failure	Distance within ladder/staircase steps Temporary incapacitation Localisation problem Obstruction
Ambiguous information	Design failure	Sensor failure Incorrect coding scheme
Incomplete information	Design failure Inadequate procedure	Indicator failure Display clutter Inadequate display hardware

		Navigation Problems	Cargo operation problems

Table AII.28 General and Specific Antecedents for Permanent Interface Problems

General consequent	General antecedent	Specific antecedent
Access problems	Inadequate work place layout	Provision of only one access
Mislabelling	Inadequate work place layout Maintenance failure	Poorly planned maintenance system

Table AII.29 General and Specific Antecedents for Communication

General consequent	General antecedent	Specific antecedent	
Communication failure	Distraction Functional impairment Inattention	Noise Presentation failure	Temporary incapacitation
Missing information	Mislabelling Design failure Inadequate procedure	Hidden information Presentation failure	Incorrect language Noise

Table AII.30 General and Specific Antecedents for Organisation

General consequent	General antecedent	Specific antecedent
Maintenance failure	Inappropriate maintenance system	Cost & availability of spares
Inadequate quality control	Inadequate team support Communication failure	Ineffective audits Unskilled labour
Management problem	Communication failure	Irregular working hours Commercial pressure
Design failure	Poor research & development	Commercial pressure Motivation failure
Inadequate task allocation	Inadequate team support	None defined

Social pressure	None defined	None defined

Table AII.31 General and Specific Antecedents for Training

General consequent	General antecedent	Specific antecedent
Insufficient skills	Management problem	Failure in motivating staffs
Insufficient experience	Insufficient knowledge	Inadequate training

Table AII.32 General and Specific Antecedents for Ambient Conditions

General consequent	General antecedent	Specific antecedent
Temperature	Fatigue Distraction	Loss of concentration Dizziness
Sound	Distraction	Discomfort Anxiety Loss of hearing
Humidity	Fatigue Distraction Faulty software	Loss of concentration Dizziness
Illumination	Distraction	Loss of concentration Visual obstruction
Adverse ambient conditions	Distraction Missed observation Equipment failure	Decision error Heavy weather Poor cargo planning Faulty interpretation
Others	Equipment failure	Excessive running hours

Table AII.33 General and Specific Antecedents for Working Conditions

General consequent	General antecedent	Specific antecedent
Excessive demand	Inadequate task allocation Adverse ambient conditions	Unexpected tasks Parallel tasks Needs of officer to carry out too many tasks at the same

		time for example, during final stages of cargo operations
Inadequate work place layout	Design failure Communication failure	Small design of cargo control room
Inadequate team support	Misunderstanding among crew	Isolation of crew in their own ethnic groups
Irregular working hours	None defined	Shift work Time zone change Changing schedule

Appendix III
Total Relation Matrix and Elicitation of Expert Judgment for DEMATEL model

III.1 Total Relation Matrix

The total relation matrix can be derived from the following descriptions.

Assume the following terms:

X is the normalised direct relation matrix,

H is the indirect relation matrix,

I is the identity matrix,

O is the null matrix,

T is the total relation matrix, and

$\sum_{i=1}^{m}$ represents the total influence comprising the direct and the indirect influences.

Therefore,

$$\sum_{i=1}^{m} X^i = X + X^2 + X^3 + \ldots + X^m = X + H.$$

As the $m \rightarrow \infty$ and $X^m \rightarrow O$, the total relation matrix, T can be obtained by following equation:

$$\sum_{i=1}^{\infty} X^i = X(I - X)^{-1}$$

(Lin and Wu, 2008; Papoulis and Pillai, 2002)

III.2 Expert Judgment Evaluations for DEMATEL model

The individual expert judgment evaluations of the direct relation matrix of CPCs are provided as follows:

Expert 1

CPCs	SWC	ASO	MMI	QAT	CRT	ASP
SWC	0	2	3	1	1	2
ASO	1	0	1	3	2	3
MMI	1	1	0	1	2	1

QAT	1	2	1	0	2	3
CRT	2	1	1	1	0	1
ASP	2	2	3	2	1	0

Expert 2

CPCs	SWC	ASO	MMI	QAT	CRT	ASP
SWC	0	1	2	1	2	2
ASO	1	0	1	3	2	3
MMI	1	1	0	1	2	1
QAT	2	2	2	0	2	3
CRT	1	1	1	1	0	1
ASP	2	2	1	2	1	0

Expert 3

CPCs	SWC	ASO	MMI	QAT	CRT	ASP
SWC	0	2	2	1	1	2
ASO	1	0	1	2	2	3
MMI	1	1	0	1	2	1
QAT	1	1	1	0	2	3
CRT	1	1	1	1	0	1
ASP	2	2	1	2	1	0

Expert 4

CPCs	SWC	ASO	MMI	QAT	CRT	ASP
SWC	0	1	2	2	1	2
ASO	0	0	1	0	0	2
MMI	2	0	0	0	0	0
QAT	0	1	2	0	0	2
CRT	0	1	0	0	0	0
ASP	1	2	0	1	0	0

Appendix IV

Fuzzy Sets Representation of the Human Performance Failure Probability (HPFP) for the various CPCs' Input Variables Graphs

i). Shipboard Working Condition (SWC) CPC.

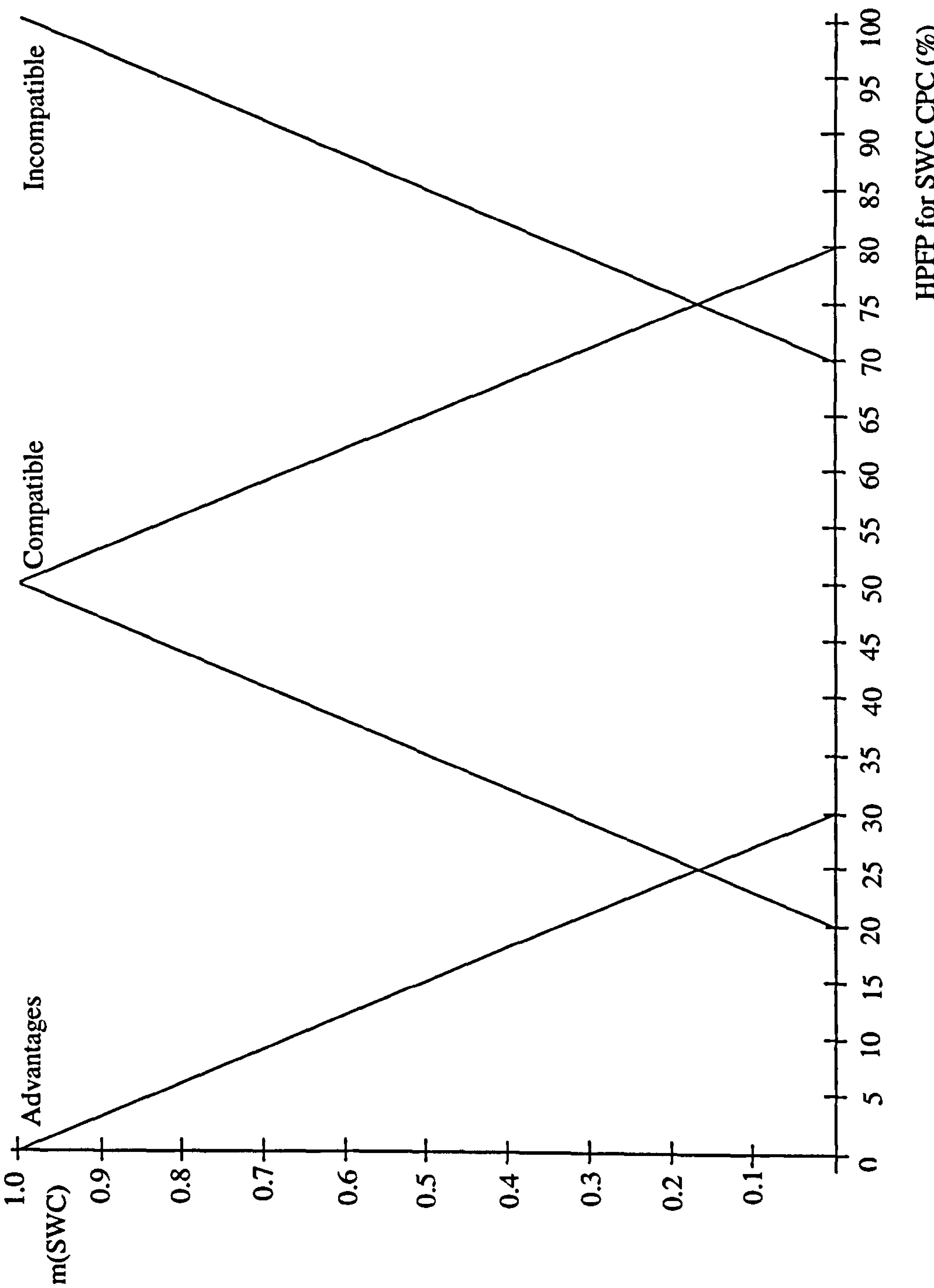

Figure AIV.1 Fuzzy Sets Representation of the HPFP for SWC Input Variables ii). Adequacy of Man Machine Interface and Shipboard Operational Support (MMI) CPC.

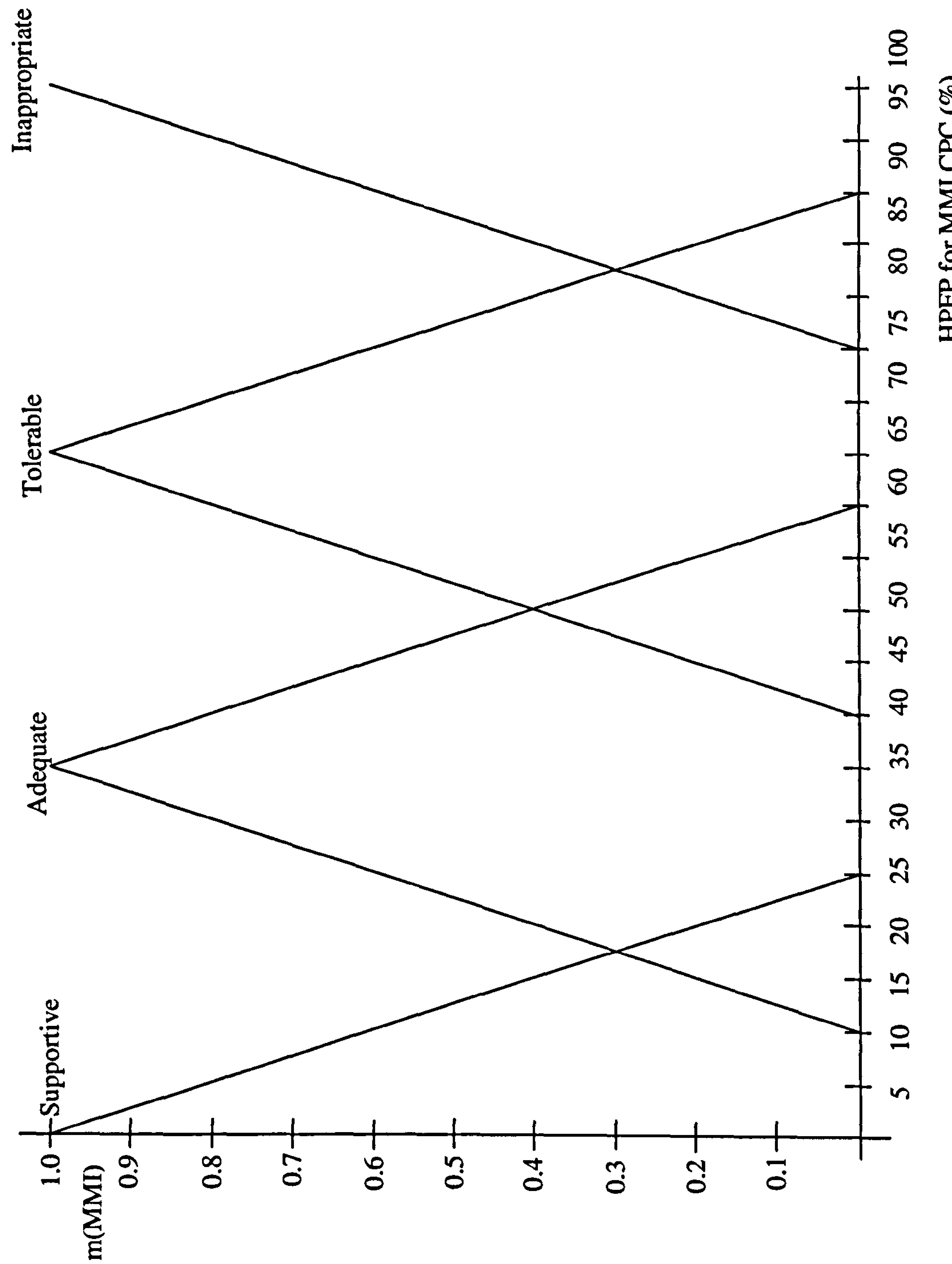

Figure AIV.2 Fuzzy Sets Representation of the HPFP for MMI Input Variables iii). Availability of Plans / Procedures (APP) CPC

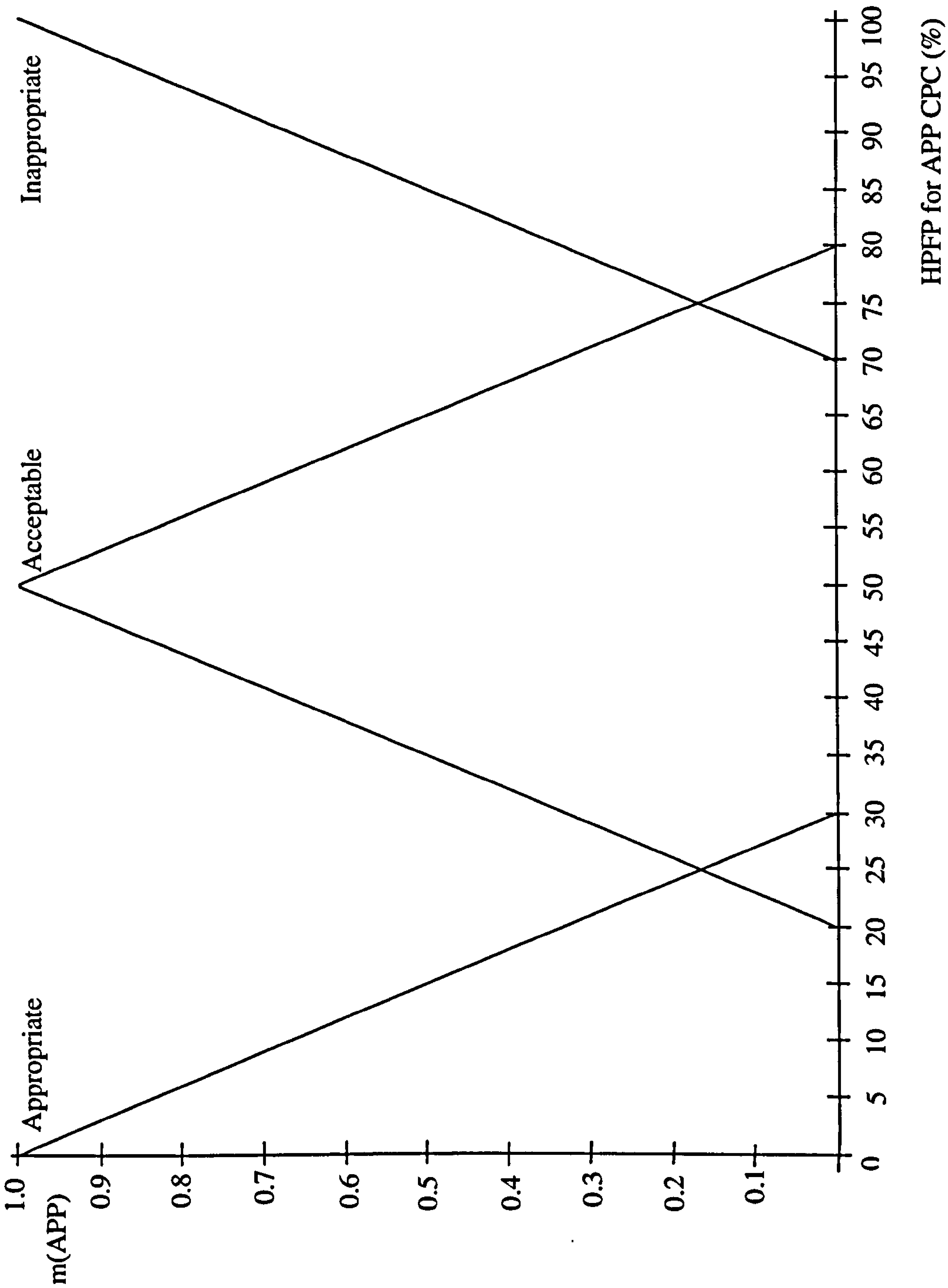

Figure AIV.3 Fuzzy Sets Representation of the HPFP for APP Input Variables iv). Number of Simultaneous Goals (NSG) CPC

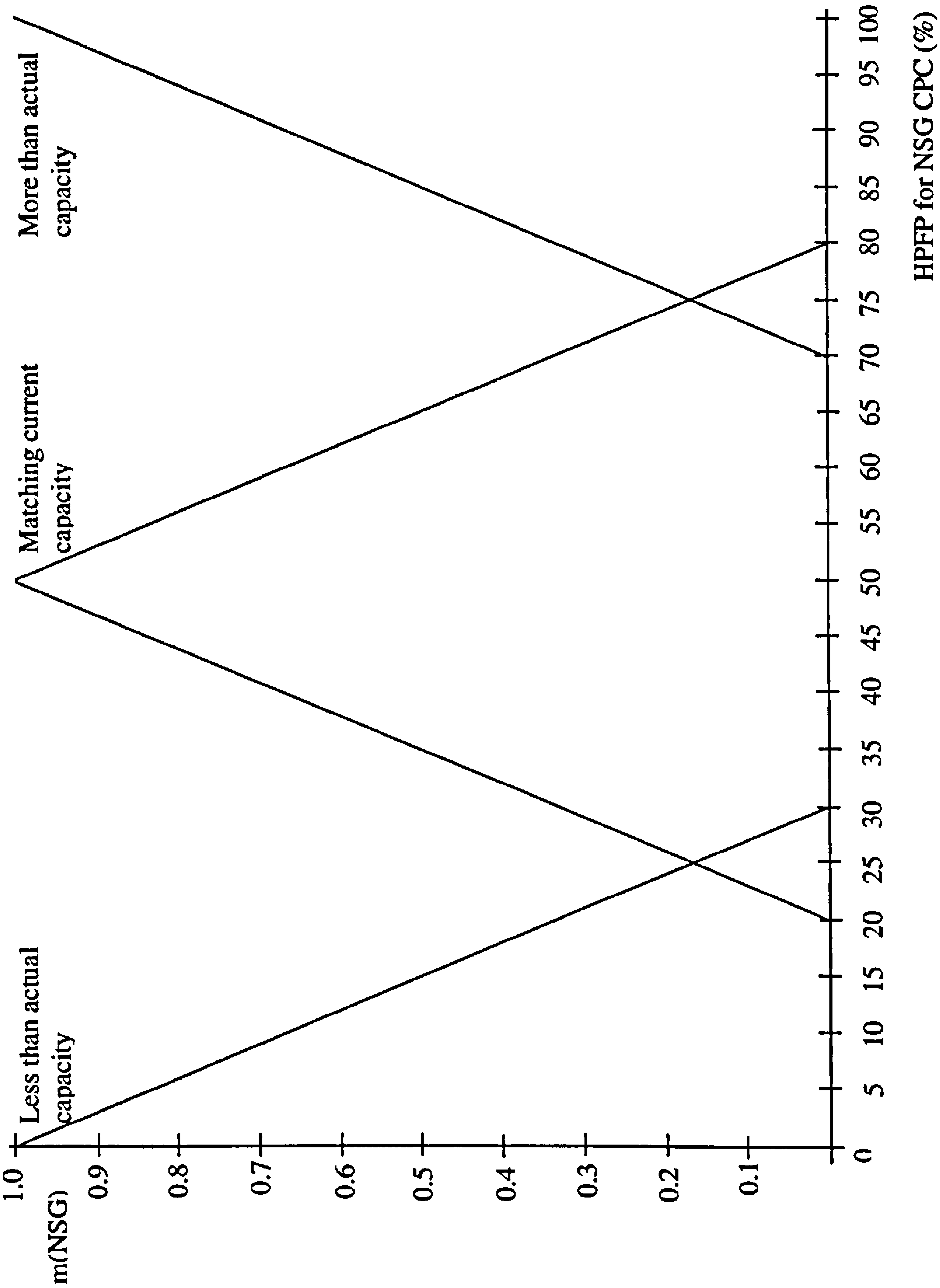

Figure AIV.4 Fuzzy Sets Representation of the HPFP for NSG Input Variables v). Available Time (QAT) CPC

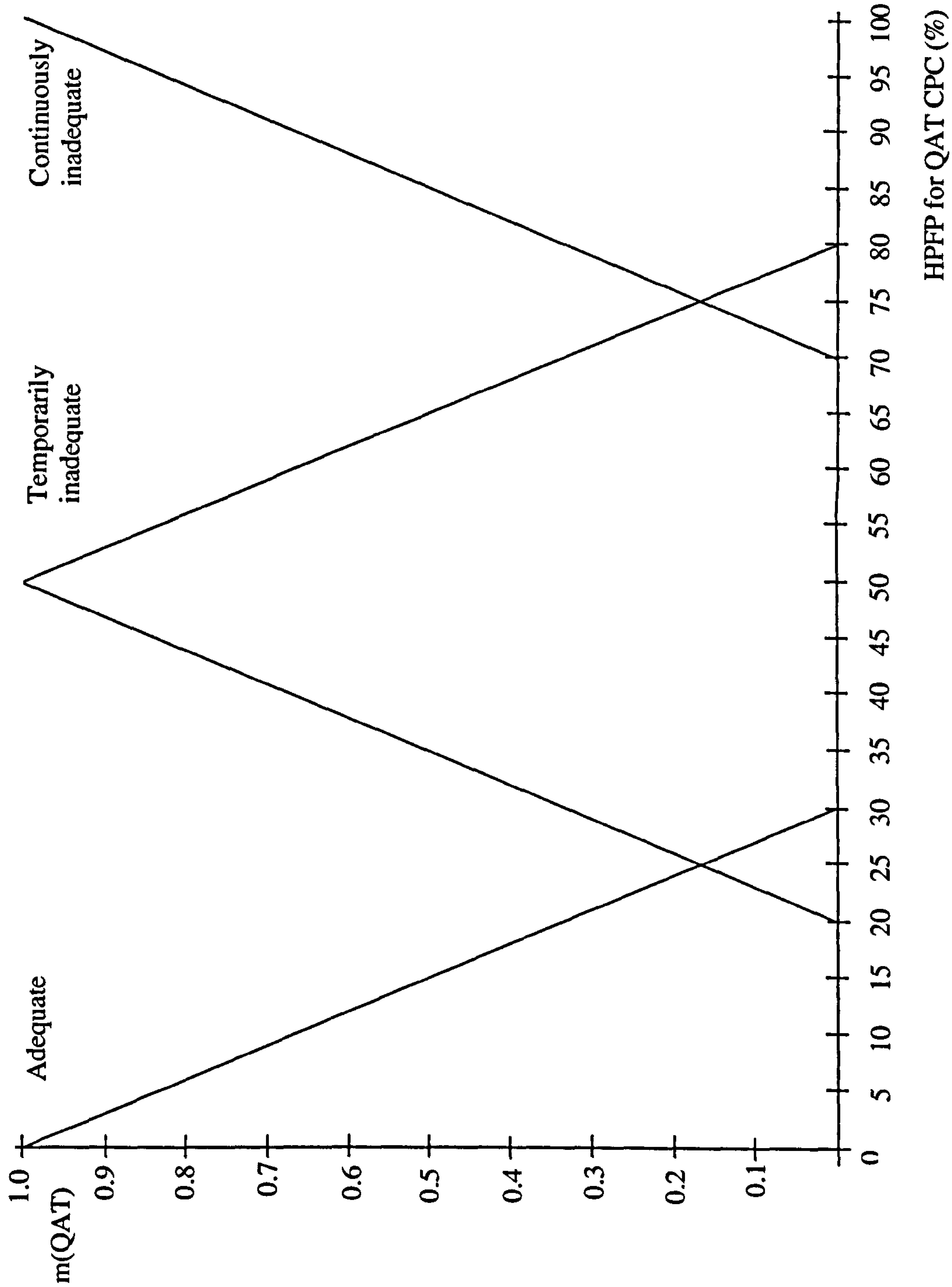

Figure AIV.5 Fuzzy Sets Representation of the HPFP for QAT Input Variables vi). Time of day (Circadian Rhythm) (CRT) CPC

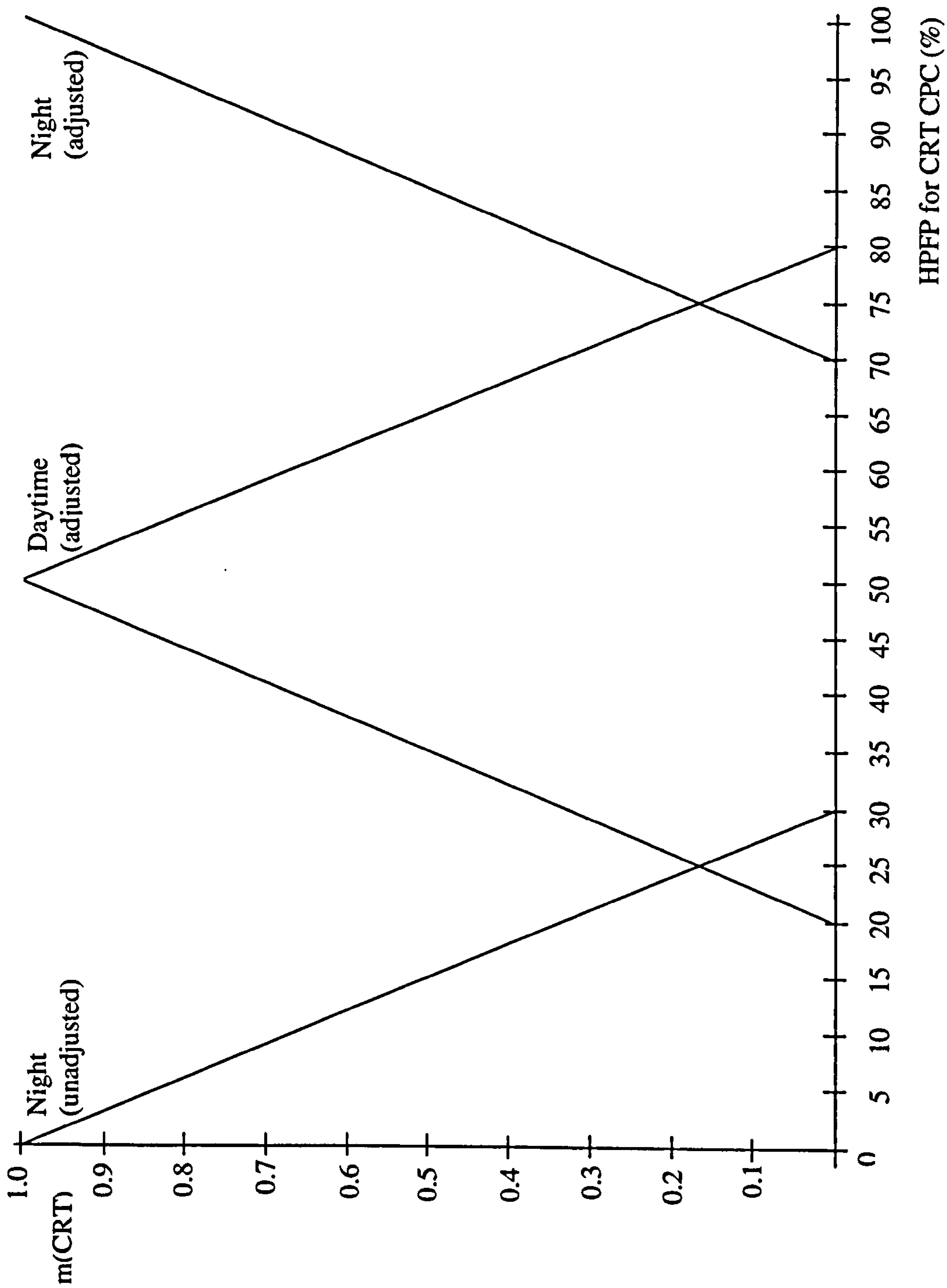

Figure AIV.6 Fuzzy Sets Representation of the HPFP for CRT Input Variables vii). Adequacy of Shipboard Training and Preparation (ASP) CPC

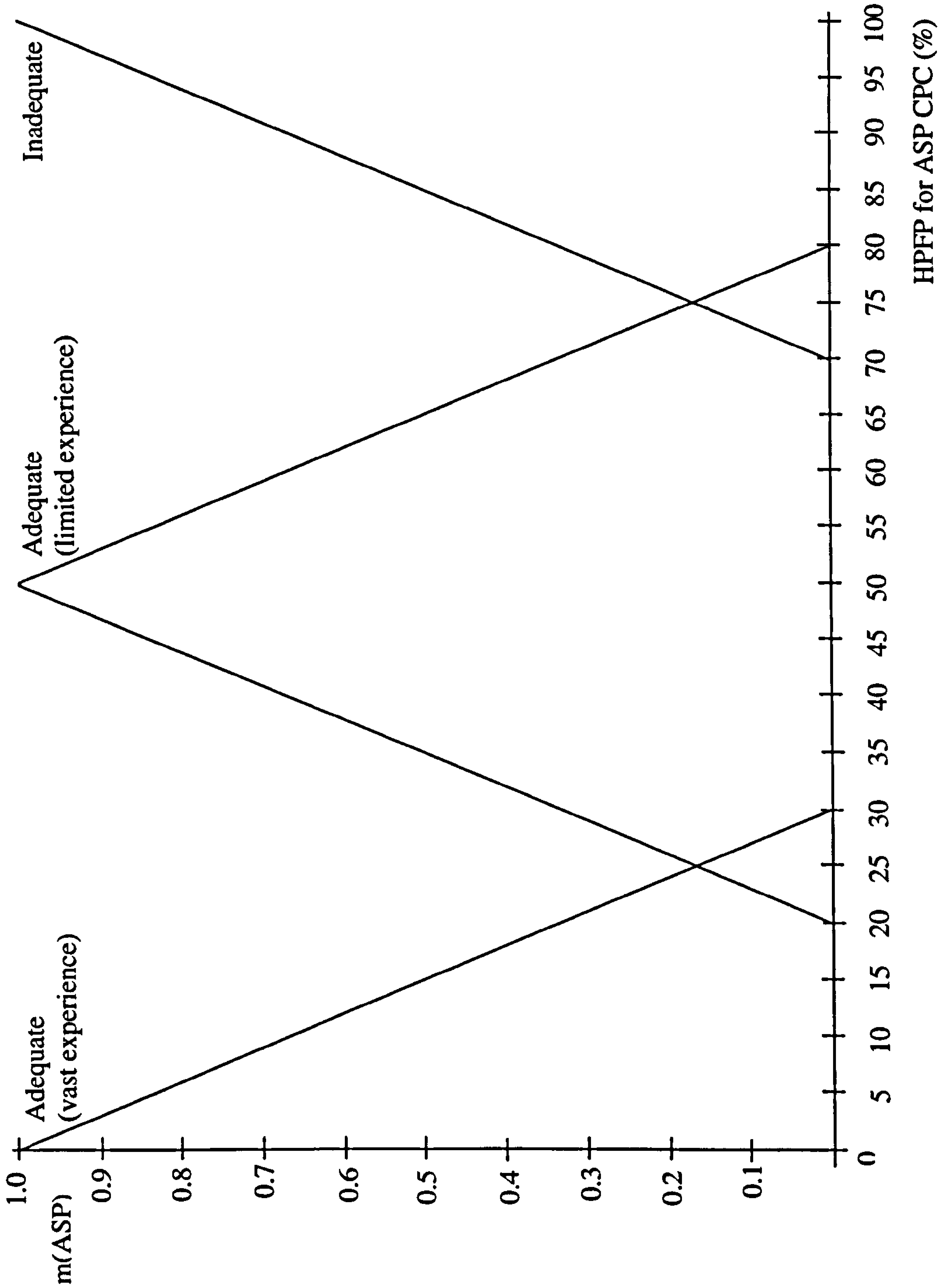

Figure AIV.7 Fuzzy Sets Representation of the HPFP for ASP Input Variables viii). Shipboard Crew Collaboration Quality (SCQ) CPC.

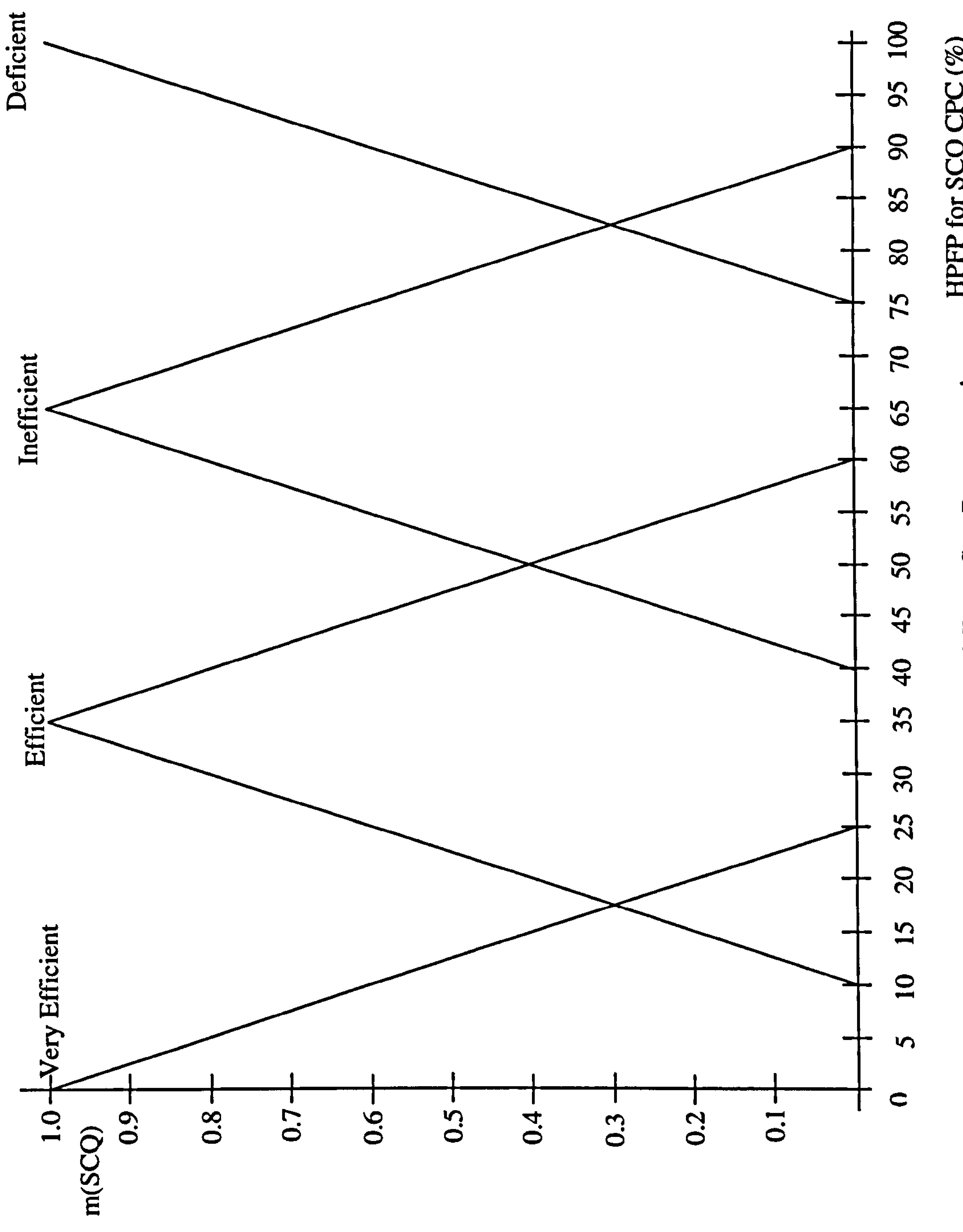

Figure AIV.8 Fuzzy Sets Representation of the HPFP for SCQ Input Variables

Appendix V

V.1 Expert Judgment Evaluation for Integrated AHP and Fuzzy TOPSIS model

V.1.1 Pairwise Comparison of Criteria Matrix

The individual expert judgment evaluations of the pairwise comparison of criteria matrix are provided as follows:

Expert 1

Criteria	C_F	T_E	E_C	L_F	$HPFP_R$
C_F	1.000	0.111	0.111	0.111	1.000
T_E	9.000	1.000	1.000	5.000	1.000
E_C	9.000	1.000	1.000	5.000	1.000
L_F	9.000	0.200	0.200	1.000	1.000
$HPFP_R$	1.000	1.000	1.000	1.000	1.000

Expert 2

Criteria	C_F	T_E	E_C	L_F	$HPFP_R$
C_F	1.000	1.000	1.000	1.000	1.000
T_E	1.000	1.000	2.000	2.000	1.000
E_C	1.000	0.500	1.000	2.000	1.000
L_F	1.000	0.500	0.500	1.000	1.000
$HPFP_R$	1.000	1.000	1.000	1.000	1.000

Expert 3

Criteria	C_F	T_E	E_C	L_F	$HPFP_R$
C_F	1.000	1.000	1.000	1.000	1.000
T_E	1.000	1.000	2.000	3.000	1.000
E_C	1.000	0.500	1.000	3.000	1.000
L_F	1.000	0.333	0.333	1.000	1.000
$HPFP_R$	1.000	1.000	1.000	1.000	1.000

Expert 4

Criteria	C_F	T_E	E_C	L_F	$HPFP_R$
C_F	1.000	1.000	2.000	2.000	1.000
T_E	1.000	1.000	2.000	0.500	1.000
E_C	0.500	0.500	1.000	0.333	1.000
L_F	0.500	2.000	3.000	1.000	1.000
$HPFP_R$	1.000	1.000	1.000	1.000	1.000

The abbreviations used are as follow:

a). C_F – Cost to implement the selected RCO.

b). T_E – Time taken to complete the selected RCO.

c). E_C – Efforts required to implement the selected RCO.

d). L_F – Lifespan of the selected RCO.

e). $HPFP_R$ – Human Performance Failure Probability reductions

V.1.2 Fuzzy Decision Matrix of RCOs/Criteria

The individual expert judgment evaluations of the pairwise comparison of criteria matrix are provided as follows:

Expert 1

Criteria / RCOs	C_F	T_E	E_C	L_F
Pc_v	VG	P	P	P
D_v	F	G	G	VP
T_f	F	MP	P	P
G_d	MP	MP	VG	VG

Expert 2

Criteria / RCOs	C_F	T_E	E_C	L_F
Pc_v	F	MP	F	F
D_v	P	G	G	VP
T_f	F	MP	P	P
G_d	P	VG	VG	VG

Expert 3

Criteria / RCOs	C_F	T_E	E_C	L_F
Pc_v	F	P	F	F
D_v	P	G	G	P
T_f	F	MP	MP	P
G_d	MP	F	VG	VG

Expert 4

Criteria / RCOs	C_F	T_E	E_C	L_F
Pc_v	G	MG	F	P
D_v	P	G	F	MG
T_f	MG	MP	MP	F
G_d	MP	MP	MP	VG

The abbreviations used are as follow:

a). C_F – Cost to implement the selected RCO.

b). T_E – Time taken to complete the selected RCO.

c). E_C – Efforts required to implement the selected RCO.

d). L_F – Lifespan of the selected RCO.

e). Pc_v – Periodical checking of the cargo tanks' inert gas branch valves.

f). D_v – Dismantling of cargo tanks' inert gas branch valves during vessel's drydocking.

g). T_f – Continuous training and familiarisation of crew onboard oil tankers to be conducted to emphasise the significance of proper use of cargo tanks' inert gas branch valves.

h). G_d – A good structural design at shipbuilding phase, along with a reliable locking arrangement of cargo tanks' inert gas branch valves and an appropriate warning system such as an audible alarm, visual light warning signals, or a combination of the two, which could be provided in the cargo control room to show the status of the cargo tanks' inert gas branch valves.

Appendix VI

Human Performance Failure Probability (HPFP) Estimations

VI.1 HPFP of 'Carina' incident ($HPFP_{Carina}$)

(i). The evaluation of CPCs for the '*Carina*' incident is illustrated in Table VI.1.

Table VI.1 The CPCs for the '*Carina*' Incident

CPCs	Description of Evaluation	CPCs Linguistic Terms by Expert Judgment
ASO	Failure of monitoring to ensure that all the cargo tanks inert gas branch valves are kept in open position during discharging cargo operations.	0.80 **Inefficient** / 0.20 Efficient
SWC	Cargo operations could distract the shipboard working condition.	0.70 **Incompatible** / 0.30 Compatible
MMI	Manual monitoring of inert gas branch valves status indicating open/ shut position can be observed.	0.80 **Tolerable** / 0.20 Adequate
APP	Lack of procedures to monitor the status of inert gas branch valves while cargo operation is in progress.	0.60 **Inappropriate** / 0.40 Acceptable
NSG	Vessel was having a vetting inspection along with discharging cargo operations.	0.70 **More than actual capacity** / 0.30 Matching current capacity
QAT	Continuous cargo operations could distract monitoring the status of inert gas branch valves.	0.60 **Continuously inadequate** / 0.40 Adequate
CRT	Time of the day is not relevant for the case.	Not relevant
ASP	Lack of training and awareness on the importance of monitoring inert gas branch valves.	0.80 **Inadequate, experience** / 0.20 Adequate, limited experience
SCQ	Inefficient crew management during cargo operations in port.	**0.60 Inefficient** / 0.40 Efficient

(ii). Pairwise comparisons of the nine CPCs to determine the relative importance among the CPCs using AHP by expert judgment were carried out using the CPC scale shown in Table 6.1. Table VI.2 illustrates the result of expert judgment pairwise comparison of the CPCs.

Table VI.2 Judgment Matrix for Pairwise Comparison of CPCs

CPC	ASO	SWC	MMI	APP	NSG	QAT	CRT	ASP	SCQ
ASO	1	2	4	2	3	4	5	6	8
SWC	1/2	1	2	3	3	3	5	5	6
MMI	1/4	1/2	1	3	3	2	3	4	7
APP	1/2	1/3	1/3	1	3	2	3	3	4
NSG	1/3	1/3	1/3	1/3	1	3	3	3	3
QAT	1/4	1/3	1/2	1/2	1/3	1	3	2	3
CRT	1/5	1/5	1/3	1/3	1/3	1/3	1	3	3
ASP	1/6	1/5	1/4	1/3	1/3	1/2	1/3	1	2
SCQ	1/8	1/6	1/7	1/4	1/3	1/3	1/3	1/2	1

(iii). Compute the weights of the nine CPCs.

The sums of each column of the reciprocal matrix of CPCs of ASO, SWC, MMI, APP, NSG, QAT, CRT, ASP and SCQ are 3.325, 5.067, 8.893, 10.750, 14.333, 16.167, 23.667, 27.500 and 37.000 respectively. The normalised relative weights of the CPC matrix for the nine CPCs are produced by dividing each element in Table VI.2 by its column sum. The normalised relative weight of each element in the pairwise comparison judgment of the CPCs is shown in Table VI.3.

Table VI.3 Judgment Matrix for Normalised Relative Weight of CPCs

CPC	ASO	SWC	MMI	APP	NSG	QAT	CRT	ASP	SCQ
ASO	0.301	0.395	0.450	0.186	0.209	0.247	0.211	0.218	0.216
SWC	0.150	0.197	0.225	0.279	0.209	0.186	0.211	0.182	0.162
MMI	0.075	0.099	0.112	0.279	0.209	0.124	0.127	0.145	0.189
APP	0.150	0.066	0.037	0.093	0.209	0.124	0.127	0.109	0.108
NSG	0.100	0.066	0.037	0.031	0.070	0.186	0.127	0.109	0.081
QAT	0.075	0.066	0.056	0.047	0.023	0.062	0.127	0.073	0.081
CRT	0.060	0.039	0.037	0.031	0.023	0.021	0.042	0.109	0.081
ASP	0.050	0.039	0.028	0.031	0.023	0.031	0.014	0.036	0.054
SCQ	0.038	0.033	0.016	0.023	0.023	0.021	0.014	0.018	0.027

From the normalised comparison CPC matrix, nine priority eigenvectors representing each CPC are computed using Equation 6.3. The relative weights of ASO, SWC, MMI, APP, NSG, QAT, CRT, ASP and SCQ CPCs are 0.270, 0.200, 0.151, 0.114, 0.090, 0.068, 0.049, 0.034 and 0.024 respectively.

(iv). Consistency validation.

A principal eigenvalue is obtained using Equation 6.4.

Principal eigenvalue, $\lambda_{max} = \frac{1}{9} \times$

$$\left\{\left[\frac{\begin{pmatrix}(0.270 \times 1.000) + (0.200 \times 2.000) + (0.151 \times 4.000) + (0.114 \times 2.000) + (0.090 \times 3.000) + \\ (0.068 \times 4.000) + (0.049 \times 5.000) + (0.034 \times 6.000) + (0.024 \times 8.000)\end{pmatrix}}{0.270}\right] + \right.$$

$$\left[\frac{\begin{pmatrix}(0.270 \times 0.500) + (0.200 \times 1.000) + (0.151 \times 2.000) + (0.114 \times 3.000) + (0.090 \times 3.000) + \\ (0.068 \times 3.000) + (0.049 \times 5.000) + (0.034 \times 5.000) + (0.024 \times 6.000)\end{pmatrix}}{0.200}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.270 \times 0.250) + (0.200 \times 0.500) + (0.151 \times 1.000) + (0.114 \times 3.000) + (0.090 \times 3.000) + \\ (0.068 \times 2.000) + (0.049 \times 3.000) + (0.034 \times 4.000) + (0.024 \times 7.000)\end{pmatrix}}{0.151}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.270 \times 0.500) + (0.200 \times 0.333) + (0.151 \times 0.333) + (0.114 \times 1.000) + (0.090 \times 3.000) + \\ (0.068 \times 2.000) + (0.049 \times 3.000) + (0.034 \times 3.000) + (0.024 \times 4.000)\end{pmatrix}}{0.114}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.270 \times 0.333) + (0.200 \times 0.333) + (0.151 \times 0.333) + (0.114 \times 0.333) + (0.090 \times 1.000) + \\ (0.068 \times 3.000) + (0.049 \times 3.000) + (0.034 \times 3.000) + (0.024 \times 3.000)\end{pmatrix}}{0.090}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.270 \times 0.250) + (0.200 \times 0.333) + (0.151 \times 0.500) + (0.114 \times 0.500) + (0.090 \times 0.333) + \\ (0.068 \times 1.000) + (0.049 \times 3.000) + (0.034 \times 2.000) + (0.024 \times 3.000)\end{pmatrix}}{0.068}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.270 \times 0.200) + (0.200 \times 0.200) + (0.151 \times 0.333) + (0.114 \times 0.333) + (0.090 \times 0.333) + \\ (0.068 \times 0.333) + (0.049 \times 1.000) + (0.034 \times 3.000) + (0.024 \times 3.000)\end{pmatrix}}{0.049}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.270 \times 0.167) + (0.200 \times 0.200) + (0.151 \times 0.250) + (0.114 \times 0.333) + (0.090 \times 0.333) + \\ (0.068 \times 0.500) + (0.049 \times 0.333) + (0.034 \times 1.000) + (0.024 \times 2.000)\end{pmatrix}}{0.034}\right] +$$

$$\left.\left[\frac{\begin{pmatrix}(0.270 \times 0.125) + (0.200 \times 0.167) + (0.151 \times 0.143) + (0.114 \times 0.250) + (0.090 \times 0.333) + \\ (0.068 \times 0.333) + (0.049 \times 0.333) + (0.034 \times 0.500) + (0.024 \times 1.000)\end{pmatrix}}{0.024}\right]\right\}$$

$$= 9.701$$

The CI is computed using Equation 6.5 and illustrated as follows:

$$CI = \left[\frac{1}{8}(9.701 - 9)\right]$$
$$= 0.088$$

The RI value is taken from Table 6.2 to compute the CR using Equation 6.6 and presented as follows:

$$CR = \left(\frac{0.088}{1.45}\right)$$
$$= 0.060$$

The CR value obtained is less than 0.1. Therefore the subjective expert judgment on CPCs is consistent.

(v). Convert the membership functions of the tabulated CPCs to single crisp values for the nine CPCs using the defuzzification method.

The fuzzification is carried out referring to the fuzzy set representation of the HPFP for the CPCs input variable graph as shown in Figure 6.3 and Appendix IV. The defuzzified crisp values of CPCs are obtained using Equation 6.7. Finally, a list consisting of nine defuzzified crisp values of CPCs is produced and presented in Table VI.4.

Table VI.4 Defuzzified Crisp Values of CPCs

CPC	CPC_L
ASO	0.590
SWC	0.745
MMI	0.590
APP	0.710
NSG	0.745

QAT	0.570
CRT	0.000
ASP	0.780
SCQ	0.530

(vi). Compute a HPFP value for the '*Carina*' incident.

The $HPFP_{Carina}$ is obtained using Equation 6.8 as illustrated as follows:

$$HPFP_{Carina} = [(0.270 \times 0.590) + (0.200 \times 0.745) + (0.151 \times 0.590) + (0.114 \times 0.710) + (0.090 \times 0.745) + (0.068 \times 0.570) + (0.049 \times 0.000) + (0.034 \times 0.780) + (0.024 \times 0.530)] = 0.623$$

VI.2 HPFP of D_v (HPFP D_v)

(a). The evaluation of CPCs for the D_v is illustrated in Table VI.5

Table VI.5 The CPCs on implementation of the D_v

CPCs	Description of Evaluation	CPC Linguistic Terms by Expert Judgment
ASO	Failure of monitoring to ensure that all the cargo tanks inert gas branch valves are kept in open position during discharging cargo operations	0.55 **Inefficient** / 0.45 Efficient
SWC	Cargo operations could distract the shipboard working condition	0.70 **Incompatible** / 0.30 Compatible
MMI	Manual monitoring of inert gas branch valves status indicating open/ shut position can be observed	0.80 **Tolerable** / 0.20 Adequate
APP	Lack of procedures to monitor the status of inert gas branch valves while cargo operation is in progress	0.60 **Inappropriate** / 0.40 Acceptable
NSG	Vessel was having a vetting inspection along with discharging cargo operations	0.70 **More than actual capacity** / 0.30 Matching current capacity
QAT	Continuous cargo operations could distract monitoring the status of inert gas branch valves	0.70 **Continuously inadequate** / 0.30 Adequate

CRT	Time of the day is not relevant for the case	Not relevant
ASP	Lack of training and awareness on the importance of monitoring inert gas branch valves	0.55 **Inadequate, experience /** 0.45 Adequate, limited experience
SCQ	Inefficient crew management during cargo operations in port	**0.30 Inefficient /** 0.70 Efficient

(b). Pairwise comparisons of the nine CPCs to determine the relative importance among the CPCs using AHP by expert judgment were carried out using the CPC scale shown in Table 6.1. Table VI.6 illustrates the result of expert judgment pairwise comparison of the CPCs.

Table VI.6 Judgment Matrix for Pairwise Comparison of CPCs

CPC	ASO	SWC	MMI	APP	NSG	QAT	CRT	ASP	SCQ
ASO	1	2	4	2	3	4	5	6	4
SWC	1/2	1	2	3	3	3	5	5	6
MMI	1/4	1/2	1	3	3	2	3	4	7
APP	1/2	1/3	1/3	1	3	2	3	3	4
NSG	1/3	1/3	1/3	1/3	1	3	3	3	3
QAT	1/4	1/3	1/2	1/2	1/3	1	3	2	3
CRT	1/5	0.20	1/3	1/3	0.33	1/3	1	3	3
ASP	1/6	1/5	1/4	1/3	1/3	1/2	1/3	1	2
SCQ	1/4	1/6	1/7	1/4	1/3	1/3	1/3	1/2	1

(c). Compute the weights of the nine CPCs.

The sums of each column of the reciprocal matrix of CPCs of ASO, SWC, MMI, APP, NSG, QAT, CRT, ASP and SCQ are 3.450, 5.067, 8.893, 10.750, 14.333, 16.167, 23.667, 27.500 and 33.000 respectively. The normalised relative weights of the CPC matrix for the nine CPCs are produced by dividing each element in Table VI.6 by its column sum. The normalised relative weight of each element in the pairwise comparison judgment of the CPCs is shown in Table VI.7.

Table VI.7 Judgment Matrix for Normalised Relative Weight of CPCs

CPC	ASO	SWC	MMI	APP	NSG	QAT	CRT	ASP	SCQ
ASO	0.290	0.395	0.450	0.186	0.209	0.247	0.211	0.218	0.121

SWC	0.145	0.197	0.225	0.279	0.209	0.186	0.211	0.182	0.182
MMI	0.072	0.099	0.112	0.279	0.209	0.124	0.127	0.145	0.212
APP	0.145	0.066	0.037	0.093	0.209	0.124	0.127	0.109	0.121
NSG	0.097	0.066	0.037	0.031	0.070	0.186	0.127	0.109	0.091
QAT	0.072	0.066	0.056	0.047	0.023	0.062	0.127	0.073	0.091
CRT	0.058	0.039	0.037	0.031	0.023	0.021	0.042	0.109	0.091
ASP	0.048	0.039	0.028	0.031	0.023	0.031	0.014	0.036	0.061
SCQ	0.072	0.033	0.016	0.023	0.023	0.021	0.014	0.018	0.030

From the normalised comparison CPC matrix, nine priority eigenvectors representing each CPC are computed using Equation 6.3. The relative weights of ASO, SWC, MMI, APP, NSG, QAT, CRT, ASP and SCQ CPCs are 0.259, 0.202, 0.153, 0.115, 0.090, 0.068, 0.050, 0.035 and 0.028 respectively.

(d). Consistency validation.

A principal eigenvalue is obtained using Equation 6.4.

Principal eigenvalue, $\lambda_{max} = \frac{1}{9} \times$

$$\left\{\left[\frac{\begin{pmatrix}(0.259 \times 1.000) + (0.202 \times 2.000) + (0.153 \times 4.000) + (0.115 \times 2.000) + (0.090 \times 3.000) + \\ (0.068 \times 4.000) + (0.050 \times 5.000) + (0.035 \times 6.000) + (0.028 \times 4.000)\end{pmatrix}}{0.259}\right] + \right.$$

$$\left[\frac{\begin{pmatrix}(0.259 \times 0.500) + (0.202 \times 1.000) + (0.153 \times 2.000) + (0.115 \times 3.000) + (0.090 \times 3.000) + \\ (0.068 \times 3.000) + (0.050 \times 5.000) + (0.035 \times 5.000) + (0.028 \times 6.000)\end{pmatrix}}{0.202}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.259 \times 0.250) + (0.202 \times 0.500) + (0.153 \times 1.000) + (0.115 \times 3.000) + (0.090 \times 3.000) + \\ (0.068 \times 2.000) + (0.050 \times 3.000) + (0.035 \times 4.000) + (0.028 \times 7.000)\end{pmatrix}}{0.153}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.259 \times 0.500) + (0.202 \times 0.333) + (0.153 \times 0.333) + (0.115 \times 1.000) + (0.090 \times 3.000) + \\ (0.068 \times 2.000) + (0.050 \times 3.000) + (0.035 \times 3.000) + (0.028 \times 4.000)\end{pmatrix}}{0.115}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.259 \times 0.333) + (0.202 \times 0.333) + (0.153 \times 0.333) + (0.115 \times 0.333) + (0.090 \times 1.000) + \\ (0.068 \times 3.000) + (0.050 \times 3.000) + (0.035 \times 3.000) + (0.028 \times 3.000)\end{pmatrix}}{0.090}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.259\times0.250)+(0.202\times0.333)+(0.153\times0.500)+(0.115\times0.500)+(0.090\times0.333)+\\(0.068\times1.000)+(0.050\times3.000)+(0.035\times2.000)+(0.028\times3.000)\end{pmatrix}}{0.068}\right]+$$

$$\left[\frac{\begin{pmatrix}(0.259\times0.200)+(0.202\times0.200)+(0.153\times0.333)+(0.115\times0.333)+(0.090\times0.333)+\\(0.068\times0.333)+(0.050\times1.000)+(0.035\times3.000)+(0.028\times3.000)\end{pmatrix}}{0.050}\right]+$$

$$\left[\frac{\begin{pmatrix}(0.259\times0.167)+(0.202\times0.200)+(0.153\times0.250)+(0.115\times0.333)+(0.090\times0.333)+\\(0.068\times0.500)+(0.050\times0.333)+(0.035\times1.000)+(0.028\times2.000)\end{pmatrix}}{0.035}\right]+$$

$$\left.\left[\frac{\begin{pmatrix}(0.259\times0.250)+(0.202\times0.167)+(0.153\times0.143)+(0.115\times0.250)+(0.090\times0.333)+\\(0.068\times0.333)+(0.050\times0.333)+(0.035\times0.500)+(0.028\times1.000)\end{pmatrix}}{0.028}\right]\right\}$$

$$= 9.804$$

The CI is computed using Equation 6.5 and illustrated as follows:

$$CI = \left[\frac{1}{8}(9.804 - 9)\right]$$

$$= 0.101$$

The RI value is taken from Table 6.2 to compute the CR using Equation 6.6 and presented as follows:

$$CR = \left(\frac{0.101}{1.45}\right)$$

$$= 0.069$$

The CR value obtained is less than 0.1. Therefore the subjective expert judgment on CPCs is consistent.

(e). Convert the membership functions of the tabulated CPCs to single crisp values for the nine CPCs using the defuzzification method.

The fuzzification is carried out referring to the fuzzy set representation of the HPFP for the CPCs input variable graph as shown in Figure 6.3 and Appendix IV. The defuzzified crisp values of CPCs are obtained using Equation 6.7. Finally, a list consisting of nine defuzzified crisp values of CPCs is produced and presented in Table VI.8.

Table VI.8 Defuzzified Crisp Values of CPCs

CPC	CPC_L
ASO	0.515
SWC	0.745
MMI	0.590
APP	0.710
NSG	0.745
QAT	0.640
CRT	0.000
ASP	0.693
SCQ	0.440

(f). Compute a HPFP value for the D_v.

The HPFP D_v is obtained using Equation 6.8 as illustrated as follows:

$$\begin{aligned} \text{HPFP } D_v = {} & [(0.259 \times 0.515) + (0.202 \times 0.745) + (0.153 \times 0.590) + (0.115 \times 0.710) + \\ & (0.090 \times 0.745) + (0.068 \times 0.640) + (0.050 \times 0.000) + (0.035 \times 0.693) + \\ & (0.028 \times 0.440)] \\ = {} & 0.603 \end{aligned}$$

VI.3 HPFP of Pc_v (HPFP Pc_v)

(a). The evaluation of CPCs for the Pc_v is illustrated in Table VI.9

Table VI.9 The CPCs on implementation of Pc_v

CPCs	Description of Evaluation	CPCs Linguistic Terms by Expert Judgment
ASO	Failure of monitoring to ensure that all the cargo tanks inert gas branch valves are kept in open position during discharging cargo operations.	0.80 **Inefficient** / 0.20 Efficient
SWC	Cargo operations could distract the shipboard working condition.	0.70 **Incompatible** / 0.30 Compatible
MMI	Manual monitoring of inert gas branch valves status indicating open/ shut position can be observed.	0.80 **Tolerable** / 0.20 Adequate

APP	Lack of procedures to monitor the status of inert gas branch valves while cargo operation is in progress.	0.60 **Inappropriate** / 0.40 Acceptable
NSG	Vessel was having a vetting inspection along with discharging cargo operations.	0.70 **More than actual capacity** / 0.30 Matching current capacity
QAT	Continuous cargo operations could distract monitoring the status of inert gas branch valves.	0.60 **Continuously inadequate** / 0.40 Adequate
CRT	Time of the day is not relevant for the case.	Not relevant
ASP	Lack of training and awareness on the importance of monitoring inert gas branch valves.	0.80 **Inadequate, experience** / 0.20 Adequate, limited experience
SCQ	Inefficient crew management during cargo operations in port.	**0.60 Inefficient** / 0.40 Efficient

(b). Pairwise comparisons of the nine CPCs to determine the relative importance among the CPCs using AHP by expert judgment were carried out using the CPC scale shown in Table 6.1. Table VI.10 illustrates the result of expert judgment pairwise comparison of the CPCs.

Table VI.10 Judgment Matrix for Pairwise Comparison of CPCs

CPC	ASO	SWC	MMI	APP	NSG	QAT	CRT	ASP	SCQ
ASO	1	2	4	2	3	4	5	6	6
SWC	1/2	1	2	3	3	3	5	5	6
MMI	1/4	1/2	1	3	3	2	3	4	7
APP	1/2	1/3	1/3	1	3	2	3	3	4
NSG	1/3	1/3	1/3	1/3	1	3	3	2	2
QAT	1/4	1/3	1/2	1/2	1/3	1	3	2	3
CRT	1/5	1/5	1/3	1/3	1/3	1/3	1	3	3
ASP	1/6	1/5	1/4	1/3	1/2	1/2	1/3	1	2
SCQ	1/6	1/6	1/7	1/4	1/2	1/3	1/3	1/2	1

(c). Compute the weights of the nine CPCs.

The sums of each column of the reciprocal matrix of CPCs of ASO, SWC, MMI, APP, NSG, QAT, CRT, ASP and SCQ are 3.367, 5.067, 8.893, 10.750, 14.667, 16.167, 23.667, 26.500 and 34.000 respectively. The normalised relative weights of the CPC matrix for the nine CPCs are produced by dividing each element in Table VI.10 by its column sum. The normalised relative weight of each element in the pairwise comparison judgment of the CPCs is shown in Table VI.11.

Table VI.11 Judgment Matrix for Normalised Relative Weight of CPCs

CPC	ASO	SWC	MMI	APP	NSG	QAT	CRT	ASP	SCQ
ASO	0.297	0.395	0.450	0.186	0.205	0.247	0.211	0.226	0.176
SWC	0.149	0.197	0.225	0.279	0.205	0.186	0.211	0.189	0.176
MMI	0.074	0.099	0.112	0.279	0.205	0.124	0.127	0.151	0.206
APP	0.149	0.066	0.037	0.093	0.205	0.124	0.127	0.113	0.118
NSG	0.099	0.066	0.037	0.031	0.068	0.186	0.127	0.075	0.059
QAT	0.074	0.066	0.056	0.047	0.023	0.062	0.127	0.075	0.088
CRT	0.059	0.039	0.037	0.031	0.023	0.021	0.042	0.113	0.088
ASP	0.050	0.039	0.028	0.031	0.034	0.031	0.014	0.038	0.059
SCQ	0.050	0.033	0.016	0.023	0.034	0.021	0.014	0.019	0.029

From the normalised comparison CPC matrix, nine priority eigenvectors representing each CPC are computed using Equation 6.3. The relative weights of ASO, SWC, MMI, APP, NSG, QAT, CRT, ASP and SCQ CPCs are 0.266, 0.202, 0.153, 0.115, 0.083, 0.069, 0.050, 0.036 and 0.027 respectively.

(d). Consistency validation.

A principal eigenvalue is obtained using Equation 6.4.

Principal eigenvalue, $\lambda_{max} = \frac{1}{9} \times$

$$\left\{\left[\frac{\begin{pmatrix}(0.266 \times 1.000) + (0.202 \times 2.000) + (0.153 \times 4.000) + (0.115 \times 2.000) + (0.083 \times 3.000) + \\ (0.069 \times 4.000) + (0.050 \times 5.000) + (0.036 \times 6.000) + (0.027 \times 6.000)\end{pmatrix}}{0.266}\right] + \right.$$

$$\left[\frac{\begin{pmatrix}(0.266 \times 0.500) + (0.202 \times 1.000) + (0.153 \times 2.000) + (0.115 \times 3.000) + (0.083 \times 3.000) + \\ (0.068 \times 3.000) + (0.050 \times 5.000) + (0.035 \times 5.000) + (0.028 \times 6.000)\end{pmatrix}}{0.202}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.266\times0.250)+(0.202\times0.500)+(0.153\times1.000)+(0.115\times3.000)+(0.083\times3.000)+\\(0.068\times2.000)+(0.050\times3.000)+(0.035\times4.000)+(0.028\times7.000)\end{pmatrix}}{0.153}\right]+$$

$$\left[\frac{\begin{pmatrix}(0.259\times0.500)+(0.202\times0.333)+(0.153\times0.333)+(0.115\times1.000)+(0.090\times3.000)+\\(0.068\times2.000)+(0.050\times3.000)+(0.035\times3.000)+(0.028\times4.000)\end{pmatrix}}{0.115}\right]+$$

$$\left[\frac{\begin{pmatrix}(0.259\times0.333)+(0.202\times0.333)+(0.153\times0.333)+(0.115\times0.333)+(0.090\times1.000)+\\(0.068\times3.000)+(0.050\times3.000)+(0.035\times3.000)+(0.028\times3.000)\end{pmatrix}}{0.083}\right]+$$

$$\left[\frac{\begin{pmatrix}(0.259\times0.250)+(0.202\times0.333)+(0.153\times0.500)+(0.115\times0.500)+(0.090\times0.333)+\\(0.068\times1.000)+(0.050\times3.000)+(0.035\times2.000)+(0.028\times3.000)\end{pmatrix}}{0.069}\right]+$$

$$\left[\frac{\begin{pmatrix}(0.259\times0.200)+(0.202\times0.200)+(0.153\times0.333)+(0.115\times0.333)+(0.090\times0.333)+\\(0.068\times0.333)+(0.050\times1.000)+(0.035\times3.000)+(0.028\times3.000)\end{pmatrix}}{0.050}\right]+$$

$$\left[\frac{\begin{pmatrix}(0.259\times0.167)+(0.202\times0.200)+(0.153\times0.250)+(0.115\times0.333)+(0.090\times0.500)+\\(0.068\times0.500)+(0.050\times0.333)+(0.035\times1.000)+(0.028\times2.000)\end{pmatrix}}{0.036}\right]+$$

$$\left.\left[\frac{\begin{pmatrix}(0.259\times0.167)+(0.202\times0.167)+(0.153\times0.143)+(0.115\times0.250)+(0.090\times0.500)+\\(0.068\times0.333)+(0.050\times0.333)+(0.035\times0.500)+(0.028\times1.000)\end{pmatrix}}{0.027}\right]\right\}$$

$$=9.751$$

The CI is computed using Equation 6.5 and illustrated as follows:

$$\mathrm{CI}=\left[\tfrac{1}{8}(9.751-9)\right]$$

$$=0.094$$

The RI value is taken from Table 6.2 to compute the CR using Equation 6.6 and presented as follows:

$$\mathrm{CR}=\left(\frac{0.094}{1.45}\right)$$

$$=0.065$$

The CR value obtained is less than 0.1. Therefore the subjective expert judgment on CPCs is consistent.

(e). Convert the membership functions of the tabulated CPCs to single crisp values for the nine CPCs using the defuzzification method.
The fuzzification is carried out referring to the fuzzy set representation of the HPFP for the CPCs input variable graph as shown in Figure 6.3 and Appendix IV. The defuzzified crisp values of CPCs are obtained using Equation 6.7. Finally, a list consisting of nine defuzzified crisp values of CPCs is produced and presented in Table VI.12.

Table VI.12 Defuzzified Crisp Values of CPCs

CPC	CPC_L
ASO	0.530
SWC	0.745
MMI	0.590
APP	0.710
NSG	0.815
QAT	0.570
CRT	0.000
ASP	0.693
SCQ	0.470

(f). Compute a HPFP value for the Pc_v.
The HPFP Pc_v is obtained using Equation 6.8 and illustrated as follows:

$$\begin{aligned} \text{HPFP } Pc_v = {} & [(0.266 \times 0.530) + (0.202 \times 0.745) + (0.153 \times 0.590) + (0.115 \times 0.710) + \\ & (0.083 \times 0.815) + (0.069 \times 0.570) + (0.050 \times 0.000) + (0.036 \times 0.693) + \\ & (0.027 \times 0.470)] \\ = {} & 0.607 \end{aligned}$$

VI.4 HPFP of T_f (HPFP T_f)

(a). The evaluation of CPCs for the T_f is illustrated in Table VI.13

Table VI.13 The CPCs on implementation of the T_f

CPCs	Description of Evaluation	CPC Linguistic Terms by Expert Judgment
ASO	Failure of monitoring to ensure that all the cargo tanks inert gas branch valves are kept in open position during discharging cargo operations	0.70 **Inefficient** / 0.30 Efficient
SWC	Cargo operations could distract the shipboard working condition	0.70 **Incompatible** / 0.30 Compatible
MMI	Manual monitoring of inert gas branch valves status indicating open/ shut position can be observed	0.80 **Tolerable** / 0.20 Adequate
APP	Lack of procedures to monitor the status of inert gas branch valves while cargo operation is in progress	0.60 **Inappropriate** / 0.40 Acceptable
NSG	Vessel was having a vetting inspection along with discharging cargo operations	0.70 **More than actual capacity** / 0.30 Matching current capacity
QAT	Continuous cargo operations could distract monitoring the status of inert gas branch valves	0.60 **Continuously inadequate** / 0.40 Adequate
CRT	Time of the day is not relevant for the case	Not relevant
ASP	Lack of training and awareness on the importance of monitoring inert gas branch valves	0.60 **Inadequate, experience** / 0.40 Adequate, limited experience
SCQ	Inefficient crew management during cargo operations in port	**0.55 Efficient** / 0.45 Inefficient

(b). Pairwise comparisons of the nine CPCs to determine the relative importance among the CPCs using AHP by expert judgment were carried out using the CPC scale shown in Table 6.1. Table VI.14 illustrates the result of expert judgment pairwise comparison of the CPCs.

Table VI.14 Judgment Matrix for Pairwise Comparison of CPCs

CPC	ASO	SWC	MMI	APP	NSG	QAT	CRT	ASP	SCQ
ASO	1	2	4	2	3	4	5	7	8
SWC	1/2	1	2	3	3	3	5	5	6
MMI	1/4	1/2	1	3	3	2	3	4	7
APP	1/2	1/3	1/3	1	3	2	3	3	4
NSG	1/3	1/3	1/3	1/3	1	3	3	3	3
QAT	1/4	1/3	1/2	1/2	1/3	1	3	2	3
CRT	1/5	1/5	1/3	1/3	1/3	1/3	1	3	3
ASP	1/7	1/5	1/4	1/3	1/3	1/2	1/3	1	3
SCQ	1/8	1/6	1/7	1/4	1/3	1/3	1/3	1/3	1

(c). Compute the weights of the nine CPCs.

The sums of each column of the reciprocal matrix of CPCs of ASO, SWC, MMI, APP, NSG, QAT, CRT, ASP and SCQ are 3.301, 5.067, 8.893, 10.750, 14.333, 16.167, 23.667, 28.333 and 38.000 respectively. The normalised relative weights of the CPC matrix for the nine CPCs are produced by dividing each element in Table VI.14 by its column sum. The normalised relative weight of each element in the pairwise comparison judgment of the CPCs is shown in Table VI.15.

Table VI.15 Judgment Matrix for Normalised Relative Weight of CPCs

CPC	ASO	SWC	MMI	APP	NSG	QAT	CRT	ASP	SCQ
ASO	0.303	0.395	0.450	0.186	0.209	0.247	0.211	0.247	0.211
SWC	0.151	0.197	0.225	0.279	0.209	0.186	0.211	0.176	0.158
MMI	0.076	0.099	0.112	0.279	0.209	0.124	0.127	0.141	0.184
APP	0.151	0.066	0.037	0.093	0.209	0.124	0.127	0.106	0.105
NSG	0.101	0.066	0.037	0.031	0.070	0.186	0.127	0.106	0.079
QAT	0.076	0.066	0.056	0.047	0.023	0.062	0.127	0.071	0.079
CRT	0.061	0.039	0.037	0.031	0.023	0.021	0.042	0.106	0.079
ASP	0.043	0.039	0.028	0.031	0.023	0.031	0.014	0.035	0.079
SCQ	0.038	0.033	0.016	0.023	0.023	0.021	0.014	0.012	0.026

From the normalised comparison CPC matrix, nine priority eigenvectors representing each CPC are computed using Equation 6.3. The relative weights of ASO, SWC, MMI, APP, NSG, QAT, CRT, ASP and SCQ CPCs are 0.273, 0.199, 0.150, 0.113, 0.089, 0.067, 0.049, 0.036 and 0.023 respectively.

(d). Consistency validation.

A principal eigenvalue is obtained using Equation 6.4.

Principal eigenvalue, $\lambda_{max} = \frac{1}{9} \times$

$$\left\{\left[\frac{\begin{pmatrix}(0.273 \times 1.000) + (0.199 \times 2.000) + (0.150 \times 4.000) + (0.113 \times 2.000) + (0.089 \times 3.000) + \\ (0.067 \times 4.000) + (0.049 \times 5.000) + (0.036 \times 7.000) + (0.023 \times 8.000)\end{pmatrix}}{0.273}\right] + \right.$$

$$\left[\frac{\begin{pmatrix}(0.273 \times 0.500) + (0.199 \times 1.000) + (0.150 \times 2.000) + (0.113 \times 3.000) + (0.089 \times 3.000) + \\ (0.067 \times 3.000) + (0.049 \times 5.000) + (0.036 \times 5.000) + (0.023 \times 6.000)\end{pmatrix}}{0.199}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.273 \times 0.250) + (0.199 \times 0.500) + (0.150 \times 1.000) + (0.113 \times 3.000) + (0.089 \times 3.000) + \\ (0.067 \times 2.000) + (0.049 \times 3.000) + (0.036 \times 4.000) + (0.023 \times 7.000)\end{pmatrix}}{0.150}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.273 \times 0.500) + (0.199 \times 0.333) + (0.150 \times 0.333) + (0.113 \times 1.000) + (0.089 \times 3.000) + \\ (0.067 \times 2.000) + (0.049 \times 3.000) + (0.036 \times 3.000) + (0.023 \times 4.000)\end{pmatrix}}{0.113}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.273 \times 0.333) + (0.199 \times 0.333) + (0.150 \times 0.333) + (0.113 \times 0.333) + (0.089 \times 1.000) + \\ (0.067 \times 3.000) + (0.049 \times 3.000) + (0.036 \times 3.000) + (0.023 \times 3.000)\end{pmatrix}}{0.089}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.273 \times 0.250) + (0.199 \times 0.333) + (0.150 \times 0.500) + (0.113 \times 0.500) + (0.089 \times 0.333) + \\ (0.067 \times 1.000) + (0.049 \times 3.000) + (0.036 \times 2.000) + (0.023 \times 3.000)\end{pmatrix}}{0.067}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.273 \times 0.200) + (0.199 \times 0.200) + (0.150 \times 0.333) + (0.113 \times 0.333) + (0.089 \times 0.333) + \\ (0.067 \times 0.333) + (0.049 \times 1.000) + (0.036 \times 3.000) + (0.023 \times 3.000)\end{pmatrix}}{0.049}\right] +$$

$$\left.\left[\frac{\begin{pmatrix}(0.273 \times 0.143) + (0.199 \times 0.200) + (0.150 \times 0.250) + (0.113 \times 0.333) + (0.089 \times 0.333) + \\ (0.067 \times 0.500) + (0.049 \times 0.333) + (0.036 \times 1.000) + (0.023 \times 3.000)\end{pmatrix}}{0.036}\right] + \right\}$$

$$\left[\frac{\begin{pmatrix}(0.273 \times 0.125) + (0.199 \times 0.167) + (0.150 \times 0.143) + (0.113 \times 0.250) + (0.089 \times 0.333) + \\ (0.067 \times 0.333) + (0.049 \times 0.333) + (0.036 \times 0.333) + (0.023 \times 1.000)\end{pmatrix}}{0.023}\right]$$

$$= 9.741$$

The CI is computed using Equation 6.5 and illustrated as follows:

$$CI = \left[\frac{1}{8}(9.741 - 9)\right]$$

$$= 0.093$$

The RI value is taken from Table 6.2 to compute the CR using Equation 6.6 and presented as follows:

$$CR = \left(\frac{0.093}{1.45}\right)$$

$$= 0.064$$

The CR value obtained is less than 0.1. Therefore the subjective expert judgment on CPCs is consistent.

(e). Convert the membership functions of the tabulated CPCs to single crisp values for the nine CPCs using the defuzzification method.

The fuzzification is carried out referring to the fuzzy set representation of the HPFP for the CPCs input variable graph as shown in Figure 6.3 and Appendix IV. The defuzzified crisp values of CPCs are obtained using Equation 6.7. Finally, a list consisting of nine defuzzified crisp values of CPCs is produced and presented in Table VI.16.

Table VI.16 Defuzzified Crisp Values of CPCs

CPC	CPC_L
ASO	0.560
SWC	0.745
MMI	0.590
APP	0.710
NSG	0.745
QAT	0.570
CRT	0.000

ASP	0.710
SCQ	0.485

(f). Compute a HPFP value for the T_f.

The HPFP T_f is obtained using Equation 6.8 and illustrated as follows:

$$\text{HPFP } T_f = [(0.273 \times 0.560) + (0.199 \times 0.745) + (0.150 \times 0.590) + (0.113 \times 0.710) + (0.089 \times 0.745) + (0.067 \times 0.570) + (0.049 \times 0.000) + (0.036 \times 0.710) + (0.023 \times 0.485)]$$
$$= 0.612$$

VI.5 HPFP of G_d (HPFP G_d)

(a). The evaluation of CPCs for the G_d is illustrated in Table VI.17

Table VI.17 The CPCs on implementation of the G_d

CPCs	Description of Evaluation	CPC Linguistic Terms by Expert Judgment
ASO	Failure of monitoring to ensure that all the cargo tanks inert gas branch valves are kept in open position during discharging cargo operations	0.90 **Efficient** / 0.10 Inefficient
SWC	Cargo operations could distract the shipboard working condition	0.60 **Incompatible** / 0.40 Compatible
MMI	Manual monitoring of inert gas branch valves status indicating open/ shut position can be observed	0.90 **Adequate** / 0.10 Tolerable
APP	Lack of procedures to monitor the status of inert gas branch valves while cargo operation is in progress	0.60 **Inappropriate** / 0.40 Acceptable
NSG	Vessel was having a vetting inspection along with discharging cargo operations	0.60 **More than actual capacity** / 0.40 Matching current capacity
QAT	Continuous cargo operations could distract monitoring the status of inert gas branch valves	0.60 **Temporarily inadequate** / 0.40 Adequate

CRT	Time of the day is not relevant for the case	Not relevant
ASP	Lack of training and awareness on the importance of monitoring inert gas branch valves	0.80 **Adequate, limited experience** / 0.20 Inadequate, experience
SCQ	Inefficient crew management during cargo operations in port	**0.90 Efficient** / 0.10 Inefficient

(b). Pairwise comparisons of the nine CPCs to determine the relative importance among the CPCs using AHP by expert judgment were carried out using the CPC scale shown in Table 6.1. Table VI.18 illustrates the result of expert judgment pairwise comparison of the CPCs.

Table VI.18 Judgment Matrix for Pairwise Comparison of CPCs

CPC	ASO	SWC	MMI	APP	NSG	QAT	CRT	ASP	SCQ
ASO	1	2	3	3	3	3	3	4	4
SWC	1/2	1	2	2	2	3	3	2	3
MMI	1/3	1/2	1	3	3	3	2	4	4
APP	1/3	1/2	1/3	1	2	3	2	2	3
NSG	1/3	1/2	1/3	1/2	1	2	2	2	2
QAT	1/3	1/3	1/3	1/3	1/2	1	2	2	2
CRT	1/3	1/3	1/2	1/2	1/2	1/2	1	2	2
ASP	1/4	1/2	1/4	1/2	1/2	1/2	1/2	1	2
SCQ	1/4	1/3	1/4	1/3	1/2	1/2	1/2	1/2	1

(c). Compute the weights of the nine CPCs.

The sums of each column of the reciprocal matrix of CPCs of ASO, SWC, MMI, APP, NSG, QAT, CRT, ASP and SCQ are 3.667, 6.000, 8.000, 11.167, 13.000, 16.500, 16.000, 19.500 and 23.000 respectively. The normalised relative weights of the CPC matrix for the nine CPCs are produced by dividing each element in Table VI.18 by its column sum. The normalised relative weight of each element in the pairwise comparison judgment of the CPCs is shown in Table VI.19.

Table VI.19 Judgment Matrix for Normalised Relative Weight of CPCs

CPC	ASO	SWC	MMI	APP	NSG	QAT	CRT	ASP	SCQ
ASO	0.273	0.333	0.375	0.269	0.231	0.182	0.188	0.205	0.174

SWC	0.136	0.167	0.250	0.179	0.154	0.182	0.188	0.103	0.130
MMI	0.091	0.083	0.125	0.269	0.231	0.182	0.125	0.205	0.174
APP	0.091	0.083	0.042	0.090	0.154	0.182	0.125	0.103	0.130
NSG	0.091	0.083	0.042	0.045	0.077	0.121	0.125	0.103	0.087
QAT	0.091	0.056	0.042	0.030	0.038	0.061	0.125	0.103	0.087
CRT	0.091	0.056	0.063	0.045	0.038	0.030	0.063	0.103	0.087
ASP	0.068	0.083	0.031	0.045	0.038	0.030	0.031	0.051	0.087
SCQ	0.068	0.056	0.031	0.030	0.038	0.030	0.031	0.026	0.043

From the normalised comparison CPC matrix, nine priority eigenvectors representing each CPC are computed using Equation 6.3. The relative weights of ASO, SWC, MMI, APP, NSG, QAT, CRT, ASP and SCQ CPCs are 0.248, 0.165, 0.165, 0.111, 0.086, 0.070, 0.064, 0.052 and 0.039 respectively.

(d). Consistency validation.

A principal eigenvalue is obtained using Equation 6.4.

Principal eigenvalue, $\lambda_{max} = \frac{1}{9} \times$

$$\left\{\left[\frac{\left((0.248 \times 1.000) + (0.165 \times 2.000) + (0.165 \times 3.000) + (0.111 \times 3.000) + (0.086 \times 3.000) + (0.070 \times 3.000) + (0.064 \times 3.000) + (0.052 \times 4.000) + (0.039 \times 4.000)\right)}{0.248}\right] + \right.$$

$$\left[\frac{\left((0.248 \times 0.500) + (0.165 \times 1.000) + (0.165 \times 2.000) + (0.111 \times 2.000) + (0.086 \times 2.000) + (0.070 \times 3.000) + (0.064 \times 3.000) + (0.052 \times 2.000) + (0.039 \times 3.000)\right)}{0.165}\right] +$$

$$\left[\frac{\left((0.248 \times 0.333) + (0.165 \times 0.500) + (0.165 \times 1.000) + (0.111 \times 3.000) + (0.086 \times 3.000) + (0.070 \times 3.000) + (0.064 \times 2.000) + (0.052 \times 4.000) + (0.039 \times 4.000)\right)}{0.165}\right] +$$

$$\left[\frac{\left((0.248 \times 0.333) + (0.165 \times 0.500) + (0.165 \times 0.333) + (0.111 \times 1.000) + (0.086 \times 2.000) + (0.070 \times 3.000) + (0.064 \times 2.000) + (0.052 \times 2.000) + (0.039 \times 3.000)\right)}{0.111}\right] +$$

$$\left[\frac{\left((0.248 \times 0.333) + (0.165 \times 0.500) + (0.165 \times 0.333) + (0.111 \times 0.500) + (0.086 \times 1.000) + (0.070 \times 2.000) + (0.064 \times 2.000) + (0.052 \times 2.000) + (0.039 \times 2.000)\right)}{0.086}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.248 \times 0.333) + (0.165 \times 0.333) + (0.165 \times 0.333) + (0.111 \times 0.333) + (0.086 \times 0.500) + \\ (0.070 \times 1.000) + (0.064 \times 2.000) + (0.052 \times 2.000) + (0.039 \times 2.000)\end{pmatrix}}{0.070}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.248 \times 0.333) + (0.165 \times 0.333) + (0.165 \times 0.500) + (0.111 \times 0.500) + (0.086 \times 0.500) + \\ (0.070 \times 0.500) + (0.064 \times 1.000) + (0.052 \times 2.000) + (0.039 \times 2.000)\end{pmatrix}}{0.064}\right] +$$

$$\left[\frac{\begin{pmatrix}(0.248 \times 0.250) + (0.165 \times 0.500) + (0.165 \times 0.250) + (0.111 \times 0.500) + (0.086 \times 0.500) + \\ (0.070 \times 0.500) + (0.064 \times 0.500) + (0.052 \times 1.000) + (0.039 \times 2.000)\end{pmatrix}}{0.052}\right] +$$

$$\left.\left[\frac{\begin{pmatrix}(0.248 \times 0.250) + (0.165 \times 0.333) + (0.165 \times 0.250) + (0.111 \times 0.333) + (0.086 \times 0.500) + \\ (0.070 \times 0.500) + (0.064 \times 0.500) + (0.052 \times 0.500) + (0.039 \times 1.000)\end{pmatrix}}{0.039}\right]\right\}$$

$= 9.555$

The CI is computed using Equation 6.5 and illustrated as follows:

$$CI = \left[\frac{1}{8}(9.555 - 9)\right]$$

$$= 0.069$$

The RI value is taken from Table 6.2 to compute the CR using Equation 6.6 and presented as follows:

$$CR = \left(\frac{0.069}{1.45}\right)$$

$$= 0.048$$

The CR value obtained is less than 0.1. Therefore the subjective expert judgment on CPCs is consistent.

(e). Convert the membership functions of the tabulated CPCs to single crisp values for the nine CPCs using the defuzzification method.

The fuzzification is carried out referring to the fuzzy set representation of the HPFP for the CPCs input variable graph as shown in Figure 6.3 and Appendix IV. The defuzzified crisp values of CPCs are obtained using Equation 6.7. Finally, a list consisting of nine defuzzified crisp values of CPCs is produced and presented in Table VI.20.

Table VI.20 Defuzzified Crisp Values of CPCs

CPC	CPC_L
ASO	0.380
SWC	0.710
MMI	0.380
APP	0.710
NSG	0.710
QAT	0.360
CRT	0.000
ASP	0.570
SCQ	0.380

(f). Compute a HPFP value for the G_d.

The HPFP G_d is obtained using Equation 6.8 and illustrated as follows:

$$HPFP\ G_d = [(0.248 \times 0.380) + (0.165 \times 0.710) + (0.165 \times 0.380) + (0.111 \times 0.710) + (0.086 \times 0.710) + (0.070 \times 0.360) + (0.064 \times 0.000) + (0.052 \times 0.570) + (0.039 \times 0.380)]$$

$$= 0.484$$