APPLICATION OF FORMAL SAFETY ASSESSMENT FOR SHIP HULL VIBRATION MODELLING

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Abstract

This research has evaluated the rules, guidelines and regulations related to ship vibrations. A historical failure data analysis is carried out to identify associated components, equipment and the areas of defects related to ship vibration problems. Ship Hull Vibration (SHV) is recognised as a major problem onboard ships and the propulsion system is identified as the major contributor to SHV. The current status of ship vibrations is reviewed and possible sources which create SHV are recognised. The major problems identified in this research are associated with risk modelling under circumstances where high levels of uncertainty exist. Following the identification of research needs, this PhD thesis has developed several analytical models for the application of Formal Safety Assessment (FSA). Such models are subsequently demonstrated by their corresponding case studies with regard to application of FSA for SHV modelling.

Firstly, in this research a generic SHV model is constructed for the purpose of risk estimation based on the identified hazards. The hazards include the SHV effects induced by ship design criteria, failure of components, and different vibration patterns associated with the ship propulsion system (propeller system and machinery) as the major contributors to SHV. Then risk estimation is carried out utilising Evidential Reasoning (ER) and a fuzzy rule base.

Secondly, ship selection (decision making) is investigated to select the best ship design based on the risk estimation results of SHV. The risk estimation is carried out using ER, a fuzzy rule base and continuous fuzzy sets. The best ship design is selected by taking into account an ER-based utility ranking approach.

Thirdly, combining discrete fuzzy sets and an Analytical Hierarchy Process (AHP) risk estimation is conducted in terms of four risk parameters to select the major causes of component failure and then SHV. Possible Risk Control Options (RCOs) are introduced, based on their effectiveness, to select the best Risk Control Option (RCO) for minimising the risks of the major causes of SHV. The best RCO was shown to be minimising causes by design and manufacture.

Finally, a cost benefit assessment is conducted to select the best propulsion system based on design and manufacture (RCO) allocating the highest weight to the vibration characteristics criterion. The weight allocation of the criteria is conduced by using AHP. The cost benefit assessment is conducted by utilising continuous fuzzy sets and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Then the best propulsion system is selected on an economic basis. The four subjective novel FSA application methodologies are constructed from existing theoretical techniques and applied to real situations for the data collection and validation. The construction of the novel methodologies and the case study applications are the major contribution to knowledge in this thesis.

It is concluded that the methodologies proposed possess significant potential for the application of FSA for SHV modelling based on the validations of their corresponding case studies. Although the developed methodologies are presented on the basis of the specific context in SHV modelling, they can also, with domain-specific knowledge, be tailored to facilitate FSA in other application areas where a high level of uncertainty in data is involved.

Table of Contents

Chapter 5. A Subjective Risk Management Approach for Modelling of Failures Onboard Ships 122

Chapter 6. A Subjective Cost Benefit Analysis Approach for Modelling Ship Propulsion Systems 163

List of Tables

List of Figures

Abbreviations

ABS	American Bureau of Shipping
AHP	Analytic Hierarchy Process
BE	Boundary Element
BEM	Boundary Element Method
BR	Blade Rate
BS	British Standard
BSRA	British Ship Research Association
CA	Criticality Analysis
CBA	Cost Benefit Assessment
CURR	Cost per Unit Risk Reduction
D-S	Dempster-Shafer
DM	Decision Making
DMs	Decision Makers
DNV	Det Norske Veritas
DoB	Degree of Belief
ER	Evidential Reasoning
ETA	Event Tree Analysis
FEA	Finite Element Analysis
FEM	Finite Element Method
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
FNIRP	Fuzzy Negative Ideal Reference Point
FPIRP	Fuzzy Positive Ideal Reference Point
FPSO	Floating Production, Storage and Offloading
FSA	Formal Safety Assessment
FST	Fuzzy Set Theory
FTA	Fault Tree Analysis
GL	Germanischer Lloyd
HAZID	HAZard IDentification
HAZOP	HAZard and OPerability Study
hcn	harmony criteria numbers
HSE	Health and Safety Executive
IDS	Intelligent Decision System
ILO	International Labour Organisation
IMO	International Maritime Organization
ISM	International Safety Management
ISO	International Organisation for Standardisation
LR	Lloyds Register
MAIB	Marine Accident Investigation Branch
MCA	Maritime and Coastguard Agency

MCDM	Multiple Criteria Decision Making
MCGDM	Multiple Criteria Group Decision Making
MF	Membership Function
MFs	Membership Functions
MSC	Marine Safety Committee
OPRC	Oil Pollution Preparedness, Response and Co-operation
PHA	Preliminary Hazard Analysis
PRA	Probabilistic Risk Assessment
PSV	Propulsion System Vibration
QRA	Quantitative Risk Assessment
RCO	Risk Control Option
RCOs	Risk Control Options
RE	Risk Estimation
r.m.s.	root mean squire
RPM	Revolutions Per Minute
SHV	Ship Hull Vibration
STG	Schiffbautechnische Gesellschaft
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution

Chapter 1 – Introduction

SUMMARY

This chapter first introduces the key definitions used in this research. The research aim and objectives are then defined, followed by the background analysis. Then the challenges of conducting the research, research methodology and scope of the thesis are demonstrated. Finally, the structure of the overall PhD thesis 'Application of Formal Safety Assessment (FSA) for Ship Hull Vibration (SHV) Modelling' is given.

1.1. Definitions for Typical Terms Used in this Research

Accident: An unintended event involving fatality, injury, ship or other property loss or damage, and/or environmental damage (IMO MSC/Circ.829, 1997; IMO MSC/Circ.1023, 2002).

Formal Safety Assessment: A structured and systematic methodology, aimed at enhancing marine safety, including protection of life, health, the marine environment and property by using a scientific approach (MSA, 1993).

Generic Model: A set of functions which are common to all ships or areas or properties under consideration (Eleye-Datubo, 2006).

Hazard: A physical situation with a potential for human injury, damage to the property or environment or some combination of those items (Henley & Kumamoto, 1992).

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

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

Safety: Freedom from unacceptable risks or personal harm.

Ship Hull Vibration: All the vibration effects associated with ship structures.

Uncertainty: A state of doubt regarding quantitative or qualitative information describing, prescribing or predicting deterministically and numerically a system, its behaviour or other characteristics (Zimmermann, 2000).

Vibration: Mechanical oscillations about an equilibrium point.

1.2. Background Analysis

Well designed, maintained and operated ships are capable of safe and cost-effective operation over their intended life-cycle. However, this is never a certainty and accidents can happen. Historically, marine safety regulations were introduced as a reaction to major accidents. Following serious accidents such as 'Herald of Free Enterprise' in 1987 and 'Exxon Valdez' in 1989, the way of dealing with safety was reviewed and altered. The revolution came with the introduction of a Formal Safety Assessment (FSA) methodology to the shipping industry by the International Maritime Organisation (IMO) in the 1990s (Eleye-Datubo, 2006). The FSA methodology has changed the traditional reactive manner towards a proactive attitude which is a goal-setting and risk-based safety regime.

FSA can be implemented as a tool to facilitate the assessment of new regulations for marine safety and protection of the marine environment, or for making a comparison between existing and possibly improved regulations, with a view to achieving a balance between the various technical and operational problems (IMO MSC/Circ.1023, 2002). Essentially, FSA provides a comprehensive way for the application of well-known risk assessment techniques. Some organisations use probabilistic risk assessment techniques whilst others utilise possibilistic risk assessment techniques due to lack of data and information. The high level of uncertainty caused by lack of data and information has been a major issue when conducting risk assessment and this has led to the development of novel risk assessment techniques.

With the increase in ship size and power requirement to obtain high speed and manoeuvrability, ship vibration problems have become a great concern. Ship Hull

Vibration (SHV), which is mainly induced by a ship's propulsion system (propeller system and machinery), can be named as the worst situation of ship vibration problems since it leads to large structural failures and crew fatigue. Ship vibration standards, guidelines and regulations have been produced by different organisations and most of them are developed on the basis of SHV. Classification societies such as Lloyds Register (LR) and American Bureau of Shipping (ABS) have developed their regulations based on standards produced by the International Organisation for Standardisation (ISO). They highlight the acceptable vibration levels in different areas of the ship as well as providing practical guidance on eliminating excessive vibration problems at an early design stage.

The marine risk assessment, conducted on the basis of the FSA methodology, can be implemented, not only for verification purposes in design and operational processes of marine systems, but also for decision making from the early stages (Wang, 2006). Decisions made at the early design stages could have a more significant impact on the performance of a ship than those at any other stage in its life-cycle. However, since such a risk assessment is conducted at initial stages, the uncertainty, due to lack or incompleteness of the data, may be high. The level of uncertainty may be higher when ship vibration problems are considered if the organisations which deal with ship vibration problems have a poor organisational structure. This leads to difficulties in obtaining adequate vibration related data on ships, systems and components. Thus the data required for quantitative analysis is either unavailable or not in an ideal format.

There have been many major ship accidents and incidents due to harmful vibrations. Therefore, there is a need for safety improvement in the shipboard environment. There are no conceptual risk assessment methodologies available for SHV. Traditional risk assessment techniques, such as Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Preliminary Hazard Analysis (PHA), Failure Modes, Effects and Criticality Analysis (FMECA), HAZard and OPerability Study (HAZOP) and Cost per Unit Risk Reduction (CURR), may not be suitable for carrying out risk assessment due to high levels of uncertainty. The solution may have to be achieved by the development of novel risk assessment methodology of SHV, based on safety principles of FSA, utilising uncertainty treatment methods such as Evidential Reasoning (ER), Analytic Hierarchy Process (AHP), and Technique for Order Preference Similarity to Ideal Solution (TOPSIS) together with a fuzzy logic approach.

1.3. Research Aim and Objectives

The main aim of this research is to develop a novel conceptual risk assessment methodology for SHV, based on the safety principles of the FSA framework under high levels of uncertainty. The development of such a methodology would enable the organisations associated with ship vibration problems to manage and control the SHV induced risks thus improving the safety of the shipboard environment.

In order to achieve the above aim, this PhD thesis will undertake the following objective tasks:

- Conduct a comprehensive literature review to identify the current status of SHV problems to carry out risk assessment of SHV.
- Generate a novel framework to estimate the risk of SHV based on the identified hazards by using ER and fuzzy rule base.
- Create a novel approach for decision making based on the SHV risk estimation results by utilising ER, fuzzy rule base and continuous fuzzy sets.
- Develop a novel methodology to select risk control options based on the high risk areas identified from risk estimation of SHV by employing AHP and discrete fuzzy sets.
- Construct a novel method for cost benefit assessment and decision making by using AHP, TOPSIS and continuous fuzzy sets with the consideration of a reasonable amount of alternatives based on the most effective risk control option identified.

These objectives will be achieved as the research proceeds from Chapter 2 to Chapter 6. The achievement of these objectives relies upon the application of the most widely utilised uncertainty treatment methods such as ER, AHP and TOPSIS. Combined with fuzzy logic these applications provide a significant contribution to the development of novel risk assessment methodologies for SHV under the safety principles of FSA.

1.4. Challenges of Conducting the Research

SHV failure data is scarce or incomplete; as such the uncertainty associated with SHV problems may significantly undermine the risk assessment conducted based on traditional risk assessment techniques. In order to deal with SHV problems, novel risk assessment techniques have to be developed and applied. These novel uncertainty treatment methods should be capable of providing satisfactory results.

The first challenge under uncertainty comes when risk estimation is conducted for the identified hazards. Hazard identification is normally carried out by employing traditional hazard identification techniques such as PHA and HAZOP studies. Hazard identification and risk estimation can also be conducted by utilising techniques like FTA and ETA. However, due to high levels of uncertainty related to SHV problems, such techniques may be unsuitable; therefore the solution is achieved by developing a novel approach with the combination of fuzzy rule base and ER.

The second challenge is associated with decision making based on SHV risk estimation results under a high level of uncertainty. The problem becomes more complex if interval data has to be taken into account. Interval data increases the complexity of criteria aggregation which further increases the complexity of the problem. It should be noted that when the complexity of a problem increases, uncertainty will be further increased. These problems are solved and decision making is conducted by combining continuous fuzzy sets, fuzzy rule base and ER.

The third challenge under uncertainty arises when risk control options are chosen for identified areas of high risk estimation. Traditionally, high risk areas are identified by applying FMECA. Due to high levels of uncertainty of SHV problems, FMECA may not be effectively used with confidence. Therefore, a novel approach is developed by combining discrete fuzzy sets and AHP to produce sufficient risk management information to choose suitable risk control options.

The fourth challenge is that cost benefit assessment and decision making techniques such as CURR cannot be implemented due to high levels of uncertainty. This challenge is overcome by combining AHP, continuous fuzzy sets and TOPSIS. The cost benefit assessment is conducted through subjective modelling.

The five steps of the FSA framework (hazard identification, risk estimation, risk control options selection, cost benefit assessment and decision making) can be facilitated to deal with SHV problems by developing the above mentioned four subjective fuzzy modelling based approaches with a combination of various uncertainty treatment methods. Expert judgements play a vital role in this subjective assessment. The uncertainty which comes from the lack of data is recognised as the major challenge of conducting this research. There is also the challenge of validating the generic models developed in each technical chapter. These are all novel models in an area in which no conceptual scientific risk assessment work has been done so far. However, this challenge is partially met by applying these models to ocean going ships and carrying out a partial validation.

1.5. Research Methodology and Scope of Thesis

The main research methodology of this thesis is based on risk assessment conducted under the safety principles of FSA. As described in the previous sections it is achieved by using the four core technical chapters of this thesis. The main methodology is outlined in Sections 1.5.1-1.5.6.

1.5.1. Introduction and Literature Review

In Chapter 1 (current chapter) a general overview of the whole PhD thesis is given and its overall structure is highlighted. In Chapter 2 a comprehensive literature review is conducted. Firstly the available guidelines and regulations related to ship vibrations are investigated and an analysis of failure data is conducted to identify problems related to ship vibrations. After recognising the research needs, a critical review of SHV is carried out and the FSA methodology is introduced. The available techniques for conducting risk assessment are outlined and a justification of the proposed research is presented.

1.5.2. Hazard Identification and Risk Estimation

Initially, possible hazards of SHV are identified in Chapter 2 by carrying out a critical review of SHV. In Chapter 3 a generic hazard identification model is developed by combining the most significant hazards identified in Chapter 2 with the judgements of experts through a brain-storming session. The weights (importance) of each criterion are also allocated, based on expert judgements. The generic model of SHV (generic hazard identification model) includes different vibration patterns, effects of ship design criteria, and failures of components associated with a ship's propulsion system (propeller system and machinery) which are the major contributors to SHV.

It has to be noted that the generic hazard identification model includes only the most significant criteria (hazards) associated with SHV problems. The most significant criteria are obtained based on discussions with the experts in the area. It would not be practical to have a very large model including too many criteria as this increases the complexity of the generic model and it may further increase the uncertainties.

The developed generic hazard identification model is utilised to carry out risk estimation of SHV. As described in Section 1.4, traditional risk estimation methods may not be suitable in this research due to the high levels of uncertainty of SHV problems. A fuzzy rule based quantitative data transformation technique is used to transfer quantitative criteria into qualitative criteria. A fuzzy rule base is further used to develop a novel mapping process to transfer criteria into a common utility space (same universe). ER is a highly recognised uncertainty treatment method. The algorithm of ER is used to synthesise all the generic hazards and the ER based Intelligent Decision System (IDS) software is utilised to produce risk estimation results graphically. The developed novel approach is validated by carrying out a case study with the application of the developed generic hazard identification model to an ocean going bulk carrier. Chapter 3 mainly covers the hazard identification and risk estimation steps of FSA methodology.

1.5.3. Risk Estimation and Decision Making

In Chapter 4 a generic ship design criteria model is developed by taking into account ship design criteria from the hazard identification model developed in Chapter 3. All the significant ship design criteria are included in the model and discussed in detail. This model can be utilised in the selection of design options at the initial stages. As such, a generic ship design criteria model is developed for decision making purposes based on SHV risk estimation results.

The weights of the generic model are allocated based on expert judgements. In Chapter 4 the uncertainty arising from interval criteria is also considered. A novel uncertainty treatment method is developed by using continuous fuzzy sets to transfer interval quantitative criteria to a qualitative form. The mapping process is developed by using a fuzzy rule base to transform criteria into a common utility space similar to Chapter 3. Also qualitative interval criteria are converted into qualitative criteria with a single value. All the normalised criteria are taken into account and the ER algorithm is used to obtain SHV risk estimation results. An ER based utility ranking approach is used to conduct decision making based on SHV risk estimation results. The developed novel approach is validated with a case study, by applying it to five different types of ocean going ships: cargo, oil tanker, container, survey and passenger. Chapter 4 highlights decision making based on risk estimation of the FSA methodology.

1.5.4. Risk Control Options Selection Based on Risk Estimation

In Chapter 5 a generic failure events modelling structure is developed by considering failures of components in the hazard identification model of Chapter 3. This model is based only on failures, as such all the significant failures and their sources are discussed in detail. In risk studies failure events are usually considered because they have significant potential in causing ship accidents. Also, in SHV problems, failures play a major role. Therefore, in this chapter a generic structure of failure modelling is developed by considering all the significant failures onboard which lead to SHV. Four risk parameters are taken into account and risks are estimated in terms of those parameters.

In Chapter 5 high risk areas which create SHV are identified on the basis of SHV risk estimation results. ER is capable of providing total risk estimation of a system by synthesising all the inputs. However, ER may have disadvantages when estimating the high risk areas in this study because there is a need for quantifying each basic criterion. AHP can deal with such situations by conducting pairwise comparisons of the associated criteria. Discrete fuzzy sets are capable of providing a sufficient numerical relationship between the linguistic terms. In this chapter (Chapter 5) subjective assessments from experts are quantified by using discrete fuzzy sets. The quantified numerical values are used to conduct pairwise comparison by using AHP.

The areas identified as having high risk estimation are investigated to identify risk control options. A novel approach for the selection of risk control options is developed on the basis of discrete fuzzy sets. The best risk control option is selected based on effectiveness. The developed novel approach is validated through a case study which is conducted on a fishing vessel. Chapter 5 shows risk estimation, risk control options selection and decision making of the FSA methodology.

1.5.5. Cost Benefit Assessment and Decision Making

In Chapter 6 a generic model of propulsion system modelling is developed by considering cost benefit criteria. It is clear that SHV is mainly caused by the ship's propulsion system. If a ship has a propulsion system with a good design and manufacture, it will give low SHV. Also 'design and manufacture' is one of the risk control options in Chapter 5. In any case, the propulsion system has to be economical; therefore, in this chapter cost benefit criteria include not only the vibration characteristics but also annual expenses and reliability of the propulsion system. These are considered as the most significant criteria associated with propulsion systems selection. The weights of the generic model are allocated by utilising AHP.

A fuzzy TOPSIS approach is conducted by combining continuous fuzzy sets with TOPSIS. It is an approach which is well suited for the cost benefit assessment of multi-tier hierarchies, similar to the one which is considered in Chapter 6. The fuzzy TOPSIS technique is further developed by identifying weaknesses of the method. The best propulsion system is selected by allocating the highest priority to vibration characteristics. The selected propulsion system is applied to an ocean going ro-ro ship which has severe vibration problems (case study). To further validate the developed model a sensitivity analysis is conducted. In Chapter 6 the final steps (cost benefit assessment and decision making) of the FSA framework are implemented and the application of FSA for SHV modelling is completed.

1.5.6. Discussions and Conclusions

In Chapter 7 discussions and integration of the methodologies developed in this research are carried out. The limitations arising from this research are highlighted. In Chapter 8 final conclusions and recommendations are drawn and areas for further research are identified.

1.6. Structure of PhD Thesis

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

Table 1.1: Summary of Chapters in Thesis

Chapter No.	Title
1	Introduction
2	Literature Review
3	A Subjective Risk Estimation Approach for Modelling Ship Hull Vibration
4	A Subjective Decision Making Approach for Modelling Ship Design Criteria
5	A Subjective Risk Management Approach for Modelling of Failures Onboard Ships
6	A Subjective Cost Benefit Analysis Approach for Modelling Ship Propulsion Systems
7	Discussion and Integration of the Developed Methodologies
8	Conclusions and Implications

Some publications arising from this research are listed in Appendix 1 of this thesis. More papers will be submitted to academic journals for consideration of possible publication soon.

Chapter 2 – Literature Review

SUMMARY

The literature review conducted in this chapter is broad. It includes review of standards and regulations of ship vibrations, historical failure data analysis, critical review of Ship Hull Vibration (SHV), introduction of Formal Safety Assessment (FSA), critical review of marine risk assessment, and justification of research. Generally, this chapter gives an overview of the current status related to SHV problems after conducting failure data analysis and review of standards and regulations. Then the critical review of traditional and novel risk assessment is conducted to select the most suitable techniques for conducting risk assessment of SHV based on safety principles of FSA. That is followed by an introduction of the FSA methodology and a study of the current status of FSA. Finally, justification of research is discussed.

2.1. Introduction

Ship vibration problems can be considered a serous issue within the shipping environment. The International Organisation for Standardisation (ISO) has developed standards in order to maintain acceptable vibration levels onboard ships. Classification Societies, such as Lloyds Register (LR), American Bureau of Shipping (ABS) and Germanischer Lloyd (GL), have produced rules and regulations regarding ship vibrations for ships classed by them. However, most of their rules and regulations are based on the ISO standards. SHV can be considered a major problem onboard ships since it may cause large structural failures and crew fatigue (MAIB, 1990-2008).

An important change in the marine industry is the application of Formal Safety Assessment (FSA) since mid 1990s. FSA has changed the traditional reactive regulatory framework towards a risk-based and goal-setting regime. A risk assessment is carried out to complete FSA. The application of traditional methods of risk assessment may prove difficult when faced with new hazards and uncertainty. Novel approaches and techniques towards risk assessment may be required in order to deal with such problems.

In this chapter the standards and regulations related to ship vibrations are reviewed and an analysis of historical failure data is conducted. After recognising SHV as a major problem onboard ships, a critical review of SHV is conducted to determine the current status of ship vibration problems. Following the discussion of the current status of ship vibration problems, an introduction to FSA and a critical review of marine risk assessment are given. Finally, the need for this PhD research is justified.

2.2. Standards, Guidelines and Regulations Related to Ship Vibrations

In this section the standards, guidelines and regulations related to vibrations onboard ships are discussed. The standards are based on either British Standards (BS) or ISO. The vibration guidelines and regulations for ships, issued by classification societies such as LR, ABS and GL, are formulated, based on ISO standards. The classification societies use such regulations for their ship classification. The UK Maritime and Coastguard Agency (MCA) produces regulations mainly focusing on health effects due to ship vibration.

2.2.1. ISO 4867 & ISO 4868

ISO 4867 was developed in 1984 as a code for the measurement and reporting of shipboard vibration data. It is also known as BS 6632 (ISO 4867, 1984). This international standard develops uniform procedures for gathering and presenting data:

a) On hull vibration in single or multiple-shaft sea-going merchant ships.
b) For vibration of propulsion-shaft systems as it affects hull vibration.

Such data is necessary to set up uniformly the vibration characteristics of hull and propulsion shaft systems and to provide a basis for design predictions, improvements and comparison against vibration reference levels. The procedures, where applicable, can also be implemented for inland ships and tug boats. In special situations, specific investigative studies might be required where objectionable vibration is found to exist. ISO 4867 is concerned with:

a) Vibration of the main hull girder and superstructure excited by the propulsion system at shaft rotational frequency, at propeller blade rate, harmonics of the blade rate and at frequencies associated with the major components of machinery.
b) Excitation of the propulsion shaft and main machinery system.

ISO 4867 gives general principles of vibration measurement onboard ships to improve the safety onboard environment. Therefore, in individual cases, items to be measured may be selected or added to meet the aims of the vibration measurement of each ship type. Such kind of measurement procedure would be useful in this study because the risk estimation results obtained from this study can be considered in conjunction with actual vibration measurements in order to provide a benchmark.

Local vibration of ships is considered in ISO 4868 (ISO 4867, 1984). It was published in 1984 as a code for the measurement and reporting of local vibration data of ship structures and equipment. It is also known as BS 6633.

2.2.2. ISO 6954 (1984) & ISO 6954 (2000)

The first version of ISO 6954 (BS 6634) was published in 1984 to highlight guidelines for the overall evaluation of vibration in merchant ships (ISO 6954, 1984). This international standard states severities of vibration which could be used as references for the relative evaluation of:

a) Hull and superstructure vibration in normally occupied spaces.
b) Shipboard vibration data, useful for the development and improvement of hull vibration reference amplitudes.

It is applicable to both turbine and diesel driven merchant ships of length between perpendiculars 100m or greater. ISO 6954 (1984) is not intended to establish vibration criteria for acceptance or testing of machinery or equipment. The applicable frequency range is 1 to 100 Hz.

The second version of ISO 6954 (BS ISO: 2000) was developed in 2000 to emphasise guidelines for the measurement, reporting and evaluation of vibration with regard to habitability on passenger and merchant ships (ISO 6954, 2000). This international standard highlights the guidelines for evaluating the habitability of different areas on a ship. The habitability is assessed by the overall frequency-weighted r.m.s. vibration values from 1 Hz to 80 Hz. ISO 6954 (2000) also contains instrumentation requirements, measurement procedures, analysis specifications and assessment guidelines for the assessment of ship vibration with respect to habitability. Vibration data acquired in accordance with this international standard is also useful for comparison with ship specifications, comparison with other vessels and further development and improvement of vibration standards.

This standard recommends that the classification to be applied to the various areas of a ship be agreed between the interested parties (e.g. ship builder and ship owner) prior to any assessment of the habitability. Table 2.1 gives guidelines for the values above which adverse comments are probable, and values below which adverse comments are not probable. The values are expressed in terms of the overall frequency-weighted r.m.s. acceleration (mm/s^2) and overall frequency-weighted r.m.s. velocity (mm/s) in the range from 1 Hz to 80 Hz.

Table 2.1: Overall Frequency-Weighted r.m.s. Values from 1 Hz to 80 Hz Given as Guidelines for the Habitability of Different Areas on a Ship

	Area Classification					
	Passenger Cabins		Crew Accommodation		Working	
	mm/s^2	mm/s	mm/s^2	mm/s	mm/s^2	mm/s
Values above which adverse comments are probable	143	4	214	6	286	8
Values below which adverse comments are not probable	71.5	2	107	3	143	4

Measurements in accordance with ISO 6954 (2000) may be carried out using different types of measuring and recording equipment, e.g. instruments of analogue, digital, spectral or time-based type. The measuring instrumentation shall meet the requirements of ISO 8041 which is the code for human response to vibration-measuring instrumentation (ISO 8041, 2005). It is acceptable to use instruments manufactured in accordance with ISO 8041 that have frequency indications above 80 Hz provided that the filter characteristics comply with ISO 2631-2.

2.2.3. List of International and National Standards Related to Ship Vibrations

The international standards, such as ISO 4867, ISO 4868, ISO 6954 (1984) and ISO 6954 (2000), are the most widely used standards in the ship vibration industry. They have been employed by classification societies such as LR, ABS and GL for the formulation of their regulations for ship vibration. Table 2.2 lists the possible international standards which are used by LR, these are also used by other classification societies and organisations related to ship vibration (LR, 2006).

Table 2.2: International Standards Related to Ship Vibrations

Serial Number	Name of the Standard
IEC.92-504	Electrical installations in ships. Special features: control and instrumentation.
ISO.2041:1990	Glossary of terms relating to mechanical vibration and shock.
ISO.2372	Mechanical vibration of machines with operating speeds from 10 to 100 rev/s - Basis for specifying evaluation standards.
ISO.2373	Mechanical vibration of certain rotating electrical machinery with shaft heights between 80 and 400 mm - Measurement and evaluation of the vibration severity.
ISO.2631-1:1997	Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration – Part 1: General requirements. Similar, but not identical to, BS.6841.
ISO.2631-2:1989	Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration – Part 2: Continuous and shock induced-vibrations in buildings (1 to 80 Hz).
ISO.3945	Mechanical vibration of large rotating machines with speed range from 10 to 200 rev/s - Measurement and evaluation of vibration severity in situ.
ISO.4548-7:1990	Methods of test for full-flow lubricating oil filters for internal combustion engines - Part 7: Vibration fatigue test.
ISO.4866:1990	Mechanical vibration and shock - Vibration of buildings - Guidelines for the measurement of vibrations and evaluation of their effects on buildings.
ISO.4867:1984	Code for the measurement of and reporting of shipboard vibration data.
ISO.4868:1984	Code for the measurement of local vibration data of ships structures and equipment.
ISO.6954:1984	Mechanical vibration and shock - guidelines for the overall

	evaluation of vibration in merchant ships.
ISO.6954:2000	Mechanical vibration - Guidelines for the measurement, reporting and evaluation of vibration with regard to habitability on passenger and merchant ships
ISO.7919-1:1996	Mechanical vibration of non-reciprocating machines - Measurements on rotating shafts and evaluation criteria - Part 1: General guidelines.
ISO.7919-2:2001	Part 2: Land-based steam turbines and generator in excess of 50 MW with normal operating speeds of 1500 RPM, 1800 RPM, 3000 RPM, and 3600 RPM.
ISO.7919-3:1996	Part 3: Coupled industrial machines.
ISO.7919-4:1996	Part 4: Gas turbine sets.
ISO.7919-5:1996	Part 5: Machine sets in hydraulic power generating and pumping plants.
ISO.8528-9:1995	Reciprocating internal combustion engine driven alternating current generating sets - Part 9: Measurement and evaluation of mechanical vibrations.
ISO.8579-2	Acceptance code for gears - Part 2: Determination of mechanical vibrations of gears during acceptance testing.
ISO.10816-1:1995	Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts - Part 1: General guidelines.
ISO.10816-2:2001	Part 2: Land-based steam turbines and generator sets in excess of 50 MW with normal operating speeds of 1500 RPM, 1800 RPM, 3000 RPM, and 3600 RPM.
ISO.10816-3:1998	Part 3: Industrial machines with nominal power above 15 kW and nominal speeds between 120 RPM and 15000 RPM when measured in situ.
ISO.10816-4:1998	Part 4: Gas turbine sets excluding aircraft derivatives.
ISO.10816-5:2000	Part 5: Machine sets in hydraulic power generating and pumping plants.
ISO.10816-6:1995	Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts - Part 6: Reciprocating machines with power ratings above 100 kW.

Most of the UK national standards (BS) are based on the ISO standards. The UK national standards are listed in Table 2.3.

Table 2.3: UK National Standards Related to Ship Vibrations

Serial Number	Name of the Standard
BS.3015:1991	Same as ISO.2041:1990
BS.5000:1980	Specification for rotating machines of particular types or for particular applications. Part 3. Generators to be driven by reciprocating internal combustion engines.
BS.6472:1992	Guide to evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz).
BS.6632:1985	Same as ISO.4867
BS.6633:1985	Same as ISO.4868
BS.6634:1985	Same as ISO.6954
BS.6841:1987	Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock.
BS.6842:1987	Measurement and evaluation of human exposure to vibration transmitted to the hand.
BS.7385:1990	Same as ISO.4866
BS.7698:1993	Same as ISO.8528
BS.7854	Same as ISO.10816
BS.ISO.7919	Same as ISO.7919
PD.12349:1997	Mechanical vibration - Guide to the health effects of vibration on the human body.
VDI.2063	Measurement and evaluation of mechanical vibrations of reciprocating piston engines and compressors.

These international and national standards are used by classification societies and other organisations to produce their ship vibration regulations. Standards can be used either individually or in combination with each other to generate regulations.

2.2.4. Lloyds Register Guidelines and Regulations

LR is one of the largest classification societies in the world. They have done a tremendous amount of work in the area of ship vibration and have developed ship vibration guidance notes for ships classed with LR (LR, 2006). These guidance notes define the application of proposed criteria for assessing the severity of shipboard vibration in the following areas:

- Accommodation and workspaces with regard to habitability.
- Local structural vibration with regard to risk of cracking.

- Machinery vibration with regard to risk of damage or accelerated wear.
- Hull surface pressure with regard to propeller induced excitation.

The differences between ISO 6954 (1984) and ISO 6954 (2000) guidelines for the overall evaluation of vibration in merchant ships are also covered. However, these guidance notes do not cover torsional, axial or lateral vibration of shafting systems. The rules and regulations of LR are based on ISO and BS and they can be applied for any ship type. The benchmark has been produced to maintain acceptable vibration levels in different areas of a ship. Anon (1999) gives a benchmark for acceptable vibration levels in passenger ships, yachts and high speed crafts for crew and passenger accommodation comfort.

LR has dealt with shaft vibration problems such as torsional, axial and lateral in 1978 (LR, 1978). Those guidelines show the calculation of torsional natural frequencies in a shafting system by using the Holzer method. The Holzer method is still in use at LR for the calculation of torsional natural frequencies in a shaft system. LR (1978) also discusses shaft vibration problems due to axial, lateral vibrations and shaft misalignment.

2.2.5. American Bureau of Shipping Guidelines and Regulations

ABS has produced guidelines of ship vibrations specifically for shipyards, naval architects and ship owners with practical guidance on the concept design to avoid excessive ship vibration at an early design stage (ABS, 2006a). These guidance notes also assist with the Finite Element Analysis (FEA) based vibration analysis procedure to predict the vibration response and evaluate the design in detail at design stages. The vibration analysis procedure represents the most current analysis procedure at ABS. These guidance notes also supply guidelines on the vibration measurement procedure during sea trials and the acceptance criteria on vibration limits based on the international standards and practice in ABS.

ABS provides the vibration acceptance criteria covering three areas as a reference by incorporating the international standards and industry practices. They are as follows:

- Vibration limits for crew and passengers.
- Vibration limits for local structures.
- Vibration limits for machinery.

ABS has produced special vibration guideline limits for main propulsion machinery. They are listed in Table 2.4.

Table 2.4: Vibration Guidelines for Main Propulsion Machinery

Propulsion Machinery	Limits (r.m.s.)
Thrust bearing and bull gear hub	5 mm/s
Other propulsion machinery components	13 mm/s
Stern tube and line shaft bearing	7 mm/s
Diesel engine at bearing	13 mm/s
Slow and medium speed diesel engine on engine top (over 1000 HP)	18 mm/s
High speed diesel engine on engine top (less 1000 HP)	13 mm/s

The vibration limits are provided in terms of broadband root mean square (r.m.s.) values with multi-frequency components (normally from 1 to 1000 Hz). The longitudinal vibration (r.m.s., free route) at thrust bearing (and bull gear hub for geared turbine drives) is to be less than 5mm/s r.m.s. For other propulsion machinery components exclusive of engines, propellers and shafting aft of the thrust bearing, the longitudinal vibration is to be less than 13mm/s r.m.s. For stern tube and line shaft bearing, the lateral vibration is to be less than 7mm/s r.m.s. For direct diesel engines (over 1000 HP, slow and medium speed diesels connected to the shafting), the vibration limits are 13mm/s at the bearings and 18mm/s on the engine tops, in all three directions. For high speed diesel engines (less than 1000 HP), the vibration is to be less than 13mm/s at the bearings and engine tops in all directions.

ABS has also published guidance notes on propulsion shafting alignment to minimise shaft system induced vibrations (ABS, 2006b) and improve passenger comfort and crew habitability on ships by highlighting whole-body vibration and maximum acceptable whole-body vibration levels (ABS, 2001a; ABS, 2002). ABS uses all those guidelines and regulations as a benchmark for their ship classification and quality control purposes.

2.2.6. Germanischer Lloyd Guidelines and Regulations

GL is a German ship classification society. They also have identified essential areas for the formulation of specifications which define vibration limits and produce ship vibration regulations concerning the following (GL, 2001):

- Effect of vibrations on human beings.
- Structural vibrations.
- Vibrations of engines and equipment items.

GL regulations are also dependent on the ISO standards. Based on the ISO standards they have developed class notations as a benchmark for their ship classification in terms of vibration levels onboard. The respective GL class notation is called "harmony class". It is focused on vibration criteria onboard passenger ships in the first step and will be followed by additional criteria for other ship types. The comfort is scaled based on harmony criteria numbers (hcn) 1 to 5, where 1 highlights an extraordinary comfort (most ambitious level). The rules and regulations not only comprise limits and assessment procedures for the normal (sea going) service condition but also account for thrusters operation. Table 2.5 shows vibration limits for passenger spaces in terms of hcn. For example, when there is a vibration level equal or less than 0.8 in first class cabins, it shows hcn '1' which is an extraordinary comfort.

Table 2.5: Vibration Limits for Passenger Spaces

Vibration Limits	Sea Mode					Thrusters Operation				
	hcn					hcn				
	1	2	3	4	5	1	2	3	4	5
Indoor Spaces										
First class cabins	0.8	1.2	1.6	2.0	2.4	1.6	2.0	2.4	2.8	3.2
Standard cabins	1.2	1.7	2.2	2.7	3.2	2.0	2.4	2.8	3.2	3.6
Public spaces (short exposure time)	2.0	2.5	3.0	3.5	4.0	-	-	-	-	-
Public spaces (long exposure time)	1.4	1.9	2.4	2.9	3.4	-	-	-	-	-
Outdoor Spaces										
Open deck recreation	2.0	2.4	2.8	3.2	3.6	-	-	-	-	-
Open deck recreation, overhangs	2.2	2.6	3.0	3.4	3.8	-	-	-	-	-

The class notation requires a detailed documentation of plans and drawings to be submitted by the building yard. On this basis the survey programs, describing the extent of vibration measurements for different criteria and operation modes, are checked and finally approved. The measurements cover a variable but relatively high percentage of the various kinds of spaces and areas of the ship. The measurements of each space investigated are documented in the survey report and finally condensed to an hcn which is the final result certified in the class notation.

GL has also published their own rules and regulations based on the ISO standards for machinery systems. Here, values quoted to avoid premature failure or malfunctions of components must not be exceeded by engines' equipment items or peripheral devices.

By referring to Sections 2.2.4-2.2.6, it is clear that the classification societies have done a tremendous amount of work for the area of ship vibrations. Vibration not only affects the ship structure but also crew and passengers; LR, ABS and GL classification societies have produced maximum acceptable levels of vibration on a ship in order to obtain appropriate comfort levels. Those levels are used for ship classification in such classification societies. Such vibration levels can also be combined with the results of developed risk estimation models in this study to support decision making process.

2.3. Historical Failure Data Analysis

In order to carry out any kind of safety or risk assessment process, either qualitative or quantitative, it is necessary to obtain reliable failure data. The amount of data available will determine the choice of safety or risk assessment methods. The relevance and accuracy of data used will increase confidence in those assessments. It is admitted that qualitative risk assessment requires less detailed historical failure data compared with Quantitative Risk Assessment (QRA) (Wang & Foinikis, 2001). Generally, failure data can be obtained from the following sources:

1. Field experience (historical data) including:
   - Data collection programmes by government agencies.
   - Data collection programmes by classification societies.
   - Data collection programmes by insurance companies and P&I clubs.

- Statistics maintained by private shipping companies.

2. Agreed judgmental estimates of experts.

Classification societies may be a very useful source of failure data mainly because of the large amount of ships classed by each one. However, data from these organisations should be critically evaluated before being used or combined with others. In this chapter, failure data from one of the world's leading classification societies, LR, is analysed. It is possibly the most complete set of data currently available for the 15-year period from 1992 to 2007. The failure data analysis in this chapter concerns defects on vessels classed by LR due to Propulsion System Vibration (PSV) and SHV (MDS, 1992-2007).

2.3.1. Propulsion System Component Defects Induced by Propulsion System Vibration

In this section failure data analysis is conducted based on defects of propulsion system induced by vibration for 34 ship types. However, based on the data, 14 ship types were identified as having a high number of defects compared with the defects of other 20 ship types. Each of the 14 selected ship types contributes at least 1% to the total number of defects. Figure 2.1 shows the total number of defects recorded for a specific ship type and Table 2.6 shows them as percentage values. More data can be found in Appendix 2.1.

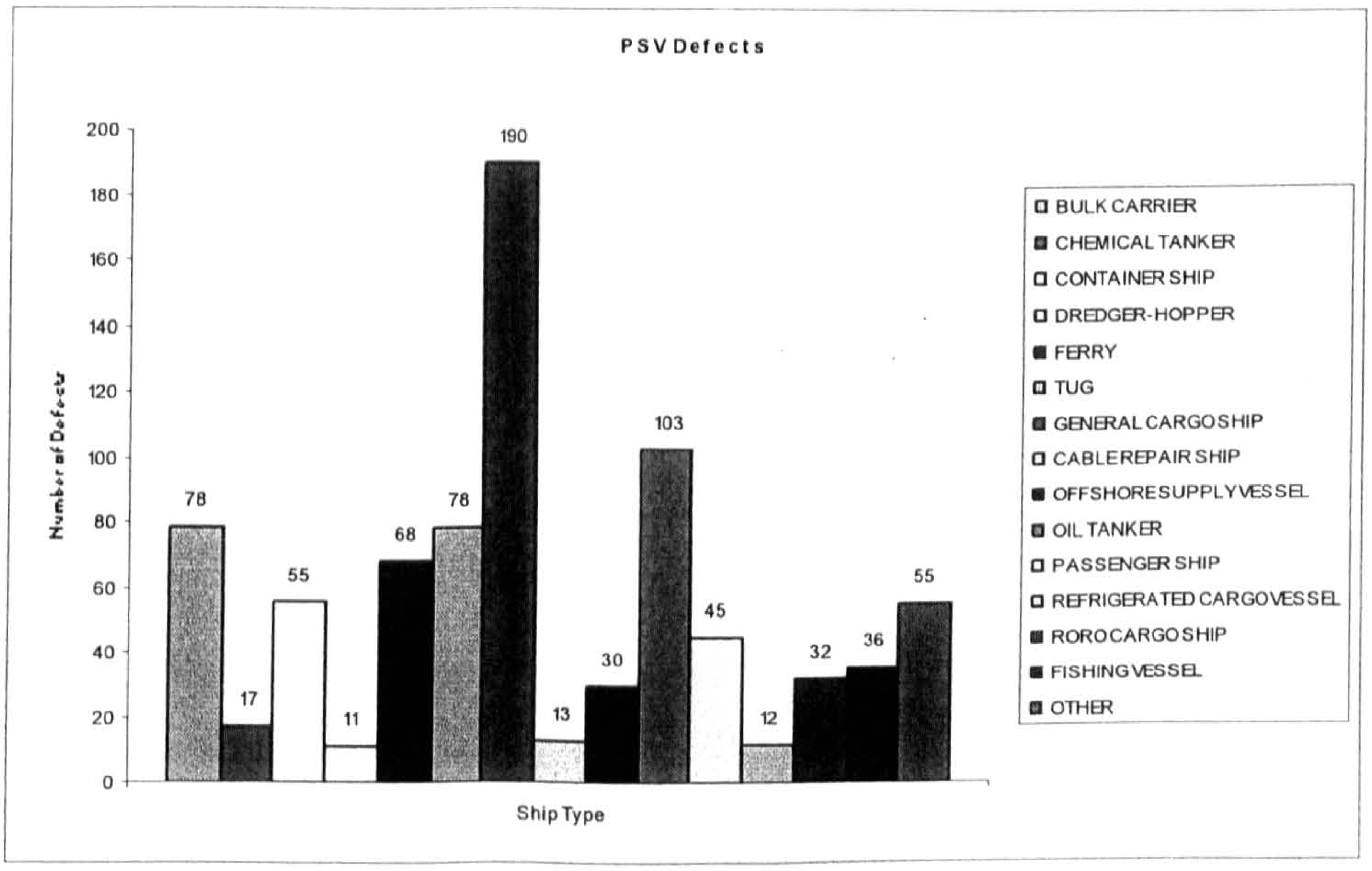


Figure 2.1: Propulsion System Vibration Defects (MDS, 1992-2007)

Table 2.6: Percentages of Propulsion System Vibration Defects

Ship Type	Percentage (%)
Bulk Carrier	9.5
Chemical Tanker	2.1
Container Ship	6.7
Dredger-Hopper	1.3
Ferry	8.3
Tug	9.5
General Cargo Ship	23.1
Cable Repair Ship	1.6
Offshore Supply Vessel	3.6
Oil Tanker	12.5
Passenger Ship	5.5
Refrigerated Cargo Vessel	1.5
RoRo Cargo Ship	3.8
Fishing Vessel	4.3
Other	6.7

From the analysis it is clear that general cargo ships have the highest number of propulsion system induced vibration defects (190) accounting for 23.1% of overall defects. General cargo ships are followed by oil tankers (103 and 12.5%), tugs (78 and 9.5%), bulk carriers (78 and 9.5%), ferries (68 and 8.3%) and so on. All those defects can be further broken down to component level. For example, four major components of the propulsion system are identified which have high numbers of defects, namely, shaft system, propellers, power generation plant and propulsion engine. They are shown in Figure 2.2 while Figure 2.3 shows the percentage values of them.

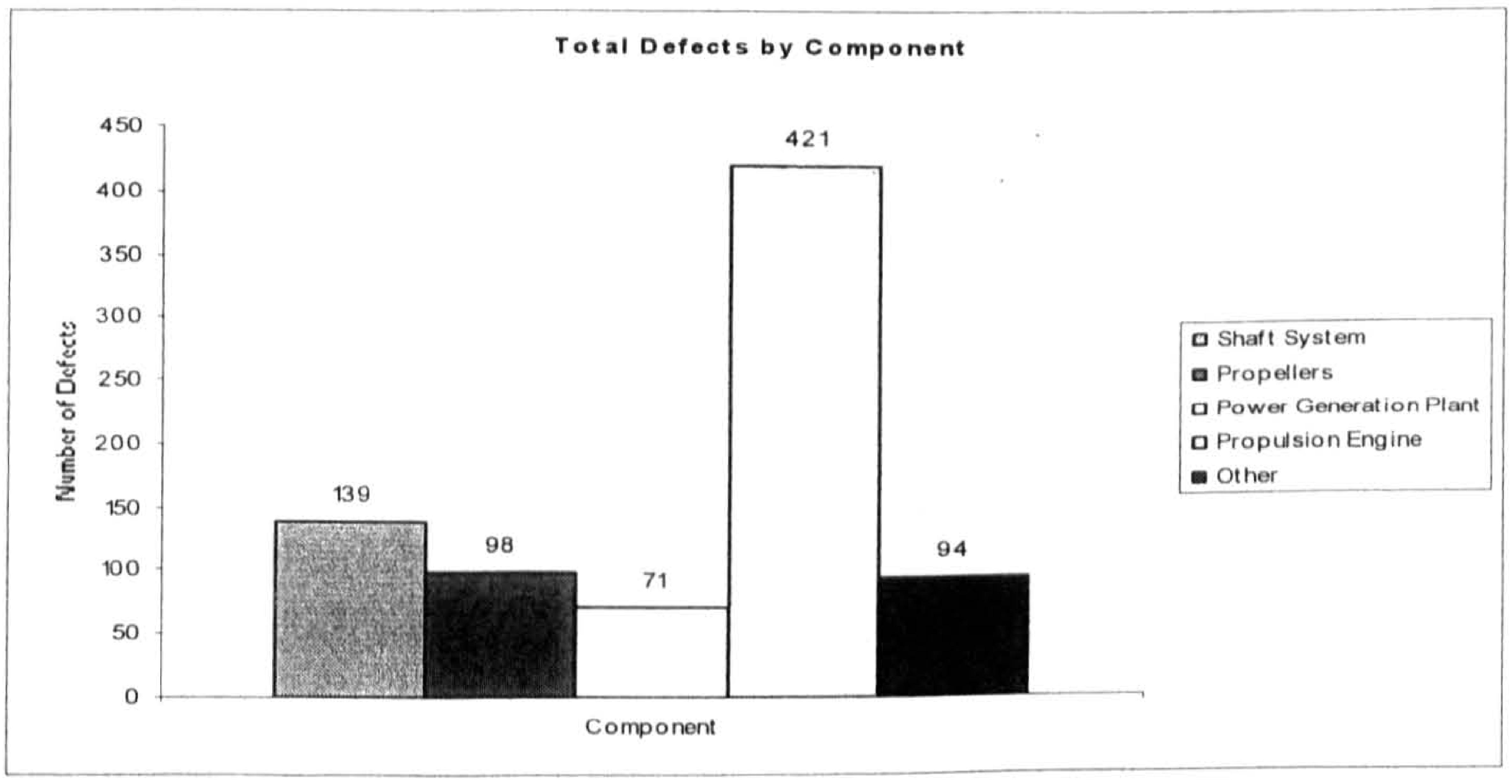


Figure 2.2: Total Propulsion System Defects by Component (MDS, 1992-2007)

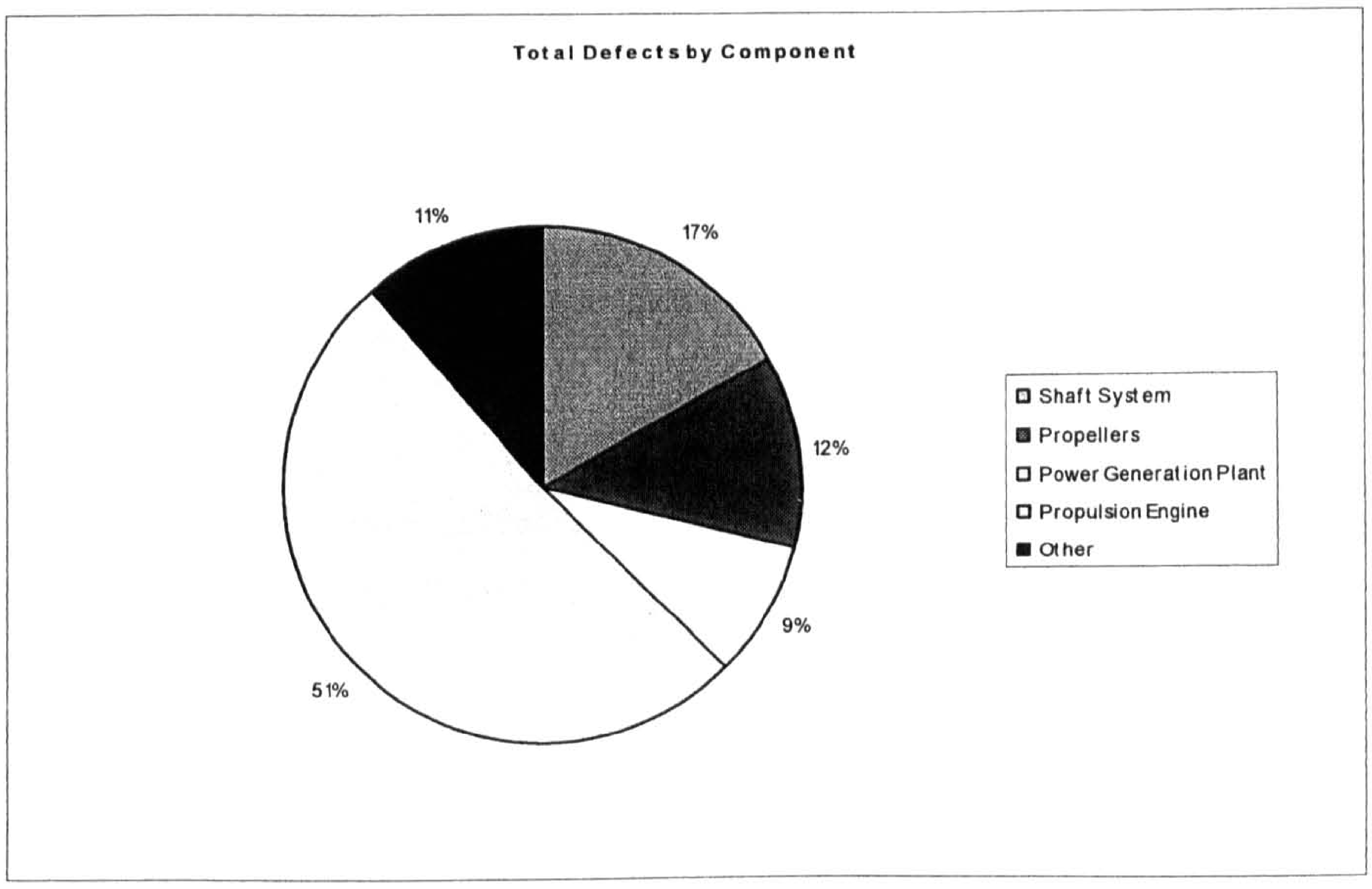


Figure 2.3: Percentages of Total Propulsion System Defects by Component (MDS, 1992-2007)

By referring to Figures 2.2 and 2.3, it is obvious that the highest number of defects of propulsion system is related to propulsion engine (51%). That is followed by shaft system (17%), propellers (12%), other small defects of components (11%) and power generation plant (9%). Table 2.7 highlights the component defects by ship type.

Table 2.7: Component Defects by Ship Type

Ship Type	Shaft System	Propellers	Power Generation Plant	Propulsion Engine	Other	Total
Bulk Carrier	6	8	1	56	7	78
Chemical Tanker	2	6	3	6	0	17
Container Ship	14	0	5	32	4	55
Dredger-Hopper	0	5	2	3	1	11
Ferry	9	6	12	23	18	68
Tug	17	15	4	12	30	78
General Cargo Ship	30	24	4	128	4	190
Cable Repair Ship	2	0	5	2	4	13
Offshore Supply Vessel	5	2	8	14	1	30

Oil Tanker	8	4	15	72	4	103
Passenger Ship	14	2	0	21	8	45
Refrigerated Cargo Vessel	1	1	0	9	1	12
RoRo Cargo Ship	8	8	7	7	2	32
Fishing Vessel	6	9	2	19	0	36
Other	17	8	3	17	10	55
Total	**139**	**98**	**71**	**421**	**94**	**823**

From Table 2.7 it is apparent that the propulsion engine has a very high number of defects for four ship types compared with defects of all the other components. These four ship types are, namely, general cargo ships (128), oil tankers (72), bulk carriers (56) and container ships (32).

2.3.2. Ship Hull Defects Induced by Ship Hull Vibration

In this section failure data analysis is conducted based on ship hull defects induced by SHV. From the LR data 14 major ship types are identified which have high numbers of defects. Those 14 ships are identified because they each contribute over 1% to the overall defects. Figure 2.4 shows the number of SHV defects associated with each ship type and Table 2.8 shows their percentages. More data can be found in Appendix 2.2.

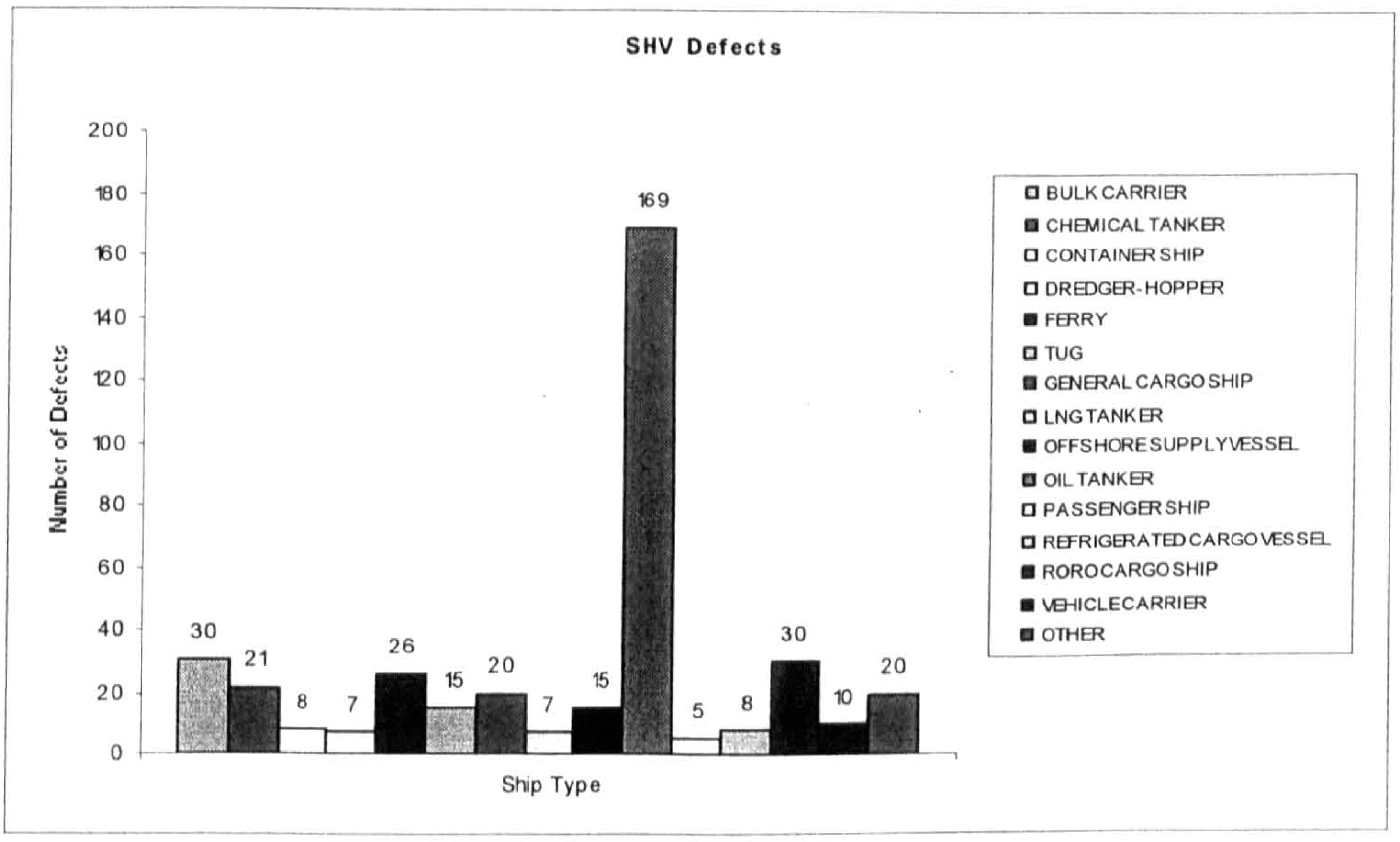


Figure 2.4: SHV Defects (MDS, 1992-2007)

Table 2.8: Percentages of SHV Defects

Ship Type	Percentage (%)
Bulk Carrier	7.7
Chemical Tanker	5.4
Container Ship	2.0
Dredger-Hopper	1.8
Ferry	6.6
Tug	3.8
General Cargo Ship	5.1
LNG Tanker	1.8
Offshore Supply Vessel	3.8
Oil Tanker	43.2
Passenger Ship	1.3
Refrigerated Cargo Vessel	2.0
RoRo Cargo Ship	7.7
Vehicle Carrier	2.6
Other	5.2

By referring to Figure 2.4 and Table 2.8 it is clear that SHV defects of oil tankers are significantly high compared with SHV defects of all the other ship types. There are 169 SHV defects recorded for oil tankers which account for 43.2% of the overall defects. SHV defects of the oil tankers are followed by those of bulk carriers (30 and 7.7%), roro cargo ships (30 and 7.7%), ferries (26 and 6.6%) and so on. SHV defects recorded are not equally distributed to sections of ship hull structure (all steel plates). Figure 2.5 highlights the areas of SHV defects recorded.

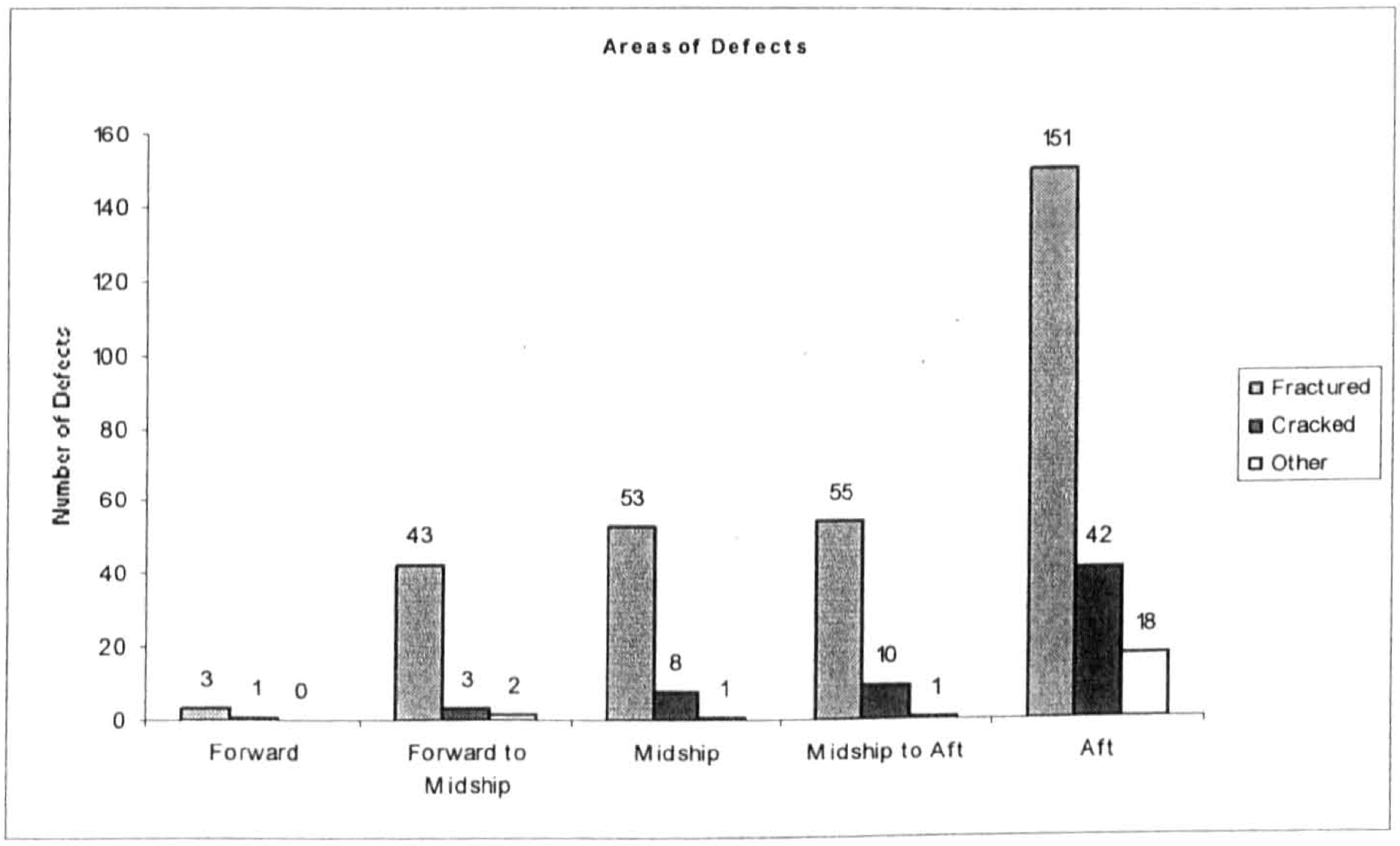


Figure 2.5: Areas of SHV Defects Recorded (MDS, 1992-2007)

According to the graphical representation of Figure 2.5 it is obvious that the ship aft section has the highest number of SHV defects recorded. In any section fracture defects are the highest and cracks are the second. Compared with fractures and cracks other small defects are minor in any section. Tables 2.9-2.13 show the areas of different types of SHV defects associated with the ship types.

Table 2.9: Number of SHV Defects of the Forward Section

Forward	Fractured	Cracked	Other
Bulk Carrier	0	0	0
Chemical Tanker	0	0	0
Container Ship	0	0	0
Dredger-Hopper	0	0	0
Ferry	0	0	0
Tug	0	0	0
General Cargo Ship	0	0	0
LNG Tanker	0	0	0
Offshore Supply Vessel	0	0	0
Oil Tanker	3	0	0
Passenger Ship	0	0	0
Refrigerated Cargo Vessel	0	0	0
RoRo Cargo Ship	0	0	0
Vehicle Carrier	0	0	0
Other	0	1	0
Total	**3**	**1**	**0**

Table 2.10: Number of SHV Defects of the Forward to Midship Section

Forward to Midship	Fractured	Cracked	Other
Bulk Carrier	1	0	0
Chemical Tanker	0	0	0
Container Ship	0	0	0
Dredger-Hopper	0	0	0
Ferry	0	0	0
Tug	2	0	0
General Cargo Ship	0	0	0
LNG Tanker	1	1	0
Offshore Supply Vessel	0	0	0

Oil Tanker	38	0	1
Passenger Ship	1	0	1
Refrigerated Cargo Vessel	0	0	0
RoRo Cargo Ship	0	1	0
Vehicle Carrier	0	0	0
Other	0	1	0
Total	**43**	**3**	**2**

Table 2.11: Number of SHV Defects of the Midship Section

Midship	Fractured	Cracked	Other
Bulk Carrier	1	2	0
Chemical Tanker	8	1	0
Container Ship	1	1	0
Dredger-Hopper	0	0	0
Ferry	0	0	0
Tug	0	0	0
General Cargo Ship	0	0	0
LNG Tanker	1	1	0
Offshore Supply Vessel	1	0	0
Oil Tanker	34	2	1
Passenger Ship	1	0	0
Refrigerated Cargo Vessel	0	0	0
RoRo Cargo Ship	1	0	0
Vehicle Carrier	0	0	0
Other	5	1	0
Total	**53**	**8**	**1**

Table 2.12: Number of SHV Defects of the Midship to Aft Section

Midship to Aft	Fractured	Cracked	Other
Bulk Carrier	1	0	0
Chemical Tanker	6	0	0
Container Ship	0	1	0
Dredger-Hopper	0	0	0
Ferry	3	0	0
Tug	1	0	1
General Cargo Ship	0	0	0

LNG Tanker	1	1	0
Offshore Supply Vessel	0	0	0
Oil Tanker	38	1	0
Passenger Ship	0	0	0
Refrigerated Cargo Vessel	0	0	0
RoRo Cargo Ship	3	4	0
Vehicle Carrier	0	0	0
Other	2	3	0
Total	**55**	**10**	**1**

Table 2.13: Number of SHV Defects of the Aft Section

Aft	Fractured	Cracked	Other
Bulk Carrier	11	12	2
Chemical Tanker	3	1	2
Container Ship	4	0	0
Dredger-Hopper	6	0	1
Ferry	18	4	1
Tug	4	7	0
General Cargo Ship	14	4	2
LNG Tanker	0	1	0
Offshore Supply Vessel	12	2	0
Oil Tanker	47	4	1
Passenger Ship	1	1	0
Refrigerated Cargo Vessel	4	2	2
RoRo Cargo Ship	15	4	2
Vehicle Carrier	6	0	2
Other	6	0	3
Total	**151**	**42**	**18**

Based on Tables 2.9-2.13 it is apparent that the number of SHV defects increases gradually for almost all ship types, from the forward section, to the midship to aft section. However, in the aft section there is a significant increase in SHV defects. In each section oil tankers have the highest number of SHV defects. In every case oil tankers have suffered from fracture defects induced by SHV which can be named as the worst situation compared with cracks or other minor defects.

From the failure data analysis it is clear that SHV induced defects can give severe consequences such as fractures of steel structure. It is also clear that the number of fractures increases from ship forward to the aft. In the aft section not only fractures but also other defects increase for any ship type. Based on experts' judgements, it appears that SHV mainly comes from the propulsion system which is located in aft section (in many cases) of the ship. That is the major reason for high SHV defects in the aft section. SHV is considered as a major problem onboard ships because it not only results in large structural failures but also crew fatigue. There is a significant health risk associated with SHV. Therefore, there is a need for safety improvement of ships by minimising associated SHV.

Although PSV and SHV defects are recorded, their sources have not been clearly defined. Only a few detailed accident reports could be obtained from Marine Accident Investigation Branch (MAIB) when conducting this research. Those few accidents are highlighted in the Introduction of Chapters 3, 4, 5, and 6. Therefore, it can be seen that SHV problems have a high level of uncertainty. A critical review of SHV is conducted in the next section in order to identify possible sources of SHV and the current status of ship vibration problems.

2.4. Critical Review of Ship Hull Vibration

At the end of the 19th century there was a huge increase in propulsion power to meet the ever increasing demand for faster ships. Many cases of serious vibration were experienced at that time. The first systematic investigation of SHV was made by Schlick in 1884 (Todd, 1961). Schlick published the first of a long series of papers on SHV. The following outlines some of the relevant experimental work and theories that have been conducted in the prediction and prevention of SHV.

Schlick pointed out that hull vibration is due to some disturbing forces in engines, shafting or propellers; with reciprocating engines there is always some unbalanced force remaining, and disturbing forces may also arise from unbalance of the propellers or shafting, either mechanical or hydrodynamic. Schlick expressed the option that the only way to avoid serious vibration is to prevent resonance, this being more easily achieved by altering the pitch of the propeller so as to reduce the Revolutions Per Minute (RPM). It was recommended that greater care should be taken in the manufacture of propulsion systems in order to avoid harmful vibrations. Schlick did a tremendous amount of work in the area of ship vibrations and most of his theories are still valid.

In 1892 Yarrow expressed the opinion that vibrations were caused by the inertia forces of the reciprocating masses in the engines, except that they might also be due to bad workmanship or need of repair e.g. propellers not concentric with the shafts or the area and pitch of the propeller blades not being identical (Todd, 1961). A paper published by Yarrow in 1892 described methods of balancing of engines by using the balancing weights on the crank web.

Lewis in 1927 pointed out that the diesel engine was a relatively new form of prime mover of ships and that with its higher revolutions, as compared with those of old steam reciprocating engines, there was much more chance of synchronism with higher modes of hull vibration (Todd, 1961). Methods of calculating natural hull frequencies were reviewed and the necessity of taking into account the virtual mass effect of the surrounding water was noted.

Taylor in 1928 gave the first of many contributions to the subject of ship vibration, where hull frequency calculation problem was reviewed and applied to the method suggested by Morrow for a non-uniform bar and also dealt with torsional vibration giving a rational formula (Todd, 1961). In 1930 and 1931 Taylor carried out various experiments on merchant ships and made some observations on the decay of vibration in ship hulls in an effort to measure its damping coefficient.

Despite all the care and attention that may be devoted to the balancing of engines, auxiliaries and propellers, some vibration forces are always transmitted to the ship's structure and even if they do not give rise to resonant vibration of the whole hull, they frequently induce local resonance of deck beams, plating and so on which is objectionable on grounds of comfort, local fatigue stresses or because of its effects on instruments and control equipment (Todd, 1961). Such vibrations can be reduced by the use of vibration dampers and the theory underlying these devices was clearly set out in 1933 by Inglis of Cambridge University.

In 1935 Lewis again presented the results of theoretical and experimental investigations into the cause of hull vibration as excited by propellers (Todd, 1961). From the analysis Lewis deduced that adequate fore and aft clearance between bossing end and propeller blades is more important than propeller tip clearance and more easily arranged.

In 1947 Prohaška carried out some experiments on virtual mass for vertical vibration which in many ways confirmed the earlier theoretical work of Taylor and Lewis (Todd, 1961). Prohaska extended the work of the latter to some new ship type sections, comparing V and U shapes.

Forthergill gave a rather extensive survey of the history of ship vibration problems in 1952 (Todd, 1961). Problems such as engine unbalance, torsional vibrations and the effects of transverse engine vibrations were examined in detail.

Voigt described the work on ship vibration being carried out by the Technical Committee on Vibration of the Schiffbautechnische Gesellschaft (STG) together with the work of the Germanischer Lloyd (GL) in 1953 (Todd, 1961). Voigt dealt at some length with engine vibration and made recommendations regarding desirable propeller clearances in the aperture for single screw ships.

In the 1950s more and more propellers were designed for the purpose of reducing the vibration forces transmitted to the hull (Todd, 1961). Careful consideration was given to the number of blades to use in order to reduce the magnitude of the periodic forces and to change the blade frequency to avoid resonances. As a result propellers having five and six blades were fitted to ships at that period.

LR conducted many investigations into hull vibration, frequently in association with the British Ship Research Association (BSRA) and an account of this experience was given by Bunyan in 1955 (Todd, 1961). Bunyan dealt at length with the effects on hull vibration of changes in disposition of cargo, clearances of propeller from hull and rudder, and engine balancing, and offered suggested relationships between the frequencies of the 2-node vertical and horizontal hull modes and those of the higher modes for cargo vessels and tankers.

Due to the high power being transmitted, and perhaps due to a greater awareness of vibration problems, increasing emphasis was directed towards propeller-excited vibration at the beginning of the 1960s (Todd, 1961). This is due to the effects of varying pressure in the water causing 'surface' forces and the varying wake causing 'bearing' forces. The variations in pressure around a propeller working in open water, which is called free-field pressures, were investigated theoretically for twin screw ships by Ramsay. Ramsey showed how the pressures in the fluid were reduced with increasing tip clearance and with increasing the number of blades.

A literature survey from 1884 to 1960 was obtained from Todd (1961). Todd has also undertaken extensive work in the area of ship vibrations, most of the theories and formulas which were proposed by him are still in use.

Cavitation induced excitation forces stem from undesirable combinations of the propeller and hull designs (Fitzsimmons, 1977). This work considered the effects of cavitation number and wake non-uniformity. The results offered two options for the reduction of high excitation forces to acceptable levels for a given design. They are namely reduction of the propeller RPM (frequency of rotation) to increase the cavitation number, and improvement of wake distribution by modifications to aft-end shape.

The six vessels of the Maersk "E" class were built in 1979-1980 in Denmark (Hadler *et al.,* 1985) and were classified under LR and registered under the flag of Denmark. By applying different propeller designs for these Maersk "E" class ships, it was observed that high skew at blade tip, unloading blade tips, increase in diameter and blade area, thickening of tips and use of wide tips give very low cavitation pattern as well as very low blade frequency harmonics. As a consequence of increasing engine power output and changing the hull length, it was found that great care should be taken when developing a new propeller design in order to minimise the pressure forces generated by the propeller.

Reddy (1983) showed that the mechanical faults such as mass unbalance and misalignment lead to propeller induced vibrations, which can be detected by vibration signature analysis techniques. The propeller mass unbalance and misalignment are mainly due to the propeller-hull interaction. The propeller tip clearances have to be altered to reduce the propeller induced vibrations which is a basic design criterion.

In 1984 methodologies based on a computer program were adopted to predict propeller induced pressure pulses (Colombo & Chilo, 1984). The calculated pressure results were produced for three different propeller designs and the results were validated by tests on two ships. In particular, the calculated pressure results produced by three propeller design solutions at several points on the stern of a new single-screw roll-on/roll-off containership were discussed and compared with the same quantities measured both on a ship model and full scale ship.

Ship design considerations for minimal vibration were studied by Mano in 1985 (Mano, 1985). There are two ways to design a minimal-vibration ship: one is to avoid the hull resonance by external exciting forces and the other is to reduce the exciting forces themselves. It was found that the latest fuel efficient, long stroke, less cylinder engines have higher vibration patterns. It was showed experimentally that the vibration is mainly due to many kinds of exciting forces and moments. Also various countermeasures have been given to reduce the vibration level on ships.

During the end of the 1980s increased popularity of four and five cylinder slow speed, two stroke engines for propulsion plant, reflecting attractive installation and operating costs, had also stimulated efforts by designers to counteract adverse vibration characteristics (Anon, 1989). It was stressed that appropriate consideration should be given to the vibration aspects of a projected installation of engines at the earliest possible stage in the ship design process. Therefore, the four principal types of vibration patterns, namely torsional, axial and lateral vibration, engine out-of-balance and lateral rocking, were examined in detail in order to determine the effects of those vibration patterns onto hull vibration. Solutions, such as different types of balancers, stays, and resilient mountings, were introduced to reduce the level of vibration of engines.

In 1992 the vibration behaviour on Frigate type ships was presented (Keuning, 1992). Propeller induced vibrations, using different frequency response levels and cavitation levels, were discussed. It was found that the propeller induced vibrations are usually associated with the Blade Rate (BR) frequency and its lower harmonics and also the main excitation mechanisms are the propeller induced pressures on the hull above the propeller and the dynamic forces introduced in the ship through the shaft system. Those factors are especially important in case of a cavitating propeller.

During the mid 1990s vibration problems were observed by GL on some ships equipped with medium-speed diesel engines (Asmussen & Muller, 1995). The three types of engine vibration modes, namely transverse vibration about the longitudinal axis (H-type), the torsional vibration about the vertical axis (X-type), and longitudinal vibration about the transversal axis (L type) were demonstrated on different types of ships.

Yacamini *et al.* (1996) discussed the noise and vibration generated by auxiliary equipment such as electrical machines. The mechanisms of noise generation in an electrical machine were identified and the effects of irregularities on the machine frame were investigated using both theoretical and experimental analysis. It was found that the most common mechanical noise sources of such kinds of machines are from the bearing and the motor unbalance.

A two dimensional unsteady theoretical approach was used to calculate an optimised and generalised blade pitch motion of cyclic nature for typical single screw ship propeller that operates in a non-uniform unsteady flow (Gabriel & Atlar, 1998). The theory showed that controlling the magnitude of the angle of attack by a cyclic adaptation of the propeller blade pitch angle can reduce the magnitude of the time varying blade forces and hence reduce the induced hull pressure pulses.

An experiment was carried out to provide a clearer insight into the significance of piston-slap in the diesel excitations on hull vibration and, consequently, the underwater radiated noise (Zheng *et al.*, 2001). Finite Element Method (FEM) and Boundary Element Method (BEM) analysis of diesel piston-slap induced SHV, showed that piston-slap exerted excitation on the engine frame may cause a higher level of SHV and underwater radiated noise than the excitation exerted by diesel vertical inertia force of reciprocating masses. In order to achieve results, the numerical prediction of vibration transmission from a ship's diesel engine via a resilient mounting system, to a stiffened cylindrical hull was employed.

The challenges of providing a high level of passenger comfort on a ferry with low levels of vibration were investigated (Brescia *et al.*, 2001; Giovanni *et al.*, 2001). There were four passenger ferries and they had to work with a cruise speed of 30 knots; it was the highest speed of such kind of ferry at that time. The research included how to design ship aft and fore body design, sectional area curve, appendages, and propeller design (blade diameter, blade area ratio, number of revolutions, tip loading, tip vortex cavitation and direction of rotation) for minimal vibrations. In particular, the design of a rudder has been discussed in terms of manoeuvrability.

A similar kind of work was carried out in 2003 for high powered container ships by the Maritime Research Institute Netherlands (MARIN) (Holtrop & Valkhof, 2003). That research was limited to propeller design, although suggestions to minimise the vibration in terms of propeller design were given in detail.

Acoustic Boundary Element (BE) models of a twin-screw cruise liner were used to solve the Helmholtz equation in order to explore the nature of fluctuating hull pressure pulses due to the propellers (Kinns *et al.*, 2003; Kinns & Bloor, 2004; Kinns & Pim, 2005). The main aim of the research was to show how the fluctuating pressures above the propeller excite hull vibration. The implications of the results for specification of ship requirements and estimation of ship vibrations were discussed.

A number of rules and regulations were introduced by the International Maritime Organization (IMO) in 1982 to improve safety of the crew and comfort of the passengers (IMO, 1982). These rules have been used as a tool by the UK MCA to produce guidelines for ship safety.

ABS (2001b) shows that the vibrations can have a negative impact on the crew as well as passengers. For the crew, this negative impact may be realised as poor performance, physical fatigue or an increase in human errors. The reports published by IMO highlight the fact that crew member fatigue is increasingly recognised as a major factor in maritime accidents (IMO MSC/Circ. 565, 2001; IMO, 2001). When crew member fatigue leads to human error it jeopardises ship, passenger and crew safety. The International Labour Organisation (ILO) also demonstrates that the vibration covers any vibration which is transmitted to the human body through solid structures and is harmful to health or otherwise dangerous (ILO, 1977a; ILO 1977b). This can be referred to SHV onboard ships. ILO has developed vibration regulations especially for workers.

Some previous studies associated with ship vibration problems have been discussed in the aforementioned sections. It is obvious that since the end of 19th century, researchers and organisations have done a tremendous amount of work for the study of ship vibration. Vibration is hazardous and has resulted in severe consequences structurally as well as physically. SHV can be highlighted as a major problem onboard ships since it leads to large structural failures and crew fatigue. Referring to the accidents and defects caused by SHV, the resulting damages can be further emphasised. ISO standards, as well as ship vibration regulations of many ship classification societies, have been developed based on SHV. Simultaneously, it has been found that the risk caused by SHV problems has not been appropriately categorised and estimated yet. In this research the safety principles of FSA are adopted to carry out risk studies of SHV.

2.5. Marine Safety and Formal Safety Assessment

IMO is a body that contributes to the standardisation of the legislations and regulations related to marine activities. The international safety based marine regulations have been driven by the serious marine accidents. For instance, the capsize of the 'Herald of Free Enterprise' in 1987 raised serious questions with regards to operational requirements and the role of management and so stimulated discussions at the IMO (Wang, 2006). This finally resulted in the acceptance of the International Safety Management (ISM) Code for the Safe Operation of Ships and for Pollution Prevention. The 'Exxon Valdez' accident in 1989 badly damaged the environment with a large-scale oil spill. It assisted the implementation of the international convention on Oil Pollution Preparedness, Response and Co-operation (OPRC) in 1990. Double hull or mid-deck structural requirements for new and existing oil tankers were subsequently applied.

By taking into account the increase in public concern regarding safety at sea and pollution prevention, the UK realised that the time was right for exploration of the safety case principles to be applied for shipping. This coincided with the publishing in 1992 of Lord Carver's report on the investigation of the 'Herald of Free Enterprise' accident. Recognising the need for a change in the shipping regulatory framework and in response to Lord Carver's report, the UK MCA quickly responded and in 1993 proposed the FSA methodology to the IMO in relation to ship design and operation. The IMO defines FSA as a structured and systematic methodology, aimed at enhancing marine safety, including protection of life, health, the marine environment and property, based on risk and cost benefit assessments which lead to decisions (IMO MSC/Circ.1023, 2002). The adoption of FSA for shipping represents a fundamental cultural change, from a largely reactive approach, to one which is integrated, proactive and soundly based upon the evaluation of risk. The proactive approach of FSA can be considered a benefit because it enables hazards that have not yet given rise to accidents to be properly considered. There are also other benefits (MSA, 1993):

- A consistent regulatory regime which addresses all aspects of safety in an integrated way.

- Cost effectiveness, whereby safety investment is targeted where it will achieve the greatest benefit.
- Confidence that regulatory requirements are in proportion to the severity of risks.
- A rational basis for addressing new risks posed by ever changing marine technology.

FSA can be applied by different parties. It is important that the process is clearly documented and formally recorded in a uniform and systematic manner (IMO MSC/Circ.829, 1997). This will ensure that the FSA process is transparent and can be understood by all parties irrespective of their experience in the application of risk and cost benefit assessment techniques. The FSA methodology comprises the following five steps:

Step 1: HAZard IDentification (HAZID)
Step 2: Risk Estimation (RE)
Step 3: Selection of Risk Control Options (RCOs)
Step 4: Cost Benefit Assessment (CBA)
Step 5: Decision Making (DM)

The interaction between the five steps can be demonstrated in a process flowchart as shown in Figure 2.6 (IMO MSC/Circ.1023, 2002). As can be seen, there are repeated iterations between the steps which makes it effective as it constantly checks itself for changes within the analysis. The framework was initially studied by the IMO Marine Safety Committee (MSC) in May 1993. Since then several MSC meetings have been subsequently held to deal with FSA in more detail.

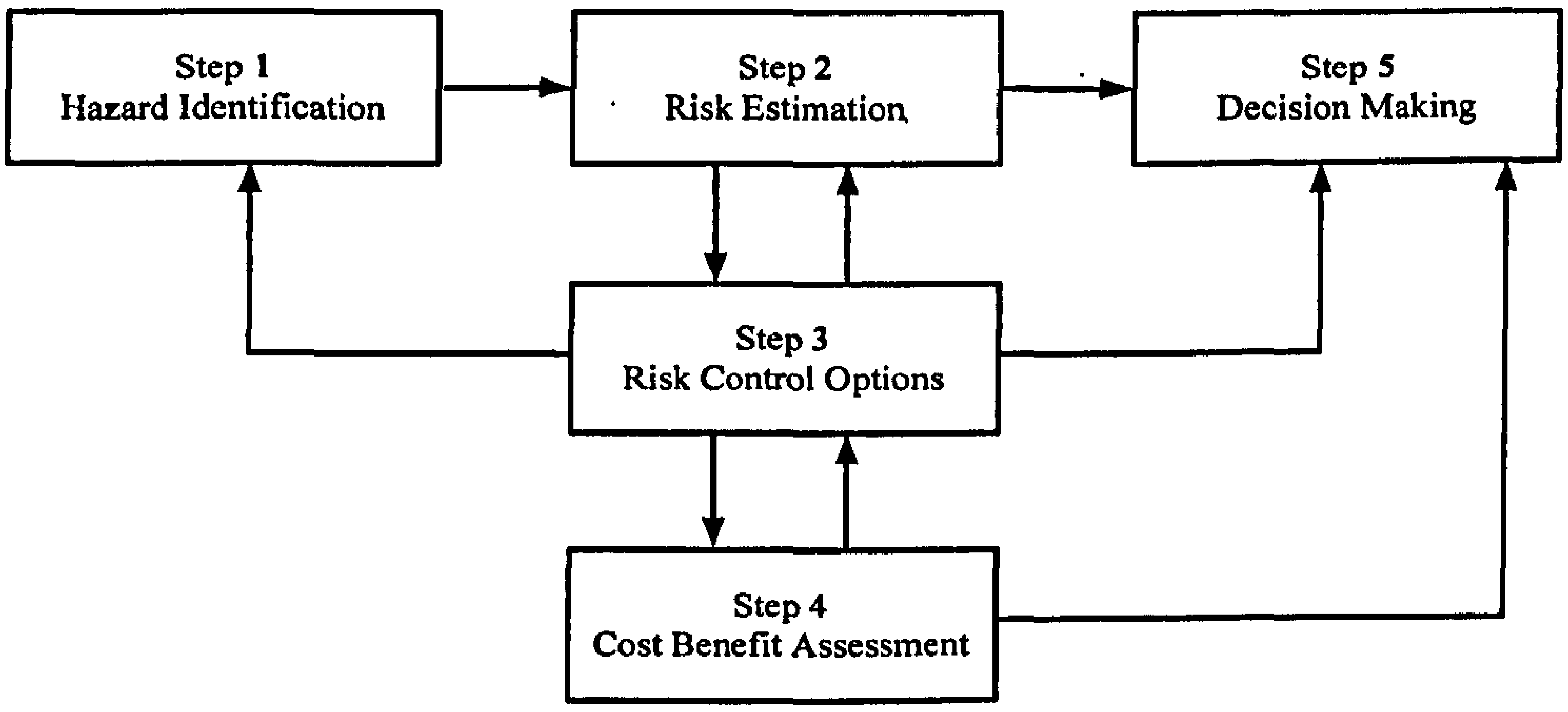


Figure 2.6: Flowchart of FSA Methodology

Figure 2.6 highlights a flowchart of the FSA methodology. The process starts with the decision makers defining the problem to be assessed along with any relevant boundary conditions or constraints. These are presented to the group who would carry out the FSA and provide results to the decision makers for use in their activities. In cases where decision makers require additional work to be conducted, they would revise the problem statement or boundary conditions or constraints and resubmit this to the group and repeat the process as necessary. Within the FSA methodology, Step 5 interacts with each of the other steps in arriving at decision making recommendations. The group carrying out the FSA process should comprise suitably qualified and experienced people to reflect the range of influences and the nature of the problem being addressed.

2.5.1. Hazard Identification

Hazard identification is the first step of the FSA methodology. This step aims at identifying and generating a selected list of possible hazards specific to the problem under consideration. In FSA a hazard is defined as 'a physical situation with potential for human injury, damage to property, damage to the environment or some combination'. Hazard identification is concerned with the use of "brainstorming" techniques by participating trained and experienced personnel to determine the hazards (Wang, 2000). The SHV hazards can be highlighted as:

- Different vibration patterns.
- Hazards induced by ship design criteria.
- Failures onboard ships.

Human error issues can also be systematically dealt with within the FSA framework. It is understood that SHV significantly increases human error due to fatigue and poor performance of the crew onboard which could lead to serious accidents. This has been highlighted in Section 2.4 (ABS, 2001b; IMO MSC/Circ. 565, 2001; IMO, 2001). The significant hazards can be chosen in this step by screening all the identified hazards which contribute to SHV, and then structural failure and crew fatigue. In this step various scientific risk assessment techniques can be applied based on the data availability.

2.5.2. Risk Estimation

Risk estimation is the second step of the FSA methodology. Information produced from Step 1 will be processed to estimate risk. In the risk estimation phase, the likelihood and possible consequences of each hazard will be estimated either on a qualitative or quantitative basis. The main aim of this step can be highlighted as estimating risks and factors influencing level of safety (Wang & Trbojevic, 2007). The estimation of risks involves studying how hazardous events or states develop and interact to cause an accident.

A ship consists of a set of systems such as shaft system, propellers, rudder, auxiliary equipment, power generation plant, and propulsion engine. A serious vibration of a system may cause disastrous consequences. Risk estimation may be carried out with respect to each phase of shipping and each such system. More detailed information of risk estimation can be found in Chapter 3.

2.5.3. Risk Control Options

Selection of risk control options is the third step of the FSA framework. This can also be considered as risk management. The current step aims at proposing and selection of effective and practical risk control options to high risk areas identified from the information produced by the risk estimation in Step 2 (Wang & Foinikis, 2001). At this level the implementation cost benefits of risk control options are not of concern. In general, there are three main characteristics according to which risk control options are evaluated and which can be outlined as follows:

- Those relating to the fundamental type risk reduction (i.e. preventive or mitigating).
- Those relating to the type of action required and therefore to the costs of the action (i.e. engineering or procedural).
- Those relating to the confidence that can be placed in the measure (i.e. active or passive, single or redundant).

Risk control options can reduce frequencies of failures and/or mitigate their possible effects and consequences. In this research, the best risk control option is selected on the basis of effectiveness.

2.5.4. Cost Benefit Assessment

Cost benefit assessment is the fourth step of the FSA framework. This step aims at identifying benefits from reduced risks and costs associated with the implementation of each risk control option for comparisons (Pillay & Wang, 2001). Cost benefit assessment may be carried out using various techniques. However, application of the technique is dependent on the availability of data.

In this research, the chosen alternatives which make up the most effective risk control option as identified in Step 3 are then subjected to cost benefit assessment to select the most economical alternative. These alternatives are chosen to have a minimum level of SHV onboard.

2.5.5. Decision Making

Decision making is the fifth and final step of the FSA framework. The final step aims at making decisions and giving recommendations for safety improvement. The information produced from Step 4 can be implemented to assist in the choice of cost-effective options for risk reduction. It has to be noted that cost factor should not be the only criterion taken into account. As such, at this level multiple criteria decision making techniques may be utilised (Wang *et al.*, 1996).

It is clear that the FSA methodology is not a fixed structure (Figure 2.6). Decision makers can arrive at decisions by using different paths. In this research a flexible approach is used in the application of FSA into SHV so that SHV problems can be addressed in detail. It is not possible to develop a generic hazard identification model by including all the criteria. Therefore, a generic hazard identification model is developed using the most significant criteria and then risk estimation is carried out (Chapter 3). Taking into account significant ship design criteria from the hazard identification model, a generic ship design model is then developed for decision making based on risk estimation (Chapter 4).

Considering failures of components in the hazard identification model, a generic model is constructed including all the significant failures onboard. The high risk areas are identified and the best risk control option is selected based on effectiveness (Chapter 5). Finally, cost benefit assessment is conducted to select the best alternative for SHV risk reduction (Chapter 6). By utilising this flexible FSA approach SHV problems are dealt with in detail and applicability of FSA into SHV is highlighted. The benefit of such a flexible approach as used in this research is that it enables the decision maker to tackle SHV problems in a holistic way.

2.5.6. Research Activities Related to Formal Safety Assessment

FSA is still a relatively new approach to marine safety which involves using the techniques of risk and cost benefit assessment to assist in the decision making activities. It has to be noted that FSA approach differs significantly from the safety case regimes found in many industries. The main purpose of developing FSA was for it to be applied to the regulatory regime for shipping (Pillay & Wang, 2001).

However, over the years, its potential has been recognised not only as a tool to develop safety rules and regulations but also as a tool to identify safety related problems with design, operation and procedures of marine systems. Since the mid 1990s, many research activities in marine risk modelling, cost benefit assessment and decision making have been carried out to improve both design and operations. The research activities conducted based on the FSA framework include:

- Trial study on high speed passenger catamaran vessels (IMO, 1997a; IMO, 1998a).
- Trial study on high speed crafts (IMO, 1997b; IMO, 1998b; IMO, 1998c).
- Trial study on oil tankers (IMO, 1998d; IMO, 1998e).
- Trial study on bulk carriers (IMO, 1998f; IMO, 2000; IMO, 2002a; IMO, 2002b).
- Trial study on passenger roro vessels with dangerous goods (IMO, 1998g).
- Application to fishing vessels (Pillay, 2001; Loughran *et al.*, 2003).
- Application to marine transportation (Soares & Teixeira, 2001).
- Application to offshore support vessels (Sii, 2001).
- Application to containerships (Wang & Foinikis, 2001).
- Application to ports (Trbojevic, 2002; Ung *et al.*, 2006; Ung, 2007).
- Application to cruising ships (Lois, 2004; Lois *et al.*, 2004).
- Application to liner shipping (Yang *et al.*, 2005; Yang, 2006).

It is clear that FSA has been utilised in many applications. However, there are still many areas in which the application of FSA could be of benefit; its application to

SHV problems is one. It was described earlier that SHV failure data is scarce (Section 2.3). Therefore, there is a high level of uncertainty associated with SHV problems. It may not be possible to use traditional risk assessment methods since their application is dependent on the availability of failure data. This uncertainty requires the development and application of novel risk assessment techniques for the treatment of SHV problems.

2.6. Critical Review of Marine Risk Assessment

Risk assessment is a vital element of risk studies. Probability theory, which is based on the discoveries made by famous 16th and 17th century scholars such as Girolamo Cardano, Galileo Galilei, Blaise Pascal, Pierre De Fermat and Chevalier De Mere is the foundation of contemporary risk assessment (Garrick *et al.*, 2004).

In the 1500s Cardano and Galilei contributed towards expressing probabilities and frequencies of past events. Fermat and Mere made valuable contributions to the theory of numbers in the mid 1600s and about the same time Pascal found out the concepts of decision theory (Garrick *et al.*, 2004). The Royal Port group created a piece of pioneering work of philosophy and probably the first definition of risk as 'fear of harm ought to be proportional not merely to the gravity of the harm but also to the probability of the event'.

In the 1700s Thomas Bayes constructed a theorem rooted in fundamental logic for combining old information with new information for the assignment probabilities. Bayes is considered as the real father of contemporary risk assessment (Garrick *et al.*, 2004). By following the Bayes theorem, a French mathematician, Marquis Pierre Simon De Laplace, constructed the primary basis of contemporary probability theory. Diverse issues, such as gambling strategies, military strategies, determining mortality rates and debating the existence of God were the areas under discussion of early analytical explorations and precursors to the new science of risk assessment.

The widespread, formal application of risk assessment to critical infrastructure started in earnest in the late 1900s. Many risk assessment methods have been developed to support scientifically-based risk assessment and decision making. The choice of a risk assessment technique is dependent on available data and purpose of use. In risk assessment the availability of the data plays a crucial role. When there is not enough data available special techniques have to be employed.

These techniques are called novel risk assessment techniques and the others are named as traditional techniques in this research. Traditional techniques may be utilised when there is sufficient data available.

2.6.1. Traditional Risk Assessment

In the 1960s significant progress in the effectiveness and sophistication of risk assessment was achieved due to the application of risk assessment methodologies in different areas in industry. Fault Tree Analysis (FTA) was developed at the beginning of 1960s and was used as a tool in risk assessment. At the same time a PhD thesis was published that introduced a methodology for probabilistic integrated systems for analysing the safety of nuclear power plants (Garrick *et al.*, 2004). The breakthrough in Probabilistic Risk Assessment (PRA) of technological systems came in 1975 with the publication of the 'Reactor Safety Study' by the US Atomic Energy Commission.

The 'Reactor Safety Study' introduced many original risk assessments techniques to industry which led to major advancements in the application of Quantitative Risk Assessment (QRA). The foundation of QRA is the structuring of scenarios and methods of inferring the likelihood of events. QRA has been employed in many industries such as nuclear, chemical and petroleum (Garrick *et al.*, 2004). The nuclear industry is the most consistent user of QRA methods. Also, since the mid 1990s, risk assessment has been employed in assessing the safety of marine systems (Wang & Trbojevic, 2007; Sii, 2001; Pillay, 2001). There are many scientific PRA techniques which have been developed in the past five decades which are in use in marine and other industries today. Some of the most widely used PRA techniques include:

- Fault Tree Analysis (FTA) (Nieuwhof, 1975; Kumamoto & Henley, 1992; IMO MSC/Circ.1023, 2002)
- Event Tree Analysis (ETA) (Villemeur, 1992; Pillay, 2001; Meel & Seider, 2006)
- Preliminary Hazard Analysis (PHA) (MIL-STD-882, 1969; MIL-STD-882c, 1993; MIL-STD-882d, 2000; Wang & Trbojevic, 2007)
- Failure Modes, Effects and Criticality Analysis (FMECA) (MIL-STD-1629a, 1980; Wang & Ruxton, 1995; Jordaan, 2005)
- HAZard and OPerability Study (HAZOP) (Wells, 1996; Pillay & Wang, 2003; Labvosky *et al.*, 2007)

- Cost per Unit Risk Reduction (CURR) (Pillay, 2001; Pillay & Wang, 2003; Wang & Trbojevic, 2007)

In PRA, events which are the root causes of accidents are referred to as initiating events or accident initiators. Without initiating events, no accident can happen (Kumamoto & Henley, 1992). PRA is a framework that transforms initiating events into risk profiles. It should be noted that risk profiles are not the only products of risk studies. The PRA process and data recognise vulnerabilities in a system. No other approach has predictive abilities which are superior to that of PRA (Herrmann *et al.*, 1989). The information produced in risk assessment can be used to select effective and economical risk control options to minimise the risks.

2.6.1.1. Fault Tree Analysis

FTA was developed by H.A. Watson of the Bell Telephone Laboratories between 1961 and 1962 during an Air Force study contract for the Minuteman Launch Control System. Since the early 1970s FTA technique has been utilised as a tool in risk assessment methodologies (Kumamoto & Henley, 1992). It is probably the most widely used technique for hazard identification and risk estimation.

This technique is a process of deductive reasoning which can be applied to a system of any size for risk assessment purposes (Ang & Tang, 1984; Wang & Trbojevic, 2007). FTA is particularly suitable for the risk assessment of large marine and offshore engineering systems for which the associated undesired (top) events can be identified by experience, from previous accident and incident/accident reports.

It is a diagrammatic method used to estimate the probability of an accident (top event) resulting from sequences and combinations of faults and failure events (basic events). This technique can handle both quantitative and qualitative assessment. However, quantitative assessment may not always be possible because FTA requires knowledge of probabilities associated with basic events (Mauri, 2000).

2.6.1.2. Event Tree Analysis

ETA is a logic diagram used to evaluate the effects of an accident, a failure or an unintended event. It is used to identify the various possible outcomes of the system following a given initiating event which is generally an unsatisfactory operating event or situation. In the case of continuously operated systems, these events can occur (i.e. failure of components) in any arbitrary order (Pillay, 2001).

In ETA the components may be taken into account in any order because they do not operate chronologically with respect to each other. ETA provides a systematic and logical approach to recognise consequences and to assess the probability of occurrence of each consequence of the initiating failure event. It can be effectively utilised in the hazard identification and risk estimation of a risk assessment process. However, ETA grows in width exponentially and as a result it can only be applied effectively to small sets of components. Therefore ETA is best suited for hazard identification and risk estimation in marine systems with a limited number of components. It can handle both qualitative and quantitative criteria. This technique can be employed to investigate unknown effects from known causes, therefore ETA may be considered as an inductive technique (Villemeur, 1992).

2.6.1.3. Preliminary Hazard Analysis

PHA was introduced in the mid sixties (1966) after the Department of Defence of the United States of America requested safety studies to be performed at all stages of product development. The first standard of safety was a document published by the US Air Force in June 1966 which became MIL-STD-882 in July 1969 (Horn, 2005). However, this initial document was released in September 1963 as MIL-S-38130A (AFSA, 2000). The Department of Defence issued guidelines that were applied from 1969 onward (MIL-STD-882, 1969; MIL-STD-882c, 1993; MIL-STD-882d, 2000).

The main aims of PHA are to identify the hazards of an industrial installation as well as their causes (e.g. hazardous entities, dangerous situations, potential accidents) and to evaluate the severity of the consequences of dangerous situations and potential accidents (Villemeur, 1992). This technique can be utilised in the early stages of a marine system design process and later stages of requirement analysis.

Collective brainstorming techniques are employed during which the design or operation of the system is discussed on the basis of experience of the participants.

Checklists are commonly used to assist in identifying the hazards and results are shown in a tabular format. PHA is a qualitative inductive technique (Mauri, 2000).

2.6.1.4. Failure Modes, Effects and Criticality Analysis

FMECA was developed in the 1960s and it is a natural extension of Failure Modes and Effects Analysis (FMEA). It is possible to deal with failure modes with severe effects having sufficiently low occurrence probabilities by using this method (Villemeur, 1992). FMECA is made up of two parts, the first of which is FMEA and the second is Criticality Analysis (CA), (FMECA).

The first part contains the identification of potential failures and the effects on system's performance by identifying the potential severity of the effect. The second part consists of additional steps for calculating the risk of each failure through measurements of the severity and probability of a failure event. Both parts are capable of providing information for risk managing decisions. It is an inductive technique. FMECA handles both qualitative and quantitative assessment. It systematically details, on a component by component basis, all possible failure modes and identifies their resulting effects on the system (Kumamoto & Henley, 1992).

To maximise the effectiveness of an FMECA as a decision making tool, it has to be initiated at the earliest stage of marine design, updated and expanded to lower levels as the design progresses. FMECA involves the compilation of reliability data, where available, for individual items, and information produced from FMECA may also be used to carry out FTA. This technique has been employed successfully within many different industries and has been used in marine regulations to address safety concerns with relatively new designs (Pillay, 2001).

2.6.1.5. HAZard and OPerability Study

HAZOP technique was developed in the 1970s by loss prevention engineers working for Imperial Chemical Industries at Tees-Side UK (Villemeur, 1992; Smith, 2005). HAZOP is an inductive technique which is an extended FMECA and which can be applied by a multidisciplinary team to stimulate systematic thinking for identifying potential hazards and operability problems in systems (Kumamoto & Henley, 1992). This is a collective brainstorming technique in which the system is examined systematically, component by component, to determine how deviations from the design intent can occur, the consequences of such deviations and the preventive/mitigating measures that are required.

HAZOP involves a full detailed description of the system (up-to-date engineering drawings, line diagrams etc.) and full working knowledge of the operating arrangements. Therefore, the HAZOP study team usually includes designers and operators as well as safety engineers. Close parallels could be drawn between FTA and a HAZOP study as they both yield clear identification of top events and also a detailed description of failure modes and associated operating conditions. Information produced from HAZOP studies can be used in FMECA.

The aim of the HAZOP is to carry out a qualitative analysis in the intermediate stages of the design process to predictable hazards, thus it is an exploratory technique (Mauri, 2000). This technique can be utilised to assess the safety of marine systems (Wang & Trbojevic, 2007).

2.6.1.6. Cost per Unit Risk Reduction

CURR is one of the most widely used cost benefit assessment and decision making techniques in marine risk assessment. This technique is applied for selecting risk control options to minimise the occurrence of risks. CURR of each risk control option can be estimated by dividing the difference of the costs and benefits by the combined reduction in mortality and injury risks (Pillay & Wang, 2003). Those CURR values supply a relative ranking of the efficiency of alternative risk control options. However, it may not be possible to use this technique when there is an unacceptably high uncertainty of information present.

2.6.2. Uncertainty

There is a close connection between complexity and uncertainty. It is said to be the rise in complexity that leads to increase in uncertainty (Pillay, 2001). Uncertainties arise when there are deficiencies of information. Deficiencies of information can be of different types and come from different sources.

2.6.2.1. Types of Deficiencies

The deficiencies of information may be divided into categories such as fuzziness, ambiguity resulting from discord and ambiguity resulting from non-specificity (Klir & Yuan, 1995).

2.6.2.1.1. Fuzziness

This results from vagueness (lack of sharpness) and it is different from ambiguity. Most natural language descriptors are vague and somewhat uncertain rather than precise. Examples of fuzzy uncertain events related to ship vibrations can be given as 'maintaining propeller speed 120 RPM' and 'checking condition of cylinders when gas pressure variation is high'. The vagueness of those operating conditions could lead the crew to make their own decisions to carry out the operation. Hence, there could be a non-uniform approach for maintenance leading to serious vibrations in systems.

2.6.2.1.2. Ambiguity Resulting from Discord

Discord can be described as a conflict or dissonance. For example, in a probability distribution, $P(x)$, each probability measure is used for a specific alternative in a set of exhaustive, mutually exclusive alternatives. Each $P(x)$ shows the 'degree of belief' (based on some evidence) that a particular alternative is the correct one. Thus, the beliefs explained in a probability distribution may be in conflict with each other.

2.6.2.1.3. Ambiguity Resulting from Non-Specificity

This comes from lack of information resulting from not clearly stating or distinguishing alternatives. Non-specificity is characterised by sizes of relevant sets of alternatives. The more alternatives available in a case, the less specific the case (a case is completely specific if there is only one possible alternative).

2.6.2.2. Types of Sources Creating Deficiencies

The sources of deficiencies come from three categories. They are namely failure and incident data, systematic and consequence methodologies (Schofield, 1998).

2.6.2.2.1. Failure and Incident Data

The deficiencies affecting use of failure and incident data can be considered with respect to statistical significance of such kind of data. They are as follows (Schofield, 1998):

- The effect of small sample sizes: The effect of sample sizes could bias the results acquired because samples may not fully show the characteristics of the problem. If small sample sizes were the only source of deficiency, sample theory may provide confidence in failure rates. Then such kind of deficiency could be highlighted in the risk assessment process.
- The questionable relevance of generic data to specific items of equipment: In principle, this may be a more difficult aspect to address since the particular equipment and operating conditions may not be as relevant as first considered to the equipment and operating conditions for which data have been gathered. Under those circumstances, no method can be implemented to address what data should be suitable.
- The effect of limited reporting in relation to failure modes: This is also considered as an issue from a quantification point of view. It may result in underestimation of the potential significance of some failure modes which were not allocated within the domain of definition. The existence of such lesser failure modes is due to the fact that these failure modes have random possibility to escalate to the failure modes within the domain of definition. Inclusion or otherwise of the 'lesser' failure modes rests on factors that might not be significant statistically. Therefore, the recorded data could under-represent the potential of serious consequences e.g. possible absence of important 'near misses' in incident reporting.

2.6.2.2.2. Systematic

There are different types of assumptions utilised within a risk assessment process. Some of them relate to use of data and are subjected to the discussion of data uncertainties, which has been described in Section 2.6.2.2.1. Others relate to use of consequence methodologies which have been given in Section 2.6.2.2.3. Another category is considered with the system in this section. That includes the following (Ung, 2007):

- Identification of hazards and accident scenarios.

- The physical conditions prevailing, especially environmentally.
- The accuracy with which the mode of operation is predicted.

Assumptions made in systematic category are often highlighted explicitly and openly within an assessment, and must be based on practical knowledge about the installation. By using this path, they can be scrutinised and varied to estimate their effects on risk assessment results.

2.6.2.2.3. Consequence Methodologies

Consequence methodologies are considered with the predictions of risks arising from accident escalation. This modelling approach could at one extreme comprise very simple assumptions. At another extreme it may contain a very complex mathematical model used by sophisticated software (Ung, 2007). Alternatively, the modelling may be somewhere between these extremes. A problem with attempting to model marine accident scenarios often arises because of the complex nature of escalating events such as heat fluxes, smoke concentration, structural damages due to SHV, and human error due to fatigue, which lead to major accidents. This complexity is associated not only with the nature of marine installations and packed equipment but also with the intrinsic nature of many of the consequence phenomena under consideration. This might make the consequence become unpredictable.

2.6.3. Novel Risk Assessment of SHV under Uncertainty

It is clear that the SHV problems have a high level of uncertainty. As such it may not be possible to use traditional risk assessment techniques. Novel risk assessment techniques may have to be employed to deal with SHV problems with uncertainty. Jenson (2001) highlighted that except for probability theory, the most prominent to reasoning under uncertainty is possibility theory which is described as fuzzy logic.

2.6.3.1. Fuzzy Logic

Many changes in science and mathematics took place in 19th and 20th centuries. One of the changes concerns the concept of uncertainty. Klir & Yuan (1995) state that this change has been manifested by a gradual transition from the traditional view which insists that uncertainty is undesirable in science and should be avoided by all possible means, to an alternative view which is tolerant of uncertainty and insists that science can avoid it.

Based on the traditional view, science should endeavour for certainty in all its manifestations (precision, specificity, sharpness, consistency, etc.). Then, uncertainty (imprecision, nonspecificity, vagueness, inconsistency, etc.) is considered as unscientific. However, based on a modern view, uncertainty is regarded as essential to science.

An important point of dealing with uncertainty came in 1965 with the publication of a fuzzy logic based paper by Lotfi A Zadeh (Zadeh, 1965). Fuzzy logic is an extension of classical Boolean logic from crisp sets to fuzzy sets. As a logic for reasoning, there is nothing fuzzy on the subject of fuzzy logic. Fuzzy logic is the first new method of dealing with uncertainty since the development of probability.

Fuzzy logic has various fuzzy techniques which can be used in uncertainty treatment. They are namely fuzzy sets, fuzzy rule base, etc. Fuzzy sets have two other categories namely discrete and continuous fuzzy sets. The application of these fuzzy logic techniques is dependent on the situation and they are widely used in many applications.

Traditional risk assessment is called probabilistic risk assessment since it is dependent on probability theory. Fuzzy logic is based on possibility theory; as such, novel risk assessment here is called possibilistic risk assessment. In this research, fuzzy techniques are combined with Evidential Reasoning (ER), Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to conduct novel risk assessment of SHV under uncertainty based on the safety principles of FSA.

2.6.3.2. Fuzzy Logic Theory

The theory of fuzzy logic has, as one of its aims, the development of a methodology for the formulation and solution of problems that are too complex, or too ill-defined, to be susceptible of analysis by conventional techniques (Kandel, 1986). Since fuzzy logic theory was introduced more than four decades ago, it has found many useful applications in the electrical and electronic engineering (Yen & Langari, 1999), civil engineering, research and development projects, business management, information and control, economics and marketing, education, health and medicine, safety engineering (Wang *et al.*, 1995), risk modelling, risk management and decision making and many more. This is because it has several useful properties:

- Risk or safety assessment may involve the use of linguistic terms. Fuzzy set theory is a non-probabilistic method and it can deal with linguistic terms using MFs. Therefore, fuzzy set theory may be used in risk or safety assessment.
- It is a highly recognised uncertainty treatment method which can be used in situations where a high level of uncertainty is involved.
- Fuzzy sets can give good results for modelling qualitative information based on a linguistic approach.

The use of linguistic terms in fuzzy logic allows flexible modelling of imprecise data and information. A linguistic term is different from a numerical term in that its values are not numbers but words (e.g. good, normal, high, etc.) or sentences in a natural or artificial language (Schmucker, 1984). Since words in general are less precise than numbers, the concept of a linguistic term serves the purpose of providing a means of approximate characterisation of phenomena, which are too complex or ill-defined to be amenable to description in conventional quantitative terms.

Crisp variables (sometimes called traditional variables) do not have the natural capability to express and deal with observation and measurement of uncertainties, but the significance of fuzzy variables is that they facilitate gradual transition between states and consequently gain the natural capability (Klir & Yuan, 1995; Pillay & Wang, 2001). Although the definition of states by crisp sets is mathematically correct, in many cases, it is unrealistic in the face of unavoidable measurement errors. A measurement that falls into a close neighbourhood of each precisely defined border between states of a crisp variable is taken as evidential support for only one of the states, in spite of the inevitable uncertainty involved in the problem.

The uncertainty reaches its maximum at each border, where any measurement should be regarded as equal evidence for the two states on either side of the border. When dealing with crisp variables, the uncertainty is ignored; the measurement is regarded as evidence for one of the states, the one that includes the border point by virtue of an arbitrary mathematical definition. The idea is that unlike crisp set, which is completely determined by an indicator function taking values in {0, 1}, a fuzzy set is characterised by a membership function with membership values ranging between 0 and 1. A fuzzy set whose MF only takes on the value zero or one is called crisp.

2.6.3.2.1. Fuzzy Membership Function

A fuzzy set is represented by a MF on the universe of discourse or universal set (X) (Zadeh, 1987). X is the space where all the fuzzy variables are defined. A set, A, with points or objects in some relevant universe, X, is defined as these elements of x that satisfy the membership property defined for A. In traditional 'crisp' sets theory each element of x either is, or is not, an element of A. Elements in a fuzzy set (denoted by ~, e.g. $\tilde{A}$) can have a continuum of degrees of membership ranging between complete membership and complete non-membership.

$\mu_{\tilde{A}}(x)$ gives the degree of membership for each element ($x \in$ X). $\mu_{\tilde{A}}(x)$ is defined on [0, 1]. A MF value of 0 implies that the value does not belong to the set under consideration. A MF value of 1 means full representation of the set under consideration. A membership somewhere between these two limits indicates the degree of membership. The manner in which values are assigned to a membership is not fixed and may be established according to the preference of the person conducting the investigation.

Formally $\tilde{A}$ is represented as the ordered pair $[x, \mu_{\tilde{A}}(x)]$:

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x)) | x \in \text{X and } 0 \leq \mu_{\tilde{A}}(x) \leq 1\}$$

MFs can be found in different shapes, namely triangular curves, trapezoidal curves, S curves, π curves, bell curves and Gaussian curves (Yen & Langari, 1999). The shape of the fuzzy set depends on the best way to represent data. In general the membership (often indicated on the vertical axis) ranges between 0 (no membership) and 1 (full membership). The domain of a set is indicated along the horizontal axis. The fuzzy set shape defines the relationship between the domain and the membership values of a set.

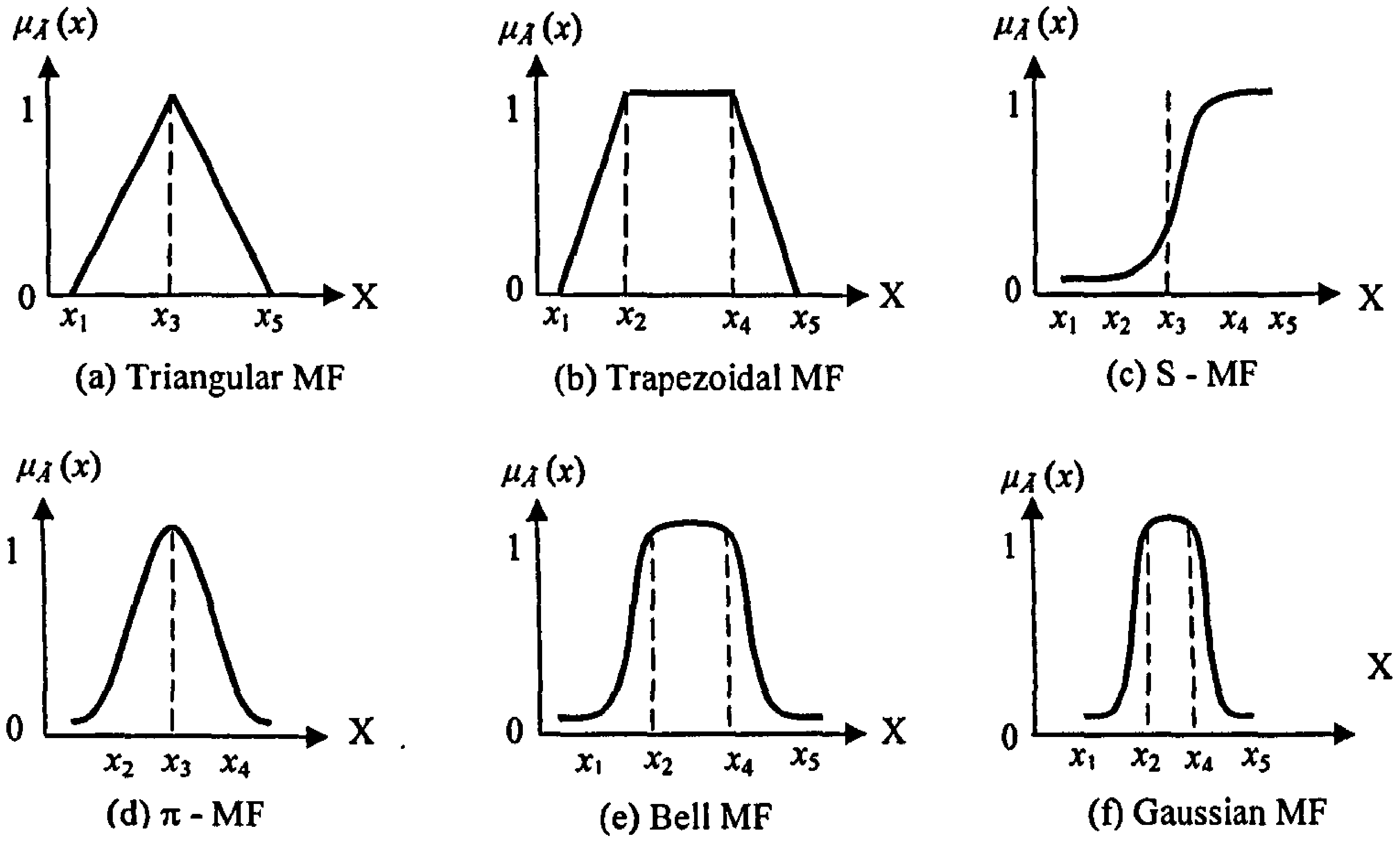


Figure 2.7: Types of Membership Functions (MFs)

Figure 2.7 shows some typical types of MFs. The triangular and trapezoidal MFs are the most commonly used in practice due to their simple formulas and computational efficiency. Obviously, the triangular MF is a special case of the trapezoidal MF. The graphical representation of magnitude of each MF depends on the expert judgements. Those shapes of MFs are defined only in the application context and as distinguished by experts. The hypothesis of using MF is to map the parameter constraint to membership grade between the scaled intervals. The membership value which is closer to one is the better solution for that constraint.

2.7. Justification of Research

When dealing with SHV problems, it is clear that the FTA, ETA, PHA, HAZOP and FMECA techniques cannot be easily implemented since such techniques need the frequencies of hazardous situations to be usually estimated based on historical failure data. Almost invariably, failures are assumed to be random in time, that is, the obtained number of failures is divided by an exposure period to give a failure rate and this is assumed to be age-dependent (Wang & Trbojevic, 2007).

In common sense, many modes of failure are more common in the earlier or later years of the life of a component or a system. Even with high quality data, sample sizes are often small and statistical uncertainties are relatively large. Therefore, as described in the previous sections, a fuzzy logic modelling approach may be more applicable to conduct hazard identification, risk estimation and risk control option selection based on risk management information. This is also true for cost benefit assessment where techniques such as CURR cannot be effectively used due to high level of uncertainty in data. As such, an appropriate solution may be a fuzzy logic modelling approach with the combination of expert judgements.

Based on the critical review of SHV and discussions of the experts in the area, it was found that the marine companies which deal with vibration problems often have a poor organisational structure. This would entail that documented vibration records on ships, systems and components would be difficult to come by and the availability of data for quantitative analysis is either unavailable or far from being in the ideal format. This was the major challenge of this research and subsequently resulted in risk assessment of SHV utilising uncertainty treatment methods such as ER, AHP and TOPSIS with the combination of fuzzy logic. In summary, this PhD research develops a novel subjective risk assessment methodology for SHV problems based on the safety principles of FSA.

2.8. Discussion

SHV has been a major problem for ships since the 19th century. Many parties have contributed to tackle SHV issues in different ways. The typical causes and mechanisms of SHV are identified by carrying out a critical review of SHV, followed by a historical failure data analysis. Many classification societies have developed their own guidelines and regulations based on ISO and national standards. They use them as a benchmark for their ship classification. It is clear that the vibration guidelines produced by most of the parties are based on SHV because they consider SHV as a major vibration pattern onboard.

Since the mid 1990s marine safety has been directed towards a risk-based and goal-setting regime. FSA can be said to be the backbone of marine safety. There are still many areas in which FSA could be applied in order to improve marine safety and SHV is recognised as one such area. Therefore in this research, risk assessment of SHV is conducted based on the safety principles of FSA. The major challenge, which is 'high level of uncertainty of SHV problems', is overcome by identifying uncertainty treatment methods such as ER, AHP and TOPSIS with combination of fuzzy logic modelling.

For those involved in the vibration industry, this research can be considered a starting point of a new method for enhancing or controlling the quality of the shipboard environment by minimising or avoiding vibration problems using scientific assessment approaches. The platform provided in this research consists of four novel chapters. They are namely, a subjective risk estimation approach for modelling ship hull vibration, a subjective decision making approach for modelling ship design criteria, a subjective risk management approach for modelling failure events of ships, and a subjective cost benefit analysis approach for modelling ship propulsion systems. By utilising these four core chapters, the five steps of FSA methodology are completed. Each chapter has its own research methodology which is subsequently demonstrated by its corresponding case study.

Chapter 3 – A Subjective Risk Estimation Approach for Modelling Ship Hull Vibration

SUMMARY

A subjective novel approach incorporating an Evidential Reasoning (ER) algorithm is developed to achieve the risk estimation of Ship Hull Vibration (SHV). A hierarchical structure for SHV modelling (hazard identification model) is constructed using a qualitative and quantitative approach. The quantitative criteria are converted to the qualitative criteria by applying a rule based quantitative data transformation technique to make use of ER. A mapping process is formulated to convert and quantify the qualitative criteria. Intelligent Decision System (IDS) software is used for synthesis in the hierarchical structure and to produce the risk estimation results graphically. The results of this chapter reveal that the ER is capable of producing the risk estimation of SHV.

3.1. Introduction

Vibrations in ships have to be taken into account very seriously, considering their negative effects on crew, cargo and the ship's structure. Levels of vibration have increased in modern ships with the increase in complexity of structure and associated equipment. Many maritime casualties have been caused as a direct result of high vibration levels, for example, "Green Lily", "Constant Faith", "Britannia Conquest", "Esso Mersey", "Elegance", "Jenmar" and "Royal Princess" to name a few (MAIB, 1990-2008).

Ship Hull Vibration (SHV) can lead to structural failure and crew fatigue, and is therefore considered to be a major contributory factor in maritime accidents. Hull vibration has grown dramatically with the increase of ship size and power requirements to obtain high speed and manoeuvrability (Mano, 1985). The ship propeller system and machinery (propulsion system) are the major contributors to SHV (MDS, 1992-2007). SHV can be addressed by considering the propeller system and machinery as a complex, multi component system that comprises sub-systems, sub-sub-systems and sub-sub-sub-systems to represent the individual components. Such a hierarchical structure (hazard identification model) is developed to estimate the risk at the top level (SHV) by using all the basic criteria.

A fuzzy rule base is implemented because it describes well the "riskiness" of the system for each combination of input variables (Bowles & Pelaez, 1995). Fuzzy rules are usually more conveniently formulated in linguistic terms than in numerical terms. They are often expressed as 'If-Then' rules, which are easily implemented by fuzzy conditional statements. More information of fuzzy logic can be found in Chapter 2.

The Evidential Reasoning (ER) approach is suitable for modelling subjective credibility induced by partial evidence (Yang & Xu, 2002). The origin of this approach is an ER algorithm produced on the basis of the Dempster-Shafer (D-S) theory. The algorithm can be used to aggregate criteria of a multilevel structure. The ER is widely used in industries such as engineering and management for decision making purposes.

The main aim of this chapter is to obtain the risk estimation of SHV for identified significant SHV hazards using the ER approach. In order to achieve this aim, this chapter describes the major causes and mechanisms which cause SHV, constructs a hierarchical structure to model the SHV criteria, gives assessment grades for each criterion, converts quantitative criteria to qualitative ones by employing a rule based technique and applies the ER approach to synthesise the risk estimates. A case study is given, based on the hierarchical structure, to validate that the ER approach is applicable to obtain the risk estimation of SHV. Further information of risk estimation can be obtained from Chapter 2.

3.2. Background

3.2.1. Evidential Reasoning Approach

Evidential Reasoning (ER) was developed in the 1990s to deal with Multiple Criteria Decision Making (MCDM) problems under uncertainty. The ER algorithm is based on the decision theory and the Dempster-Shafer (D-S) theory of evidence, which is well suited for handling incomplete assessment of uncertainty (Yang, 2001; Yang & Singh, 1994). The algorithm can be used to aggregate criteria of a multilevel structure. A rational aggregation process needs to satisfy certain common sense or self-evident rules, referred to as synthesis axioms. The original ER approach has to satisfy the following synthesis axioms approximately.

Consider there are two levels of criteria with a general criterion at the top level and a number of basic criteria at the bottom level (Yang & Xu, 2002). Each basic criterion may be assessed with reference to a set of evaluation grades. A criterion can be assessed to an individual evaluation grade or a subset of the evaluation grades with different degrees of belief. Within this ER assessment framework, the following four synthesis axioms have been proposed:

1. If no basic criterion is assessed to an evaluation grade at all, then the general criterion should not be assessed to the same grade either.
2. If all basic criteria are precisely assessed to an individual grade, then the general criterion should also be precisely assessed to the same grade.
3. If all basic criteria are completely assessed to a subset of grades, then the general criterion should be completely assessed to the same subset as well.
4. If any basic assessment is incomplete, then a general assessment obtained by aggregating the incomplete and complete basic assessments should also be incomplete with the degree of incompleteness properly assigned.

ER is widely used in many applications such as engineering design, system safety, risk assessment, organizational self-assessment and supplier assessment (e.g. motor cycle assessment, general cargo ship design, marine system safety analysis and synthesis, software safety synthesis, retrofit ferry design, executive car assessment, organizational self-assessment and many more). ER has the following useful properties (Sönmez *et al.*, 2001; Yang & Xu, 2002):

- It is difficult to deal with both quantitative and qualitative criteria under uncertainty but ER provides an alternative way of handling such information systematically and consistently.
- The uncertainty and risk surrounding the problem can be represented through the concept of Degree of Belief (DoB).
- Both complete and incomplete information can be aggregated and modelled by using the belief structure.
- The ER algorithm is integrated into a software package called IDS (Xu & Yang, 2005). It is a graphically designed decision support tool. The IDS allows Decision Makers (DMs) to build their own models and input their own data.
- The IDS software enables users to provide results of evaluation both in tabular and graphical forms.

The ER approach was applied to select the best prime contractor for a civil engineering project (Sönmez *et al.*, 2001). In that study, the process of building a multiple criteria decision model of a hierarchical structure was presented with both quantitative and qualitative criteria. The process of converting lower level criterion assessments to the upper level criterion was shown and the advantages and disadvantages of the ER approach were discussed.

Usually, in nature, quantitative criteria are represented using certain or random numbers. This may increase the complexity in criteria aggregation. A generalised and extended decision matrix was constructed where the rule and utility based techniques were developed for transforming various types of information, especially quantitative criteria within a matrix for aggregating criteria via ER (Yang, 2001). Those rule and utility based techniques can be used at different levels of criteria in a hierarchy. Two numerical examples demonstrated the applicability of the new rule and utility based ER approach.

Yang & Xu, (2002) investigated the fundamental features of the ER approach. New methods for weight normalization and basic probability assignments were proposed and the original ER approach was further developed. By using IDS software the numerical example of a motorcycle evaluation problem was examined. Similar work has been carried out to analyse the quality of a motor engine and a ship design assessment problem (Yang & Xu, 2002). An alternative way of modelling and aggregating both complete and incomplete information using a belief structure was discussed.

A subjective safety-analysis-based decision making framework was proposed for formal ship safety assessment in situations where a high level of uncertainty in data was involved (Wang, 2000). In that framework, the failure events at the lowest level in a hierarchy were modelled using fuzzy sets, and safety synthesis at different levels of the hierarchy was carried out using ER. An example was given based on a hydraulic hoisting transmission system of a marine crane consisting of five sub-systems.

Tang *et al.*, (2004) used ER to assess the condition of a transformer. The ER was combined with a diagnosis technique to provide a meaningful and accurate diagnosis. The results showed that the ER was capable of producing the condition of a transformer.

Combining the fuzzy set theory and ER method, a subjective approach to deal with threat based risks in container supply chains was presented (Yang *et al.*, 2005). A hierarchical structure was developed using FTA. The safety level has been expressed graphically using IDS.

SHV is a severe problem to the shipboard environment. Therefore, it is necessary to carry out risk estimation. Although ER's potential for application in the shipping industry is recognised, it has not been applied to risk estimation of ship vibration. A possible methodology is proposed in the following sections in order to define the applicability of ER for the risk estimation of SHV.

3.3. SHV Modelling

SHV results from the combination of various forms of exciting vibratory forces from the ship's propulsion system. The main sources of exciting vibratory forces is identified and categorised in terms of its potential for generating SHV by expert judgement (weighting (ω_i)). Figure 3.1 was generated to represent a general hierarchical model to denote the occurrence of SHV from the various sources. There are five levels in the constructed generic model (hierarchical structure). They are namely Goal, Main Criteria, Sub Criteria, Sub-Sub Criteria and Sub-Sub-Sub Criteria. Goal is the top level (highest level) and Sub-Sub-Sub Criteria are the bottom level (lowest level). This generic model was developed on the basis of a generic ship concept. A generic ship can be said to be one whose functions, features, characteristics and criteria are common to all ships of a particular type or relevant to the problem under study. The developed generic model (hazard identification model) is used to estimate the risk at the top level (SHV).

Traditionally, risk estimation is conducted either using a top-down approach or a bottom-up approach (Wang *et al.*, 2004). The selection of the approach depends on the availability of failure data, the level of analysis required, the level of innovation, the degree of complexity of the interrelationships between the design and the level of the design. The top-down approach is highly dependent on the reliability of appropriate failure data in incident and accident reports; however in the bottom up approach the available data may not be vitally important.

In a bottom-up risk estimation process, a system can be divided into sub-systems that can be further broken down to a component level in order to identify all the possible hazards. In such a process, the identification of all possible hazards is theoretically achievable. All combinations of possible failure events at both the component and sub-system levels may be studied to identify the possible serious failure events; finally, risk estimation can be carried out.

In this study, a generic model of SHV is developed using a bottom-up approach; this is because of the difficulty of obtaining sufficient accident data related to SHV. The data needed to carry out the risk estimation was obtained through expert judgements by applying the developed generic model to an ocean going ship which is already in use. However, some of the data is based on real values.

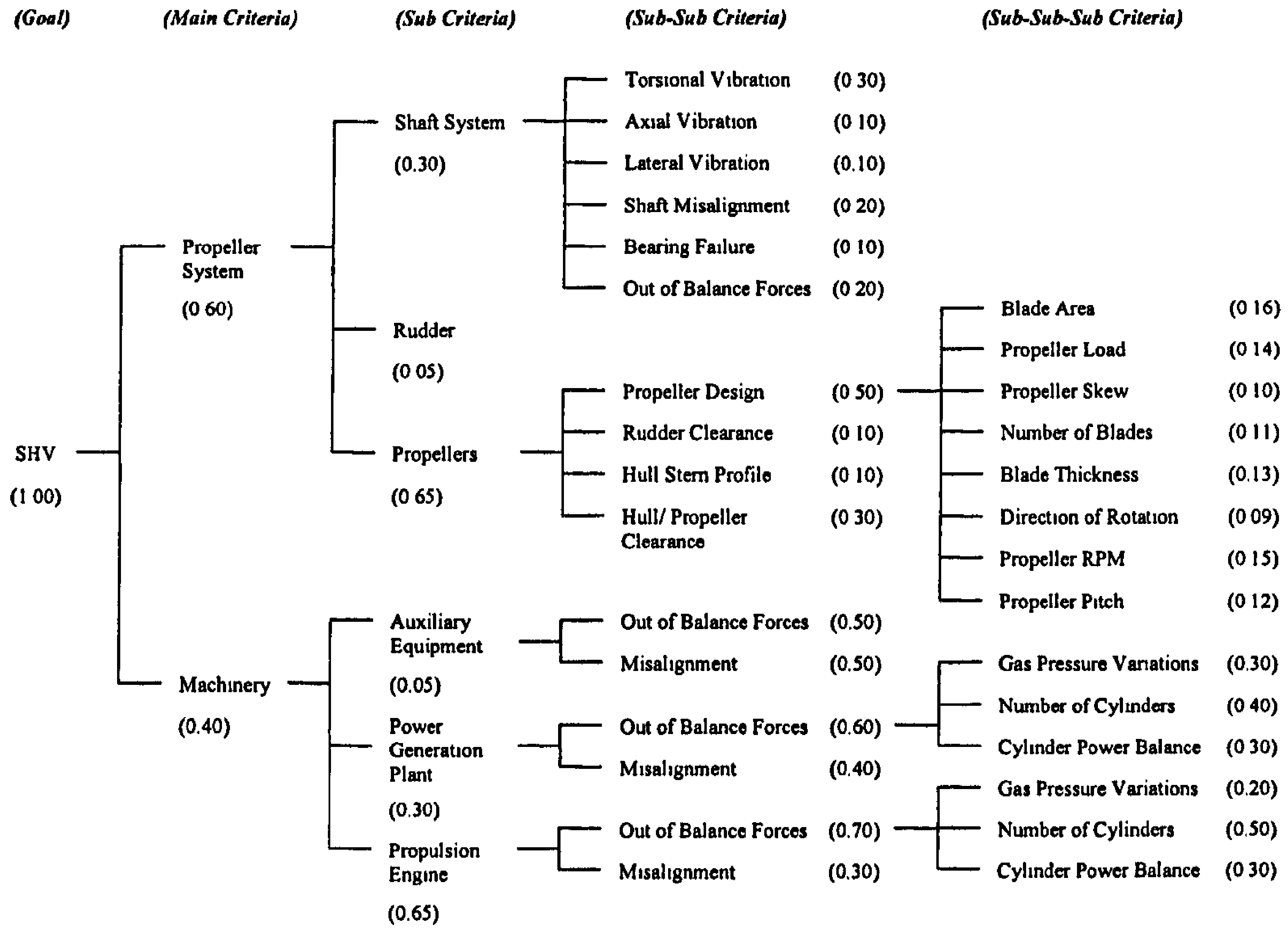


Figure 3.1: The Generic Model of SHV

In this study four experts are employed (two from industry and two from academia). The knowledge and experience of all of them are considered equal in the field. Therefore, weighting of each of them will be the same. These generic criteria in Figure 3.1 are considered because they are regarded as the most significant criteria associated with hazard identification in terms of SHV which is obtained based on extensive discussions with the above experts. They can also be considered as the most significant criteria related to hull defects induced by SHV (MDS, 1992-2007). The detailed information of experts used in this chapter and dates of the meetings are given below. During the meetings, the main aims were to identify the most significant criteria to develop a hazard identification model and to find out the applicability of the model in real situations.

Panel of Experts:

- Professor J. Wang: Professor of Marine Technology, Liverpool John Moores University, United Kingdom.
- Mr. G. Phylip-Jones: Senior Lecturer, Liverpool John Moores University, United Kingdom.
- Mr. L.B. Godaliyadde: Ship Owner/Engineer, Rogers Agencies (Pvt) Ltd, Sri Lanka.
- Mr. K.M. Wijegoonewardane: Consultant/Chief Engineer, Lakcey Shipping (Pvt) Ltd, Sri Lanka.

Dates and Venues of Meetings:

- 15/02/2006: Senior Common Room, Liverpool John Moores University, United Kingdom.
- 23/05/2006: Albert Dock, Liverpool, United Kingdom.

Note: More extensive discussions with experts were also conducted via telephone.

3.3.1. Propeller System

The shaft system, rudder and propellers have been included in the propeller system of this study. The propeller system has higher importance than the machinery when considering harmful SHV. Therefore it is given a higher weight which is 0.60. Sub Criteria (shaft system, rudder and propellers) of the propeller system have gained a complete assessment based on their associated weights (0.30 + 0.05 + 0.65 = 1). The propellers have the highest weight (0.65) and rudder has the lowest weight (0.05). Based on the literature review and expert judgements it was obtained that propellers have the highest importance and rudder has the lowest importance. However, weight of 0.30 was allocated to the shaft system.

3.3.1.1. Shaft System

There are six Sub-Sub Criteria associated with the shaft system namely, torsional vibration, axial vibration, lateral vibration, shaft misalignment, bearing failure and out of balance forces. When the propulsion shafting vibrations are considered, there are three distinct types of vibration patterns, each with specific sources, characteristics and consequences (Magazinovic, 2002). These three kinds of shafting vibrations are torsional, axial and lateral. The torsional vibration is caused by the varying gas pressure in the cylinders during the working cycle and the crankshaft/connecting rod mechanism creating varying torque in the crankshaft (Woodyard, 2004; Anon, 1989). The excitation of torsional vibration is the result of those variations. Torsional vibration involves the whole shaft system of the propulsion plant, embracing engine crankshaft, intermediate shafts and propeller shaft. This vibration causes extra stresses, which could result in serious damages in the shaft system and even fracture of the shafting (Magazinovic, 2002). Therefore, torsional vibration can be considered as the major vibration pattern of the shafting system. In contrast to easily visible or perceptible axial or lateral vibrations, torsional vibrations are "invisible".

When the crank throw is loaded by the gas pressure through the connecting rod mechanism the arms of the crank throw deflect in the axial direction of the crankshaft (Woodyard, 2004; Anon, 1989). This leads to the excitation of axial vibration. Also there is a relatively large effect from propeller's thrust variation for the excitation of shafting axial vibration (Magazinovic, 2002). Although shafting axial vibrations alone are rarely the cause of severe shafting damages, they are usually the cause of a SHV, excited by the variable force acting on the thrust block.

Lateral vibrations are mainly excited by the propeller weight, propeller induced variable forces and shafting segment's weight and unbalance (Magazinovic, 2002). The amplitudes of lateral vibrations are generally enlarged by the increased span between the line shaft bearings. They may be considered as a special case of the more general whirling vibrations which represent the resultant motion of two concurrent motions, each in perpendicular planes passing through the shaft neutral position. These vibrations are very low compared with the other vibration patterns.

When centrelines of two or more machinery shafts are not in line with each other the shaft misalignment occurs (Norton & Karczub, 2003). It leads to unbalanced forces generating in the shaft system. Those unbalanced forces create vibrations while producing greater stresses on the rotating and stationary components and result in secondary effects, such as bearing and seal failure, excessive radial and axial vibrations, high casing temperatures, and loose foundation bolts and coupling bolts (maintenanceresources.com).

Bearing failures are caused not only by shaft misalignment but also by poor maintenance activities and wear of the bearings. The shaft system is rotating machinery; this rotating machinery produces out of balance forces. The deflection in the rotating machinery is caused by such forces. Therefore it is necessary to minimise them to maintain a good quality shaft system.

The defined six Sub-Sub Criteria (torsional vibration, axial vibration, lateral vibration, shaft misalignment, bearing failure and out of balance forces) connect to the shaft system which is a sub criterion. After that, it connects to the propeller system (Main Criteria). That is because the propeller and shaft line are a complete system and if there is a vibration problem in the shaft system it affects the performance of the propeller. Finally, all those factors contribute to SHV (Goal); this is the procedure adopted for the development of the SHV model shown in Figure 3.1. It is considered that the torsional vibration has the highest impact on the shaft system and hence SHV. Therefore, it was given a weight (ω_i) of 0.30. Shaft misalignment and out of balance forces are given 0.20 each while axial and lateral vibrations are granted 0.10 each. These six Sub Criteria are considered as one single set of the shaft system. In order to obtain a complete assessment, it is considered that the total weight of a single set is equal to 1 (100%). In this case, for example, the sum (0.30 + 0.10 + 0.10 + 0.20 + 0.10 + 0.20) of all the criteria equals 1. Such kind of weight calculation is used for the development of the generic model of SHV.

3.3.1.2. Rudder

The rudder is used in ships to change direction. Rudders available can be classified under the balanced and unbalanced types. The balanced spade and gnomon rudders are a balanced type while unbalanced single pintle and unbalanced multiple pintle rudders are unbalanced types (Phylip-Jones, 1998). In this study only the rudder shape is considered because there is a possibility of giving vibration forces due to the shape. Generally, balanced type rudders are used in most of the ships. The choice of a particular rudder type depends on the size, speed and type of the ship. Since the rudder is a separate single unit and has less contribution to SHV compared with other Sub Criteria, it is allocated the least weight of 0.05.

3.3.1.3. Propellers

Propeller induced vibrations are the major contributory factor for SHV. Therefore, the highest weight of 0.65 is given to them in this generic model. Propellers have four Sub-Sub Criteria namely, propeller design, rudder clearance, hull stern profile and hull/propeller clearance. The propeller design and hull/propeller clearance are the most important factors in causing propeller induced hull vibrations so they have been allocated weights of 0.50 and 0.30 respectively. The rudder clearance and hull stern profile have weights of 0.10 each due to their relatively small contribution to SHV.

The linear distance between rudder and propeller is called the rudder clearance to the propeller; normally this distance is estimated as a percentage value of actual propeller diameter. If a ship has a large clearance between propeller and rudder, more flow can get on to the propeller. Therefore, it is possible to have a smoother pressure variation around the propeller by taking a steady flow. Large clearance also reduces the irregular pressure pulsations which are transferred from propeller to the rudder and erosive forms of the rudder (Holtrop & Valkhof, 2003). The erosive forms of the rudder can affect the manoeuvring of the ship.

The stern is the rear or aft part of a ship, technically defined as the area built up over the sternpost. The hull stern profile has become a considerably important factor in analysing ship vibration problems since the water flow which passes the propeller, and pressure pulsations which are transferred to the hull, may depend on the hull stern profile. In particular, wake distribution depends on the hull stern profile.

The importance of the propeller tip clearance to the hull (hull/propeller clearance) is emphasised in many cases (Abrahamsen, 2005). In general it is necessary to have large propeller clearances (i.e. the clearance to rudder, to bottom plating, top hull plating or to bossings) at all times to avoid harmful vibrations (Todd, 1961).

3.3.1.3.1. Propeller Design

The propeller induced vibrations are mostly dependent on the propeller design. As such it has been allocated the weight of 0.50. The amount of pressure pulsations and out of balance forces which are produced by propeller design are mainly based on the eight Sub-Sub-Sub Criteria attached to it. They are, namely, blade area, propeller load, propeller skew, number of blades, blade thickness, direction of rotation, propeller RPM, and propeller pitch.

The propeller blade area should be sufficient to produce the required thrust without the inception of bubble or extended sheet cavitation over the propeller blade (Brescia *et al.,* 2001). A large blade area is one of the most effective ways to reduce cavitation volume and radiated pressure field.

If a propeller is constructed with the centre of pressure moved towards the hub, the load is distributed and pressure is lowered at the blade tips (JISC, 2005). As the blade tips cut through the wake the cavitation effect is less, hence the propeller produces less vibration.

It is possible to distribute the pressure pulses by using a different blade shape; this is achieved by applying skew to the propeller. The skew is said to be as a blade that is swept back versus a blade that is radially symmetrical in contour. Characteristics of a skewed back propeller are a small cavitation bubble, weak drawn out impulse and reduction of a risk of vibration (JISC, 2005).

In practice, one and two blade propellers are the most efficient (mercurymarine.com). However, in terms of vibration they are the worst. As the blades are added, efficiency decreases, thus reducing the level of vibration. In recent years, with the growing frequency of propellers, four and five bladed propellers have become more popular. Also, when the number of blades of the propeller increases it tends to give more favourable thrust as well as smoother pressure variation compared with propellers with less blades.

Blade thickness is one of the factors which influence the strength of the propeller. A high level of thickening of the blades affects the balancing of the propeller because they increase its weight. Low thickening of blades gives poor strength so that they can be easily damaged and will produce cavitation and blade erosion.

Therefore, considerable thickness should be taken into account as important factors when minimising the vibrations.

The direction of propeller rotation is important because hull-induced pressure levels can be influenced by direction of rotation (Brescia *et al.*, 2001). The outward direction of rotation normally gives better efficiency, while inward rotation results in lower pressure pulses on the hull surface. This applies especially for twin screw ships where both propellers operate in opposite directions. In general, a single screw ship always uses designed direction of rotation of the propeller. The direction of rotation changes in single screw ships only in special cases, such as to reverse the ship.

It is well known that the action exerted by the propeller on the hull is due to the pressure field caused by the blade displacement (Brescia *et al.*, 2001). It is also essential to consider the propeller RPM because the total pulsating pressure on the hull plates depends on the running condition (Nilsson, 1980). The pressure field increases with the increased RPM of the propeller and leads to large pressure fluctuations and unbalanced forces on the hull plates creating hull vibration. Therefore, it is better to use a slower propeller RPM in order to obtain minimum vibration.

The pitch of the propeller blades should be taken into account when vibration problems are considered. There are special types of propellers available whose angle of pitch can be adjusted. As the blade passes the upper and lower positions in the circular area where the wake is strong, the blade pitch angle can be adjusted so that it is better suited to the actual angle of attack due to wake. This reduces the cavitation patterns on blades.

The blade area has the highest importance in causing SHV from the defined eight Sub-Sub-Sub Criteria of the propeller design. As such it is allocated the highest weight of 0.16. The propeller RPM, propeller load, blade thickness and propeller pitch have weights 0.15, 0.14, 0.13, and 0.12 respectively. However, the number of blades is given the weight of 0.11, propeller skew is assigned the weight of 0.10 and the least weight is allocated to direction of rotation (0.09).

3.3.2. Machinery

Shipboard machinery generally consists of auxiliary equipment, power generation plant and propulsion engine. The auxiliary equipment has the lowest importance (0.05) in causing SHV compared with the other two Sub Criteria in Figure 3.1. This is because auxiliary equipment has low inertia and thus generates low vibration patterns of the machinery section. Those vibration patterns are mainly due to out of balance forces (0.50) and misalignment (0.50).

The power generation plant and propulsion engine also suffer from vibration because of out of balance forces and misalignment. The power generation plant is used to produce the electricity and the propulsion engine is employed to develop the required power for propulsion. They are reciprocating machinery. Due to development of higher power, larger engine size, and larger weight, the propulsion engine has more importance than the power generation plant in production of vibrations. Therefore, the propulsion engine is given higher weight (0.65) than the one of power generation plant (0.30). This reciprocating machinery suffers from out of balance forces mainly due to the effect of cylinders (reciprocating masses). Especially, the development of long stroke, fuel efficient engines contributes to higher vibration levels for ships as these engines can generate the required power with fewer cylinders (Mano, 1985). These fewer cylinder engines result in large exciting forces, large unbalanced moments, torque variation, longitudinal and transverse engine structure vibrations. Therefore if a ship has a high number of cylinders it would be better to minimise the level of vibration.

If there is an incorrect power balance between the cylinders, it gives out of balance forces which lead to vibration. The extreme situation of incorrect power balance is misfiring. It usually produces enlarged vibratory stresses in the components of a propulsion plant (Magazinovic, 2002). No machinery is perfectly balanced, and there are always out of balance forces present leading to unwanted vibration. However, SHV caused by machinery is less important than the propellers, therefore a weight of 0.40 was allocated to the machinery section.

3.4. Methodology

The following steps are developed, based on the hierarchical structure in order to obtain the risk estimation of SHV.

Step 1: All the criteria in the hierarchical structure (Figure 3.1) are given assessment grades. Those assessment grades could be either qualitative or quantitative.

Step 2: The quantitative criteria in the hierarchy are represented by a fuzzy rule base. All of them are transformed to the qualitative ones using "a rule based information transformation technique".

Step 3: The lower level qualitative criteria are converted into upper level criteria and subsequent quantification of the belief degrees associated with each qualitative criterion is conducted by formulating "a mapping process". Fuzzy rule base is developed to demonstrate the mapping process.

Step 4: The ER algorithm is used to carry out the risk estimation of SHV. In this case the IDS software is used for synthesis of basic criteria in the hierarchical structure and to produce the results graphically.

3.4.1. Fuzzy Rule Base

The "If-Then" rules (fuzzy rule base) have two parts, namely, an antecedent that is the inputs and a consequent part which is the results (Bowles & Pelaez, 1995; Pillay & Wang, 2003). A single "If-Then" rule is illustrated by the example in Table 3.1.

Table 3.1: An Example of Rule Base for Risk Evaluation

Rule #	Occurrence	Severity	Detectability	Risk
1	Low	Very High	Moderate	Important

Rule # 1 in Table 3.1 can be read as follows:

If **occurrence** is *Low* and **severity** is *Very High* and **detectability** is *Moderate* then the **risk** is *Important.*

3.4.2. Rule Based Quantitative Data Transformation Technique

If quantitative criteria are available in the hierarchical structure, it is necessary to use a transformation technique to convert them into qualitative criteria. This is achieved through a rule based technique (Yang, 2001):

Suppose a value $h_{n,i}$ for a criterion e_i is judged to be similar to a grade H_n or:

$$h_{n,i} \Rightarrow H_n \; (n = 1, \ldots, N) \tag{3.1}$$

Without loss of generality, suppose e_i is a 'profit' criterion, that is, a larger value $h_{n+1,i}$ is preferred to a smaller value $h_{n,i}$. Let $h_{N,i}$ be the largest feasible value and $h_{1,i}$ be the smallest. Then a value h_j on e_i can be denoted by using the following equation:

$$S^i(h_j) = \{(h_{n,i},\, \gamma_{n,j}),\, n = 1, \ldots\ldots, N\} \tag{3.2}$$

$$\text{where, } \gamma_{n,j} = \frac{h_{n+1,i} - h_j}{h_{n+1,i} - h_{n,i}} \quad \text{and} \quad \gamma_{n+1,j} = 1 - \gamma_{n,j}, \text{ if } h_{n,i} \leq h_j \leq h_{n+1,i} \tag{3.3}$$

$$\gamma_{k,j} = 0 \quad \text{for} \quad k = 1, \ldots\ldots, N, \quad k \neq n, n+1. \tag{3.4}$$

For the rules described in Eq. (3.1), a value of h_j can be represented by using the following equation:

$$S(h_j) = \{(H_n,\, \beta_{n,j}),\, n = 1, \ldots\ldots, N\} \tag{3.5}$$

$$\text{where, } \beta_{n,j} = \gamma_{n,j}, \quad n = 1, \ldots\ldots, N \tag{3.6}$$

In reality, there are some quantitative criteria with a random variable and they may not take a single value but several values with different probabilities. To evaluate such a criterion e_i the below mentioned equation can be used:

$$S^i(e_i) = \{(h_j,\, p_j),\, j = 1, \ldots., M_i\} \tag{3.7}$$

where, h_j (j = 1, …., M_i) are possible values that e_i may take and p_j is the probability that e_i takes a value h_j, where $\sum_{j=1}^{M_i} p_j \leq 1$. The above distribution reads that a criterion e_i takes a value h_j with a probability p_j (j = 1, …., M_i). Note, that e_i taking a single value h_j is a special case of Eq. (3.7) with $p_j = 1$ and $p_l = 0$ (l = 1, …., M_i, $l \neq j$).

3.4.3. Mapping Process

In nature there are situations with different amounts of linguistic terms and also with different types of linguistic terms in lower level criteria and associated upper level criteria. To apply the ER approach, it is necessary to have all data and information on the basis of the same universe (common utility space). Therefore, the information and data need to be transformed before being aggregated. The fuzzy rule base is most suited to transforming fuzzy input (lower level criterion) to fuzzy output (upper level criterion). This method can function very well in dealing with risk estimation problems. However, it requires the development of multiple fuzzy rules in a hierarchical structure which has a general criterion (top level) and many basic criteria (lower level). The transformation, which has been previously mentioned, is called "Mapping Process". By taking the lower level criterion "Torsional Vibration (TV)" in the hierarchical structure in one risk estimation problem as an example, the mapping process can be introduced in the following context.

Consider the criterion "TV" (lower level) has its associated upper level criterion "Shaft System (SS)" and other lower level criteria "Axial Vibration (AV)", "Lateral Vibration (LV)", "Shaft Misalignment (SM)", "Bearing Failure (BF)" and "Out of Balance Forces (OBF)" in a risk estimation model. The upper level criterion "SS" can be expressed using such linguistic terms as Top, Excellent, Reasonable, Marginal, Critical, and Catastrophic (Table 3.4). The lower level criterion "TV" is described as Unlikely, Moderate, Highly Likely and Definite (Table 3.5). The linguistic terms associated with other lower level criteria of "SS" can be found in Table 3.5. The transformation from fuzzy inputs to outputs is shown in Figure 3.2 by using the proposed mapping process.

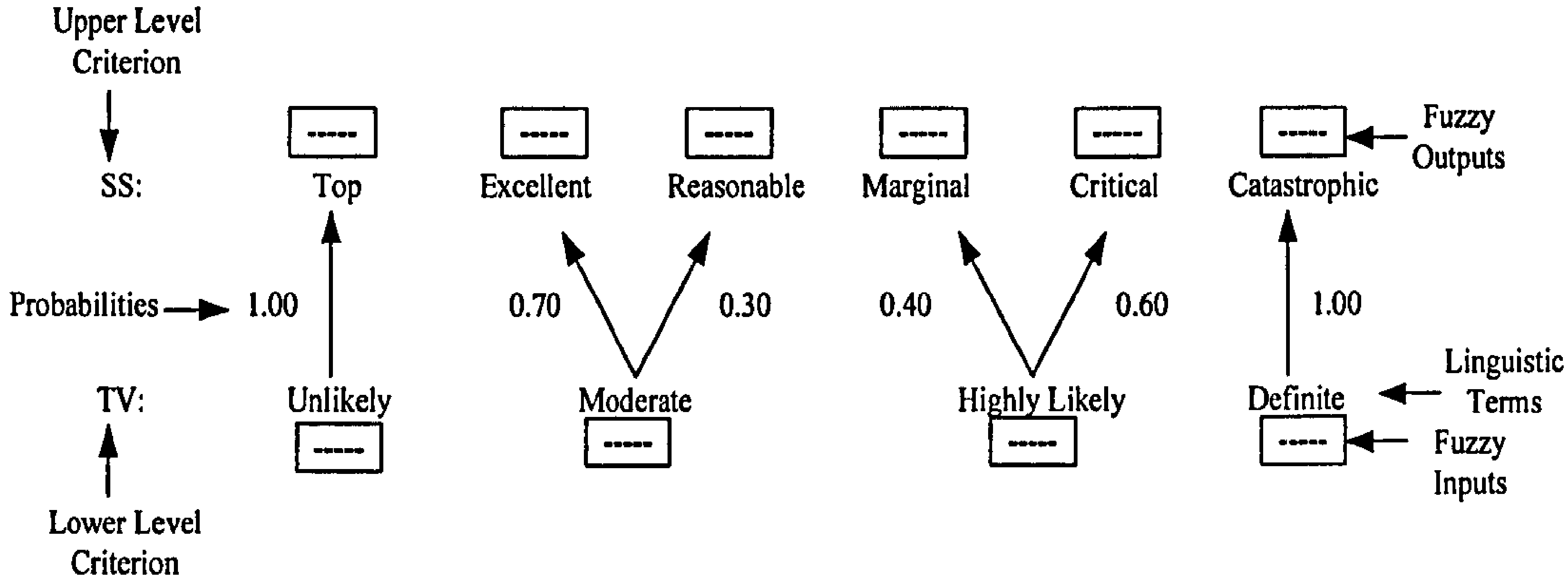


Figure 3.2: Mapping from Lower Level to Upper Level

In Figure 3.2, the values attached to the arrows are the probabilities (*P*) distributed by experts for indicating the relationships between the linguistic terms of different-level risk estimation criteria. Note that the sum of the probability values from one linguistic term is equal to 1.00. For instance, the lower level criterion "TV" with the Moderate linguistic term indicates that the level of the upper level criterion "SS" is believed to be 70% or 0.70 ($P_{TV=2}{}^{SS=2}$) Excellent and 30% or 0.30 ($P_{TV=2}{}^{SS=3}$) Reasonable. Such a mapping process can be used to transform the lower level criteria into upper level criteria by aggregating the values of fuzzy inputs and probabilities. The developed fuzzy rule base ("If-Then" rules) for "TV" and other associated lower level criteria for the transformation can be found in Appendix 3.2. The transformation process and aggregation of the calculations (quantification) to complete the mapping process is illustrated as follows:

Assume that each L^{TV} (TV = 1, 2, 3, 4) highlights the fuzzy inputs of the lower level criterion "TV" and that each U^{SS} (SS = 1, 2, ..., 6) represents the fuzzy outputs (upper level) transformed from the inputs (L^{TV}). Then Eq. (3.8) can be constructed.

$$U^{SS} = \sum_{TV=1}^{4} L^{TV} P_{TV}{}^{SS} \qquad SS = (1, 2, ..., 6) \tag{3.8}$$

where, $\sum_{SS=1}^{6} P_{TV}{}^{SS} = 1.00$

Eq. (3.8) is a generic equation and this developed algorithm can be used for any other situations of two level mapping process. The quantified values for this "TV" transformation process can be found in Table 3.12. The major advantages of this two level mapping process can be highlighted as possibility to transform any number of linguistic terms into any number of linguistic terms and ability to obtain risk estimation for each level. There is no limitation to the converting process. After all the criteria are mapped onto a common utility space, ER can be applied for the synthesis of the transformed criteria.

3.4.4. The ER Approach

In the generic model (Figure 3.1), SHV is the top level criterion and all the others are considered to be basic criteria. Suppose the model has L basic criteria e_i (i = 1,...., L) and M alternatives a_l = (l = 1, ..., M). Then the ER approach is described as follows (Yang, 2001; Yang & Xu, 2002; Xie *et al.*, 2006):

i) E has L basic criteria and it is defined by

$$E = \{e_i,\ i = 1, \ldots, L\} \tag{3.9}$$

ii) The L basic criteria consist of all the factors influencing the assessment of the associated general criterion. The relative weights estimation of the L criteria is given by $\omega = \{\omega_1 \ldots \omega_i \ldots \omega_L\}$, where ω_i is the relative weight for basic criterion i and is normalised, so that

$$0 \le \omega_i \le 1 \text{ and } \sum_{i=1}^{L} \omega_i = 1 \tag{3.10}$$

iii) Define N distinctive evaluation grades H_n (n = 1, ..., N) as a complete set of standards for assessing each alternative for all criteria, or

$$H = \{H_n,\ n=1, \ldots\ldots, N\} \tag{3.11}$$

iv) Then a multi criteria risk estimation problem could be modelled by using the following distributions for alternatives a_l = (l = 1, ..., M) on criteria e_i (i = 1,...., L):

$$S(e_i(a_l)) = \{(H_n, \beta_{n,i}(a_l)),\ n = 1, \ldots, N\},\ i = 1, \ldots L, \quad l = 1, \ldots, M \tag{3.12}$$

where, $\beta_{n,i}(a_l) \geq 0$ and $\sum_{n=1}^{N} \beta_{n,i}(a_l) \leq 1$. $\beta_{n,i}(a_l)$ denotes a degree of belief. A distribution as shown in Eq. (3.12), reads that a criterion e_i at an option a_l is assessed to a grade H_n with a degree of belief of $\beta_{n,i}(a_l)$ ($n = 1, \ldots\ldots, N$).

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

$$\beta_H = 1 - \sum_{n=1}^{N} \beta_n , \qquad 0 \leq \beta_n \leq 1, \qquad \sum_{n=1}^{N} \beta_n + \beta_H = 1 \tag{3.13}$$

The aggregation problem is to generate β_n ($n = 1, \ldots\ldots, N$) by aggregating the assessments for all the associated basic criteria e_i ($i = 1, \ldots., L$) as given in Eq. (3.12). The following ER algorithm can be used for this purpose.

3.4.5. ER Algorithm

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

$$m_{n,i} = \omega_i \beta_{n,i} \qquad n = 1, 2, \ldots\ldots, N; \quad i = 1, 2, \ldots\ldots, L \tag{3.14}$$

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

$$m_{H,i} = 1 - \sum_{n=1}^{N} m_{n,i} \qquad i = 1, 2, \ldots\ldots, L \tag{3.15}$$

The remaining probability mass $m_{H,i}$ can be split into two parts $\bar{m}_{H,i}$ and $\tilde{m}_{H,i}$, which can be calculated by using the following formulas:

$$\bar{m}_{H,i} = 1 - \omega_i \qquad i = 1, 2, \ldots\ldots, L \tag{3.16}$$

$$\tilde{m}_{H,i} = \omega_i \left(1 - \sum_{n=1}^{N} \beta_{n,i} \right) \qquad i = 1, 2, \ldots\ldots, L \tag{3.17}$$

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

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

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

Let $m_{n,I(i)}$ be a probability mass defined as the degree to which all the i criteria in $E_{I(i)}$ support the hypothesis that E is assessed to the grade H_n and let $m_{H,I(i)}$ be the remaining probability mass unassigned to individual grades after all the basic criteria in $E_{I(i)}$ have been assessed. Eqs. (3.18) and (3.19) are obviously correct when i=1.

$$m_{n,I(1)} = m_{n,1} \qquad \text{for } n = 1, 2, \ldots\ldots, N \tag{3.18}$$

$$m_{H,I(1)} = m_{H,1} \tag{3.19}$$

By using Eqs. (3.18) and (3.19), Eq. (3.20) can be constructed for i = 1, 2, ……, L-1 to obtain the coefficients $m_{n,I(L)}$, $\bar{m}_{H,I(L)}$ and $\tilde{m}_{H,I(L)}$ (Yang & Xu, 2002):

$$K_{I(i+1)} = \left[1 - \sum_{t=1}^{N} \sum_{\substack{j=1 \\ j \neq t}}^{N} m_{t,I(i)} m_{j,i+1}\right]^{-1} \tag{3.20}$$

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

$\{H_n\}$:

$$m_{n,I(i+1)} = K_{I(i+1)}[m_{n,I(i)} m_{n,i+1} + m_{H,I(i)} m_{n,i+1} + m_{n,I(i)} m_{H,i+1}] \quad n = 1, 2, \ldots\ldots, N \tag{3.21}$$

$$\tilde{m}_{H,I(i+1)} = K_{I(i+1)}[\tilde{m}_{H,I(i)} \tilde{m}_{H,i+1} + \bar{m}_{H,I(i)} \tilde{m}_{H,i+1} + \tilde{m}_{H,I(i)} \bar{m}_{H,i+1}] \tag{3.22}$$

$$\overline{m}_{H,I(i+1)} = K_{I(i+1)}\overline{m}_{H,I(i)}\overline{m}_{H,i+1} \qquad (3.23)$$

$\{H\}$:

$$m_{H,I(i)} = \tilde{m}_{H,I(i)} + \overline{m}_{H,I(i)} \qquad i = 1, 2, \ldots\ldots, L - 1 \qquad (3.24)$$

At last, the combined degrees of belief of all the basic criteria for the assessment to criterion E are calculated by:

$$\{H_n\}: \beta_n = \frac{m_{n,I(L)}}{1 - \overline{m}_{H,I(L)}} \qquad n = 1, 2, \ldots\ldots, N \qquad (3.25)$$

$$\{H\}: \beta_H = \frac{\tilde{m}_{H,I(L)}}{1 - \overline{m}_{H,I(L)}} \qquad (3.26)$$

The ER approach is used in Step 4 of the proposed methodology for synthesis of basic criteria in the hierarchical structure. The ER based Intelligent Decision System (IDS) software is employed to produce the results graphically.

3.5. Case Study

Referring to the generic model, it is understood that SHV may cause severe problems within a shipboard environment. The main aim of this section is to demonstrate how the proposed methodology can be applied to estimate the risk of SHV. Using a bottom-up approach the estimation of risk can be conducted. The generic model is applied to a real ship and some useful data can be found in Appendix 3.1.

3.5.1. SHV Quantitative and Qualitative Criteria Modelling (*Step 1*)

In general there are two types of basic criteria, namely, qualitative and quantitative. Qualitative criteria are always represented by linguistic terms such as Very Good, Good, Bad etc. Generally, a minimum of three and maximum of seven linguistic terms can be used; however this is not a fixed rule. The number of linguistic terms depends on the nature of the criterion and expert judgements. Quantitative criteria are represented by numerical values, e.g. increasing the propeller diameter by 1m, the vibration forces can be reduced by 10%. It may not be possible to use quantitative criteria in every case. Therefore, such quantitative criteria should be converted into qualitative criteria for rational synthesis using transformation techniques.

In the generic model of SHV (Figure 3.1) the assessment grades from Goal to Sub-Sub-Sub Criteria are addressed as per Tables 3.2 to 3.6.

Table 3.2: Assessment Grades for Goal

Goal	**Assessment Grades**				
SHV	Very Low	Low	Average	High	Very High

Table 3.3: Assessment Grades for Main Criteria

Main Criteria	**Assessment Grades**					
Propeller System	Top	Excellent	Reasonable	Marginal	Critical	Catastrophic
Machinery	Very Poor	Poor	Average	Good	Very Good	

Table 3.4: Assessment Grades for Sub Criteria

Sub Criteria	**Assessment Grades**					
Shaft System	Top	Excellent	Reasonable	Marginal	Critical	Catastrophic
Rudder	Unlikely	Moderate	Highly Likely	Definite		
Propellers	Very Poor	Poor	Normal	Good	Very Good	
Auxiliary Equipment	Very Bad	Bad	Average	Good	Very Good	
Power Generation Plant	Very Bad	Bad	Average	Good	Very Good	
Propulsion Engine	Very Bad	Bad	Average	Good	Very Good	

Table 3.5: Assessment Grades for Sub-Sub Criteria

Sub-Sub Criteria	**Assessment Grades**				
Torsional Vibration	Unlikely	Moderate	Highly Likely	Definite	
Axial Vibration	Unlikely	Moderate	Highly Likely	Definite	
Lateral Vibration	Unlikely	Moderate	Highly Likely	Definite	
Shaft Misalignment	Very Poor	Poor	Average	Good	Very Good
Bearing Failure	Extremely Remote	Remote	Likely	Frequent	Extremely Frequent
Out of Balance Forces	Very Weak	Weak	Likely	Strong	Very Strong
Propeller Design	Very Poor	Poor	Normal	Good	Very Good
Rudder Clearance	Quantitative				
Hull Stern Profile	Very Bad	Bad	Normal	Good	Very Good
Hull/propeller Clearance	Quantitative				
Out of Balance Forces	Very Low	Low	Average	High	Very High

Misalignment	Very Poor	Poor	Average	Good	Very Good
Out of Balance Forces	Very Low	Low	Average	High	Very High
Misalignment	Very Poor	Poor	Average	Good	Very Good
Out of Balance Forces	Very Low	Low	Average	High	Very High
Misalignment	Very Poor	Poor	Average	Good	Very Good

Table 3.6: Assessment Grades for Sub-Sub-Sub Criteria

Sub-Sub-Sub Criteria	**Assessment Grades**				
Blade Area	Quantitative				
Propeller Load	Very Low	Low	Average	High	Very High
Propeller Skew	Very Low	Low	Average	High	Very High
Number of Blades	Quantitative				
Blade Thickness	Very Low	Low	Average	High	Very High
Direction of Rotation	Unsatisfactory	Acceptable	Satisfactory		
Propeller RPM	Quantitative				
Propeller Pitch	Very Poor	Poor	Normal	Good	Very Good
Gas Pressure Variations	Very Low	Low	Average	High	Very High
Number of Cylinders	Quantitative				
Cylinder Power Balance	Very Low	Low	Average	High	Very High
Gas Pressure Variations	Very Low	Low	Average	High	Very High
Number of Cylinders	Quantitative				
Cylinder Power Balance	Very Low	Low	Average	High	Very High

Table 3.2 presents five linguistic terms associated with Goal; they range from Very Low to Very High. It is believed that if the Very High linguistic term has a high probability, the risk estimation will be very high for the considered ship in this study.

The Main Criteria consist of propeller system and machinery. According to Table 3.3 the propeller system has six linguistic terms and machinery has five linguistic terms. In this study the maximum number of linguistic terms has been taken as six for each criterion.

The shaft system in Table 3.4 has the highest number of linguistic terms whilst the rudder has the least number of linguistic terms. There are no quantitative criteria present in the Sub Criteria section.

The assessment grades for Sub-Sub Criteria and Sub-Sub-Sub Criteria are shown in Tables 3.5 and 3.6, each table including some quantitative criteria. These criteria will be transformed into qualitative criteria in order to use ER to estimate the risk of SHV, which is carried out in the next section.

3.5.2. Transformation of Quantitative Criteria into Qualitative Criteria using Rule Base Technique (*Step 2*)

In this section a rule based technique is used to convert quantitative criteria into qualitative criteria. The approach described in Section 3.4.2 can be employed for the transformation. The following example is shown in order to demonstrate this technique.

Table 3.7: Rudder Clearance

Sub-Sub Criteria	Very Poor ($h_{1,1}$)	Poor ($h_{2,1}$)	Normal ($h_{3,1}$)	Good ($h_{4,1}$)	Very Good ($h_{5,1}$)	***Estimated Value (h_l)***
e_1 = Clearance (%)	30	35	40	45	50	***36***

The effect on propeller in terms of vibrations due to rudder clearance can be classified into different grades, namely, Very Good ($h_{5,1}$), Good ($h_{4,1}$), Normal ($h_{3,1}$), Poor ($h_{2,1}$) and Very Poor ($h_{1,1}$). According to Table 3.7 the percentage values of clearances range from 30% to 50% (here rudder clearances are defined as percentage values of actual propeller diameter). These values have been obtained after conducting discussions with previously mentioned experts. The percentage clearances defined here are specific for the ship considered in this Case Study and may be different for other ship types. When the rudder clearance is small the vibration risk associated with propeller is pretty high, which is the major reason to move linguistic terms from Very Poor to Very Good as the percentage values increase.

$H = \{H_j, j = 1, \ldots, 5\}$ = {Very Poor, Poor, Normal, Good, Very Good}

For this ship, the diameter of the propeller is 2.75 m. Table 3.8 shows the distances between the rudder and propeller.

Table 3.8: Distances between Rudder and Propeller

Percentage Value (%)	Distance (m)
50	1.375

45	1.238
40	1.100
35	0.963
30	0.825

If this ship has a rudder clearance of 1.375 m, this clearance would be represented as Very Good linguistic term because the vibration risk associated with propeller will be Very Low in that situation. A large clearance allows steady water flow on to the propeller. With steady flow a smoother pressure variation around the propeller can be obtained also reducing the possibility of tip vortex cavitation on the propeller and on the rudder.

If the rudder clearance is Very Low (0.825 m) then the clearance can be classified as Very Poor because there are possibilities such as irregular pressure fluctuations, various cavitation patterns, etc; that may cause vibrations. In this study, the clearance between rudder and propeller is estimated as 36% (Table 3.7) of the value of propeller diameter which is 2.75 m; thus the actual value of clearance for this ship is 0.990 m. Using the data in Tables 3.7 and 3.8, a fuzzy rule base is developed in order to represent the clearance of the rudder (quantitative criterion) subjectively.

1. If rudder clearance to the propeller is 50%, then it is Very Good (or $h_{5,1} = 50$).
2. If rudder clearance to the propeller is 45%, then it is Good (or $h_{4,1} = 45$).
3. If rudder clearance to the propeller is 40%, then it is Normal (or $h_{3,1} = 40$).
4. If rudder clearance to the propeller is 35%, then it is Poor (or $h_{2,1} = 35$).
5. If rudder clearance to the propeller is 30%, then it is Very Poor (or $h_{1,1} = 30$).

$$H^1 = H^{\text{Clearance}} = \{h_{1,1}, h_{2,1}, h_{3,1}, h_{4,1}, h_{5,1}\} = \{30, 35, 40, 45, 50\}$$

Considering an estimated value of rudder clearance (h_1 = 36%) then for the considered ship (since $h_{3,1}$= 40% $h_{2,1}$ = 35% and $h_{2,1} < h_1 < h_{3,1}$), h_1 can be described as follows:

$$S^1\,(e_1\,(\text{Rudder})) = \{(h_{2,1}, \gamma_{2,1}), (h_{3,1}, \gamma_{3,1})\}$$

$$\gamma_{2,1} = \frac{h_{3,1} - h_1}{h_{3,1} - h_{2,1}} = \frac{40-36}{40-35} = 0.8$$

$\gamma_{3,1} = 1 - \gamma_{2,1} = 1 - 0.8 = 0.2$

$\gamma_{2,1} = \beta_{2,1} = 0.8$ and $\gamma_{3,1} = \beta_{3,1} = 0.2$

$S(e_1 \text{ (Rudder)}) = \{(H_2, 0.8), (H_3, 0.2)\} = \{(\text{Poor}, 0.8), (\text{Normal}, 0.2)\}$

In a similar way, all the remaining quantitative criteria can be transformed accordingly. The transformed assessment grades of Sub-Sub Criteria and Sub-Sub-Sub Criteria are shown in Tables 3.9 and 3.10.

Table 3.9: Transformed Assessment Grades of Sub-Sub Criteria

Sub-Sub Criteria	Transformed Assessment Grades
Rudder Clearance	{(Poor, 0.8), (Normal, 0.2)}
Hull/Propeller Clearance	{(Poor, 0.3333), (Normal, 0.6667)}

Table 3.10: Transformed Assessment Grades of Sub-Sub-Sub Criteria

Sub-Sub-Sub Criteria	Transformed Assessment Grades
Blade Area	{(Poor, 0.3), (Normal, 0.7)}
Number of Blades	{(Normal, 1.0)}
Propeller RPM	{(Normal, 0.875), (Good, 0.125)}
Number of Cylinders (PGP)	{(Very High, 0.75), (High, 0.25)}
Number of Cylinders (PE)	{(Very High, 0.75), (High, 0.25)}

Following the transformation of the criteria from quantitative criteria to qualitative criteria, there is no need for mapping from a lower level to an upper level. It can be seen from Tables 3.9 and 3.10 that all the transformed criteria are represented by the linguistic terms associated with their upper level criteria. It is possible to take the linguistic terms of the associated upper level criteria during the transformation. This is one of the main advantages of the rule based data transformation technique. Another advantage is that belief degrees associated with linguistic terms have been quantified during the transformation.

3.5.3. Conduct Mapping to Transform Qualitative Lower Level Criteria into Upper Level (*Step 3*)

The mapping process is used to convert all the qualitative lower level criteria into upper level in the hierarchical structure. Therefore the starting point of the mapping process should be from the lowest level criteria. Figure 3.3 gives guidance on how to carry out the mapping process through an example of propeller skew.

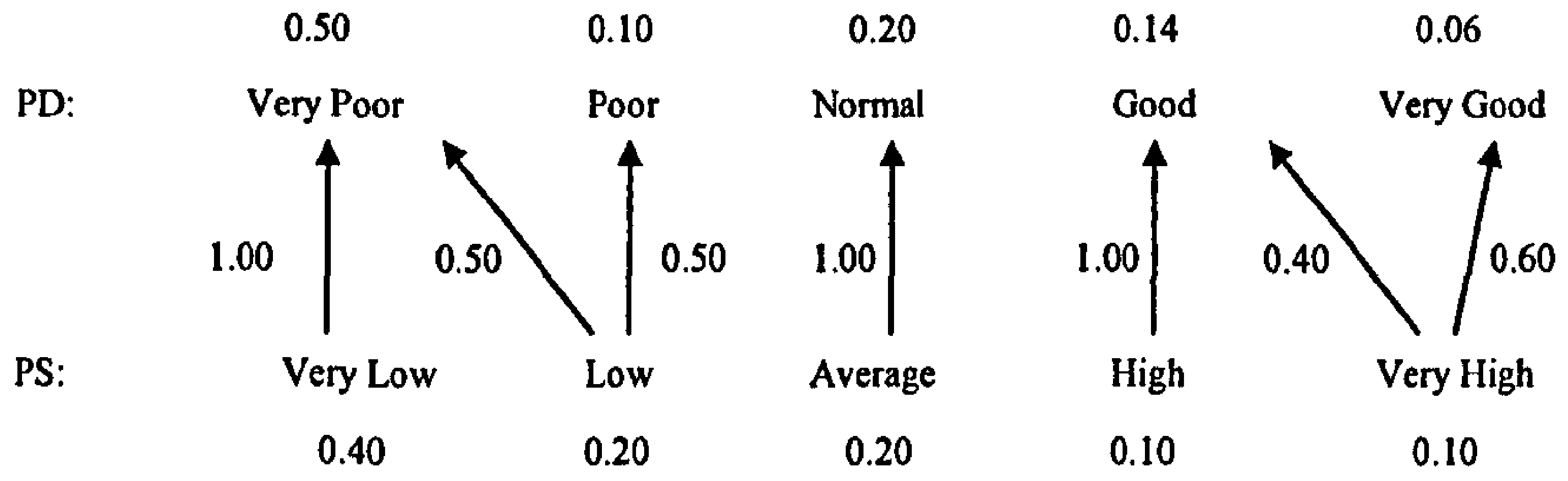


Figure 3.3: Mapping from Propeller Skew (PS) to Propeller Design (PD)

For this ship it is found that the propeller skew is fairly low, therefore, based on expert judgments, the values of 0.40, 0.20 and 0.20 were assigned to Very Low, Low and Average respectively. Also, 0.10 was given to each of High and Very High. All the inputs are represented as {(Very Low, 0.40), (Low, 0.20), (Average, 0.20), (High, 0.10), (Very High, 0.10)}. To explain this mapping process, a necessary subjective fuzzy rule base has been developed.

1. If the propeller skew is Very Low, then the propeller design is {(Very Poor, 1.00)}.
2. If the propeller skew is Low, then the propeller design is {(Very Poor, 0.50), (Poor, 0.50)}.
3. If the propeller skew is Average, then the propeller design is {(Normal, 1.00)}.
4. If the propeller skew is High, then the propeller design is {(Good, 1.00)}.
5. If the propeller skew is Very High, then the propeller design is {(Good, 0.40), (Very Good, 0.60)}.

The transformation from a lower level into an upper level quantifies the associated belief degrees of the linguistic terms of the upper level criterion. This is carried out by using the proposed algorithm in Eq. (3.8):

Very Poor: 0.40 × 1.00 + 0.20 × 0.50 = 0.50

Poor: 0.20 × 0.50 = 0.10

Normal: 0.20 × 1.00 = 0.20

Good: 0.10 × 1.00 + 0.10 × 0.40 = 0.14

Very Good: 0.10 × 0.60 = 0.06

The calculated output values {(Very Poor, 0.50), (Poor, 0.10), (Normal, 0.20), (Good, 0.14), (Very Good, 0.06)} can also be considered as the inputs to propeller design. In this particular case, the next level is to map the propeller design onto the propellers, then the propellers onto propeller system and finally onto the SHV. This mapping process is conducted from the lowest level (Sub-Sub-Sub Criteria) to the top criterion (Goal), separately for each criterion. All the transformed Sub-Sub-Sub Criteria of the propeller design are shown in Table 3.11.

Table 3.11: Inputs to Propeller Design (PD)

PD	Very Poor	Poor	Normal	Good	Very Good
BA	0.00	0.30	0.70	0.00	0.00
PL	0.00	0.25	0.75	0.00	0.00
PS	0.50	0.10	0.20	0.14	0.06
NoB	0.00	0.00	1.00	0.00	0.00
BT	0.20	0.10	0.40	0.10	0.20
DoR	0.40	0.00	0.20	0.00	0.40
PR	0.00	0.00	0.88	0.12	0.00
PP	0.52	0.14	0.16	0.08	0.10

where, BA = Blade Area; PL = Propeller Load; PS = Propeller Skew; NoB = Number of Blades; BT = Blade Thickness; DoR = Direction of Rotation; PR = Propeller RPM; PP = Propeller Pitch.

Table 3.12 shows the inputs to the shaft system, which are transformed Sub-Sub Criteria of the shaft system. There are no Sub-Sub-Sub Criteria associated with the Sub-Sub Criteria of the shaft system. In such a situation the lowest level criteria are the Sub-Sub criteria, therefore the mapping process should be started from Sub-Sub Criteria. The mapping process of all those six Sub-Sub Criteria is shown in Figure 3.2 and Appendix 3.2.

Table 3.12: Inputs to Shaft System (SS)

SS	Top	Excellent	Reasonable	Marginal	Critical	Catastrophic
TV	0.10	0.14	0.06	0.16	0.24	0.30
AV	0.10	0.42	0.18	0.08	0.12	0.10
LV	0.30	0.28	0.12	0.08	0.12	0.10
SM	0.30	0.14	0.16	0.22	0.08	0.10
BF	0.10	0.08	0.08	0.04	0.20	0.50
OBF	0.10	0.07	0.09	0.04	0.21	0.49

where, TV = Torsional Vibration; AV = Axial Vibration; LV = Lateral Vibration; SM = Shaft Misalignment; BF = Bearing Failure; OBF = Out of Balance Forces.

Once the quantified data has been obtained for the lower level criteria, the next step is to combine such data to obtain the risk estimation of the associated upper level criterion. In the next section the IDS software is used to achieve this task.

3.5.4. Application of ER for Synthesis (*Step 4*)

IDS incorporating the ER algorithm described in Section 3.4.5 is employed for a synthesis of criteria in the hierarchical structure. All the inputs with weightings of the relevant lowest level criteria are combined to determine the risk estimation of each higher level. The data in Tables 3.11 and 3.12 is used to produce the risk estimations for the propeller design and shaft system using IDS. The results are shown in Figures 3.4 and 3.5.

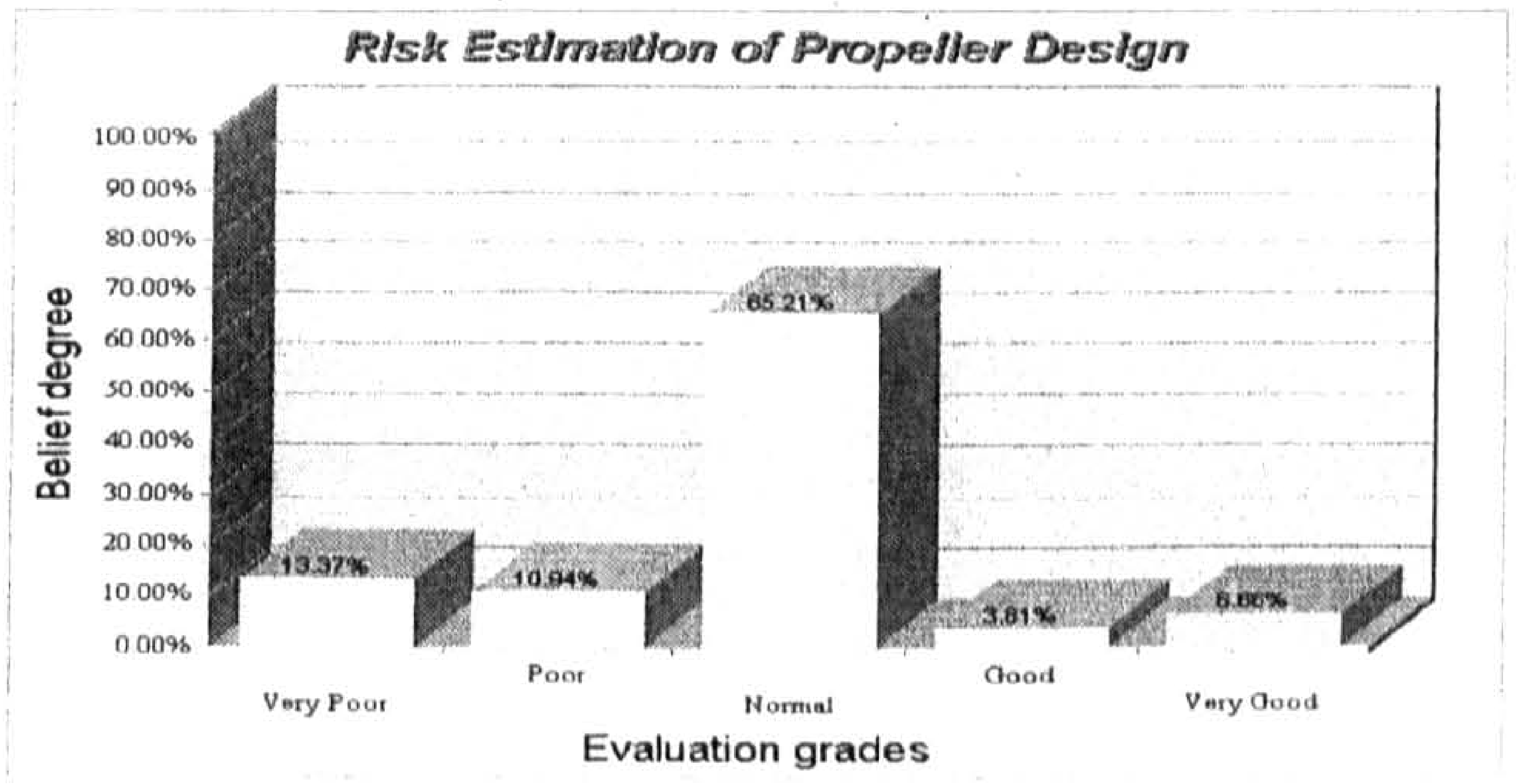


Figure 3.4: Risk Estimation of Propeller Design

It can be seen from Figure 3.4 that the highest amount of belief degree (65.21%) is associated with the Normal linguistic term. For the Very Poor and Poor linguistic terms there are 13.37% and 10.94% belief degrees available. Lower belief degrees linked to the Good (3.81%) and Very Good (6.66%). All these values are obtained after synthesising the eight Sub-Sub-Sub Criteria (Table 3.11) of the propeller design.

Similarly, the risk estimation of the shaft system was obtained through synthesising all the six Sub-Sub Criteria (Table 3.12) of the shaft system. The highest belief degree of 28.88% has been obtained for the Catastrophic linguistic term. The Critical, Marginal, and Reasonable linguistic terms have got 19.43%, 12.50%, and 9.26% belief degrees respectively. However, there is a larger degree of belief associated with the Top linguistic term (18.21%) compared with the Excellent linguistic term which has the belief degree of 11.73%. From Figure 3.5, it can be seen that the belief degrees associated with the six linguistic terms are almost equally distributed. This is because criteria such as AV, LV and SM (Appendix 3.2) associated with the shaft system are more prone to Top, Excellent and Reasonable while, TV, BF and OBF have high belief degrees for Marginal, Critical and Catastrophic.

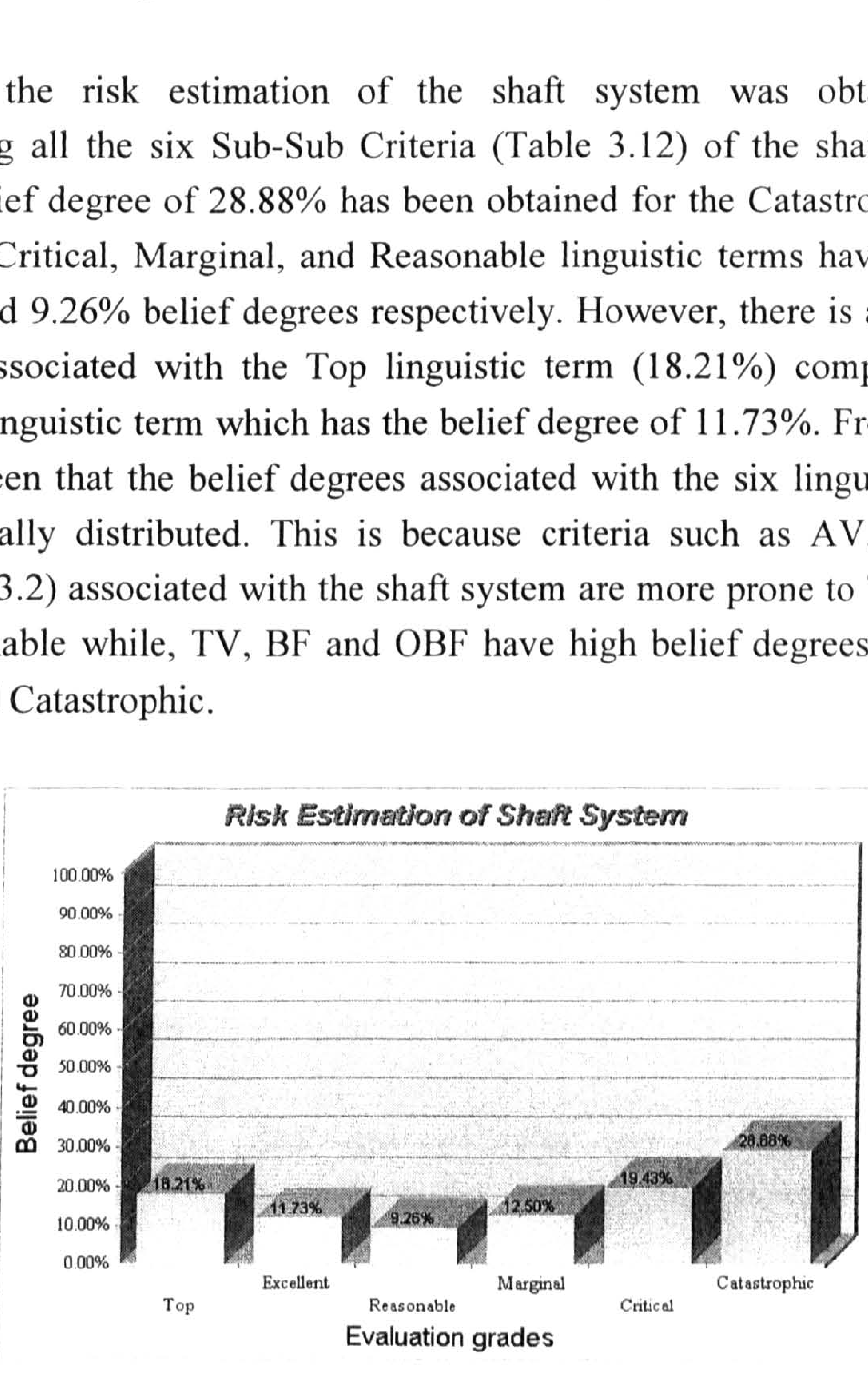


Figure 3.5: Risk Estimation of Shaft System

The risk estimations of the rudder, propellers, auxiliary equipment, power generation plant, and propulsion engine are shown graphically in Appendix 3.3. The same procedure is used to obtain the risk estimations of all the Sub Criteria. The next step is to use the mapping process to convert Sub Criteria into Main

Criteria, following which the risk estimation is obtained separately for the propeller system and machinery by using IDS (Figures 3.6 and 3.7).

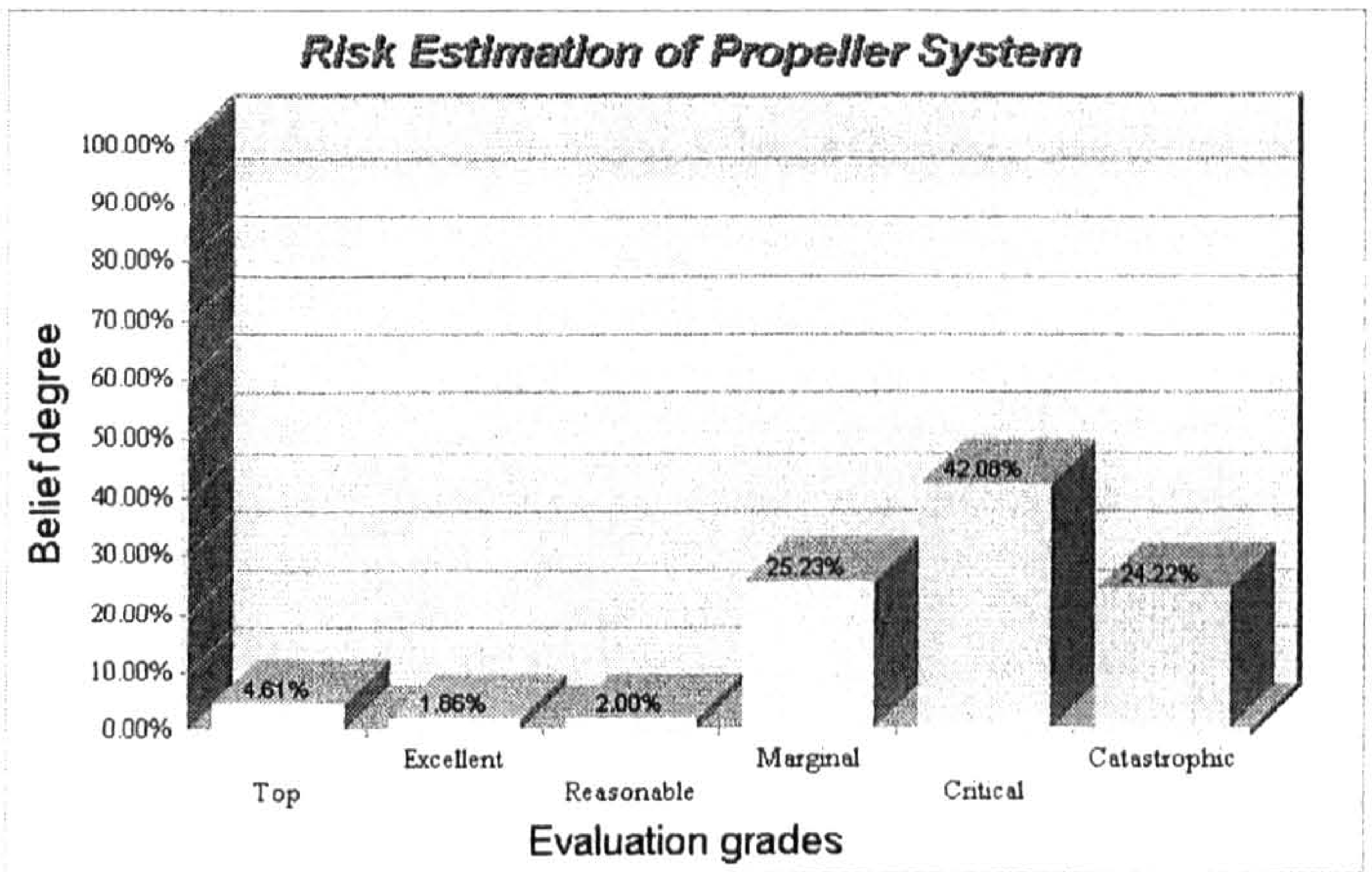


Figure 3.6: Risk Estimation of Propeller System

It is found that the ship considered in this study has high vibrations in the machinery due to engine misalignment, high number of out of balance forces etc. The propeller system is considerably better than the machinery for this particular ship in terms of SHV prediction. The propeller system has the highest belief degree of 42.08% for Critical as well as 25.23% and 24.22% for the Marginal and Catastrophic linguistic terms (Figure 3.6). Furthermore, the highest belief degree of 90.51% was obtained for Very Poor in the machinery (Figure 3.7). Therefore, based on the current results, it can be said that the achieved results are reasonable. However, the aim of this study is to estimate the overall risk, therefore, the overall risk is estimated by synthesising the results of the propeller system and machinery.

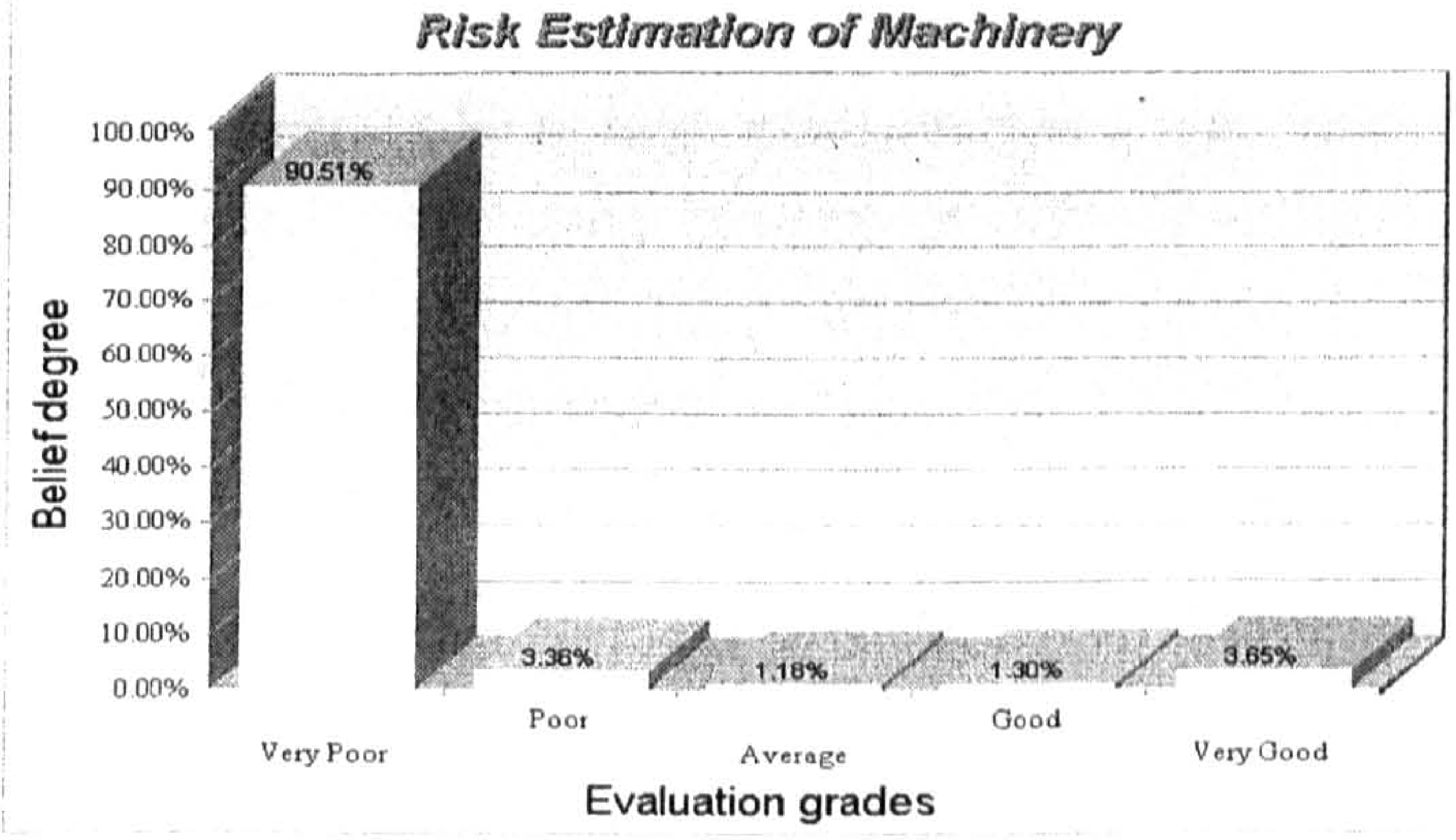


Figure 3.7: Risk Estimation of Machinery

The risk estimations of the propeller system and machinery are used to convert Main Criteria into Goal by using a mapping process. Those output values are utilised to obtain the risk estimation of SHV. The risk estimation of SHV (final result) of the considered ship is obtained and graphically shown in Figure 3.8.

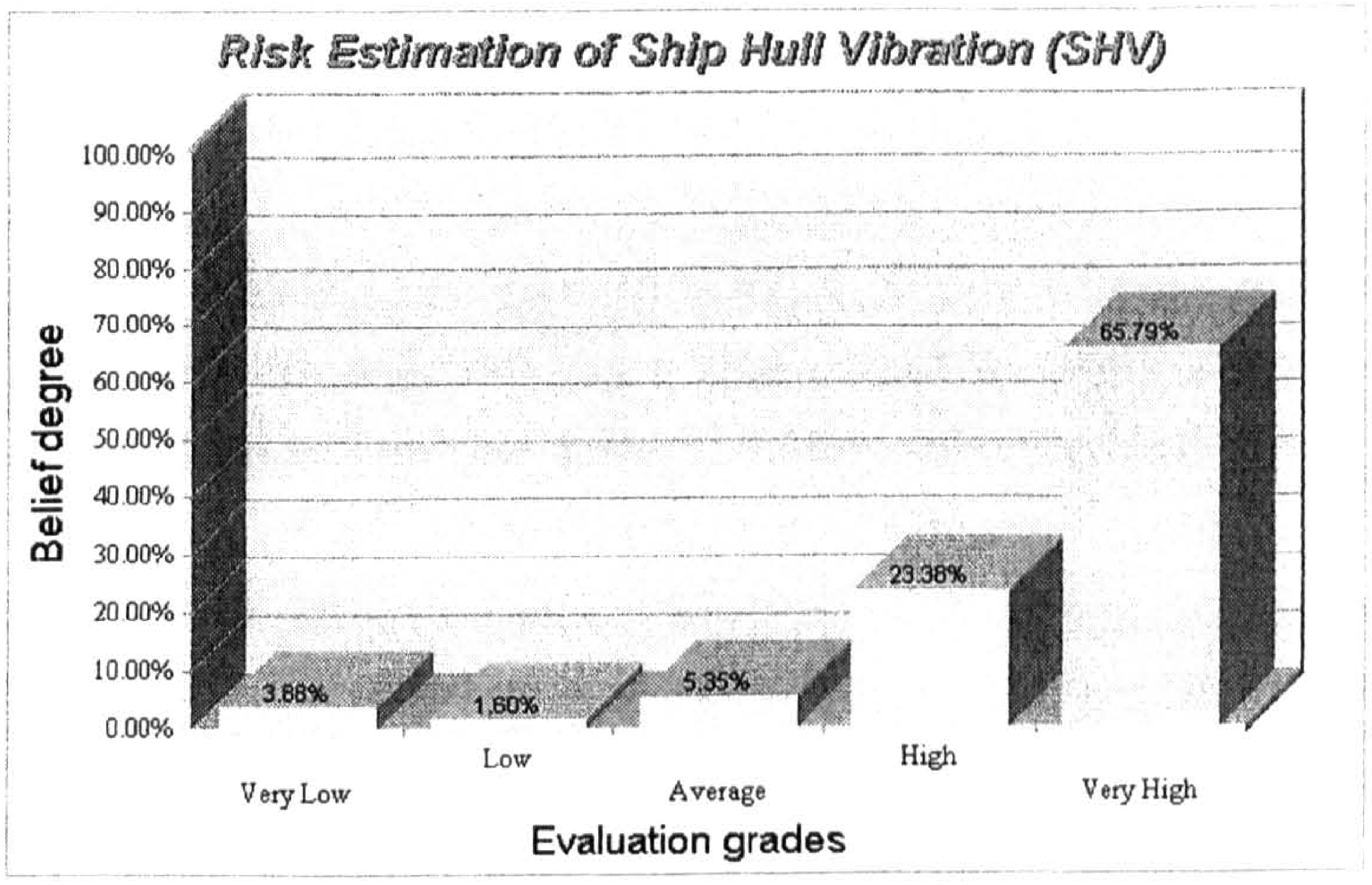


Figure 3.8: Risk Estimation of SHV

S^{SHV} = {(Very Low, 0.0388), (Low, 0.0160), (Average, 0.0535), (High, 0.2338), (Very High, 0.6579)}

3.6. Discussion and Validation of the Model

From the achieved results, the belief degrees of 65.79% and 23.38% were obtained for Very High and High. Also, there are only very small belief degrees associated with Very Low, Low and Average, i.e. 3.88%, 1.60% and 5.35% respectively. Since the Very High linguistic term has a high value of belief degree, it can be said that the risk estimation, in terms of SHV, is pretty high for this ship.

The two main criteria of SHV have been assessed as Very Low, Low and Average to a quite small extent after the mapping process. For instance, the main criterion propeller system is evaluated as Very Low (4.98%), Low (2.28%) and Average (8.77%); the other main criterion machinery is assessed as Very Low (3.64%), Low (1.04%) and Average (0.97%). Since the risk estimation of the Goal is determined by the risk estimation of each basic criterion, the risk estimation of the Goal should be evaluated as Very Low, Low and Average to a small extent. This is in harmony with the results achieved previously as the risk estimation of the Goal has been assessed as Very Low (3.88%), Low (1.60%) and Average (5.35%). Therefore, a large percentage of belief degrees has been distributed to High (23.38%) and Very High (65.79%).

Some of levels in the hierarchical structure have no criteria present. In theory it is possible to have this kind of hierarchical structure since the final result is not affected by the incompleteness of the levels.

The results obtained using ER give an overall picture of risk estimation of the Goal (SHV). ER can be described as a useful tool for estimating risk of SHV. Risk estimation of SHV can be used in ship selection and decision making problems. In the next chapter (Chapter 4) a ship selection problem is considered, to select the best ship design based on SHV risk estimation results using ER. In Chapter 4, important propeller design criteria from the hazard identification model (Figure 3.1) are used and other significant ship design criteria, such as shaft system design, engine design and ship body design, will also be taken into account, in depth, to study SHV of ships.

3.7. Conclusion

SHV has been a severe problem of onboard ships for a long time. It is becoming more of an issue due to increased power requirements of ships to obtain higher speed and more manoeuvrability than before. The level of vibration has increased with increased power requirements and complexity of machinery systems.

Ship designers try to introduce measures to control the vibration level to ensure a comfortable environment for crew and passengers and to avoid the damage of ship's equipment and instruments. Ship classification societies such as LR and ABS have produced maximum acceptable vibration levels in different areas onboard ships based on the ISO standards. The maximum vibration levels based on this developed generic model may provide classification societies with a benchmark for their ship classification, help ship designers design a ship for minimum vibration levels and help ship owners provide a good environment for working crew and passengers.

The four step methodology developed in this chapter is based on a generic model to obtain the risk estimation of SHV. The first step highlights the relevant qualitative and quantitative criteria available in the generic model. The second step describes the application of a rule based transformation technique to convert quantitative criteria into qualitative criteria. Thirdly, the quantification and transformation of all the qualitative criteria is described using a mapping process, and finally ER deals with synthesis. Following this path, the complicated process is clearly decomposed and simplified without affecting its nature.

This chapter provides a subjective risk estimation method for ship designers, ship classification societies and other organisations involved in ship vibrations. The method enables them to estimate risks by modelling ship vibrations. The results of this study provide useful information to the shipping industry regarding the control of vibrations when the corresponding risk level is high. These results can also be used for decision making purposes, such as selecting the best ship in terms of vibration level and component and equipment selection for minimum vibration level, etc. ER can be used for both risk modelling and decision making purposes, therefore it is a useful technique for studying the risks of ship vibration.

Chapter 4 – A Subjective Decision Making Approach for Modelling Ship Design Criteria

SUMMARY

A subjective novel approach to deal with interval data is presented by using generic ship design criteria. In this novel approach quantitative interval and single valued criteria are modelled and transformed to qualitative criteria by using Membership Functions (MFs) of continuous fuzzy sets. Mapping is provided to transform criteria into a common utility space. All the interval valued qualitative criteria are transformed by proposing a new algorithm in order to represent them with a single value for each linguistic term. Normalisation is carried out for all the transformed criteria. By combining all the normalised data, an Evidential Reasoning (ER) algorithm is developed to synthesise the generic ship design criteria. Finally, an ER based utility ranking approach is employed to select the ship with the best design criteria based on the risk estimation results of Ship Hull Vibration (SHV). The results of this chapter reveal that the developed approach is suitable for a ship selection problem based on the risk estimation results of SHV.

4.1. Introduction

Designing a ship is a complex process. When vibrations are involved it becomes even more complex. In general, vibrations are said to be mechanical oscillations about an equilibrium point. In definition it seems to be simple but in reality these harmful vibrations can have serious consequences. When ship vibrations are considered, Ship Hull Vibration (SHV) is treated as one of the leading contributory factors for maritime accidents since SHV results in large structural failures and crew fatigue as described in Chapter 3.

Since the fire on "FV Elegance" in 2004, which was induced by vibrations caused by engine misalignment, greater heed has been paid to matters relating to ship vibrations. "FV Elegance" was a steel hull, single screw fishing vessel with gross tonnage of 357 (MAIB, 1990-2008). This vessel suffered from severe main engine vibrations for about six months due to engine misalignment. Fire damage on 30th January 2004 was caused by fuel oil leakage from a vibration displaced vent plug on the main engine fuel oil filter which came in contact with a hot surface and ignited. This vessel was lost on 5th March 2004 due to flooding of the main engine room which occurred due to failure of the sea water piping system. The sea water piping system was fitted with flexible rubber hoses to cater for engine vibration and pipe misalignment. It is highly likely that the heat from the earlier fire caused the flexible connection to fail, resulting in the flooding.

Alignment may be considered as a basic design criterion. If a ship engine or shafting system has an unacceptable alignment it can result in serious accidents ("FV Elegance"). Therefore, reducing the generation of ship vibrations is a high priority. There are four main ship design criteria linked to SHV, namely, propeller design, shaft system design, engine design and ship body design. In this research, based on the risk estimation results of SHV, the ship with the best design criteria is identified. A generic model is developed considering the bottom level as the generic ship design criteria (Sub Criteria) classified under four Main Criteria (main ship design criteria). The top level (Goal) is taken as SHV. It has to be noted that the developed generic model in this chapter is based only on ship design criteria.

In this study, Membership Functions (MFs) of continuous fuzzy sets are implemented to model and transform the interval and single valued quantitative criteria. Fuzzy set theory is well suited to model subjective linguistic terms (Wang *et al.*, 1996). In theory, linguistic terms can be characterised by their MFs to a set of categories which describe the degrees of linguistic terms. Interval problems were first identified by Saaty and Vargas in 1987 when proposing interval judgements, for the Analytic Hierarchy Process (AHP), as a way of modelling subjective uncertainty and applying a Monte Carlo simulation approach for finding weight intervals from interval comparison matrices (Saaty & Vargas, 1987). Since then different approaches have been developed and used to deal with interval problems (Arbel & Vargas, 1993; Islam *et al.*, 1997; Fu *et al.*, 1998; Luoh & Wang, 2001; Jacobsen, 2002; Kaya & Alhajj, 2005; Xu *et al.*, 2006; Wang *et al.*, 2006).

Xu *et al.*, (2006) and Wang *et al.*, (2006) have tackled the problem by combining Evidential Reasoning (ER) and nonlinear optimization models. Nonlinear optimization models are mathematically complex and time consuming which can be considered a disadvantage in industry. Therefore, in this study, a subjective novel approach is proposed by using fuzzy sets and ER to deal with interval problems. It is easier to solve interval problems using this proposed novel approach and it also delivers reasonable results. In this work ER is employed to synthesise generic ship design criteria and an ER based expected utility approach is used for ranking of ships.

The main aim of this chapter is to select the ship with the best design criteria based on risk estimation results of SHV. In order to achieve the aim, this chapter describes the background of fuzzy sets and ER, constructs a generic model based on ship design criteria, classifies them under interval/single valued qualitative and quantitative criteria, models the interval and single valued quantitative criteria by using continuous fuzzy sets, transforms them to qualitative criteria and uses mapping. The chapter then transforms interval qualitative criteria into a single valued qualitative criteria by using the proposed novel algorithm, carries out the normalisation for all the transformed criteria, applies ER for synthesis and finally uses an ER based expected utility approach to rank the chosen ships in a prioritisation order. A case study is given, based on the generic model, to demonstrate the proposed novel approach.

4.2. Background

4.2.1. Expected Utility

An expected utility approach was developed by Yang (2001). The main aim of using a utility approach is to obtain a single crisp number for the top level criterion (final result) of each alternative in order to rank them. The utility approach has found many useful applications, such as motorcycle selection, car selection and ferry selection (Yang & Xu, 2002). This is because it has the following useful properties:

- It has an easy standard procedure for the calculation of utility values of each top level criterion.
- Incomplete basic criteria are represented by using minimum, maximum and average utilities (i.e. belief intervals).

However, this ranking is not reliable when there is a high degree of incomplete data present. In such cases, to generate a reliable ranking, the quality of the basic criteria should be improved by reducing the incompleteness of data. Please refer Chapters 2 and 3 to obtain information of ER and fuzzy logic.

Ship design criteria are becoming more important when SHV problems are considered. The potential for combining fuzzy sets with ER in the shipping industry is well recognised but it has not been applied to ship selection problems in terms of SHV. A possible methodology is proposed in the ensuing sections to select the ship with the best design criteria based on the risk estimation results.

4.3. Design Criteria Modelling

This study investigates the risk estimation of SHV for different ship types based on twenty three generic ship design criteria in Figure 4.1. Based on the SHV risk estimation results, the ship with the best design criteria is identified. The generic ship design criteria (Sub Criteria) are classified under four main design criteria (Main Criteria), namely, propeller design, shaft system design, engine design and ship body design. There are eight quantitative and fifteen qualitative criteria present. Some of the criteria are represented by interval values. The judgement of experts is represented by interval values in order to deal with differing opinions.

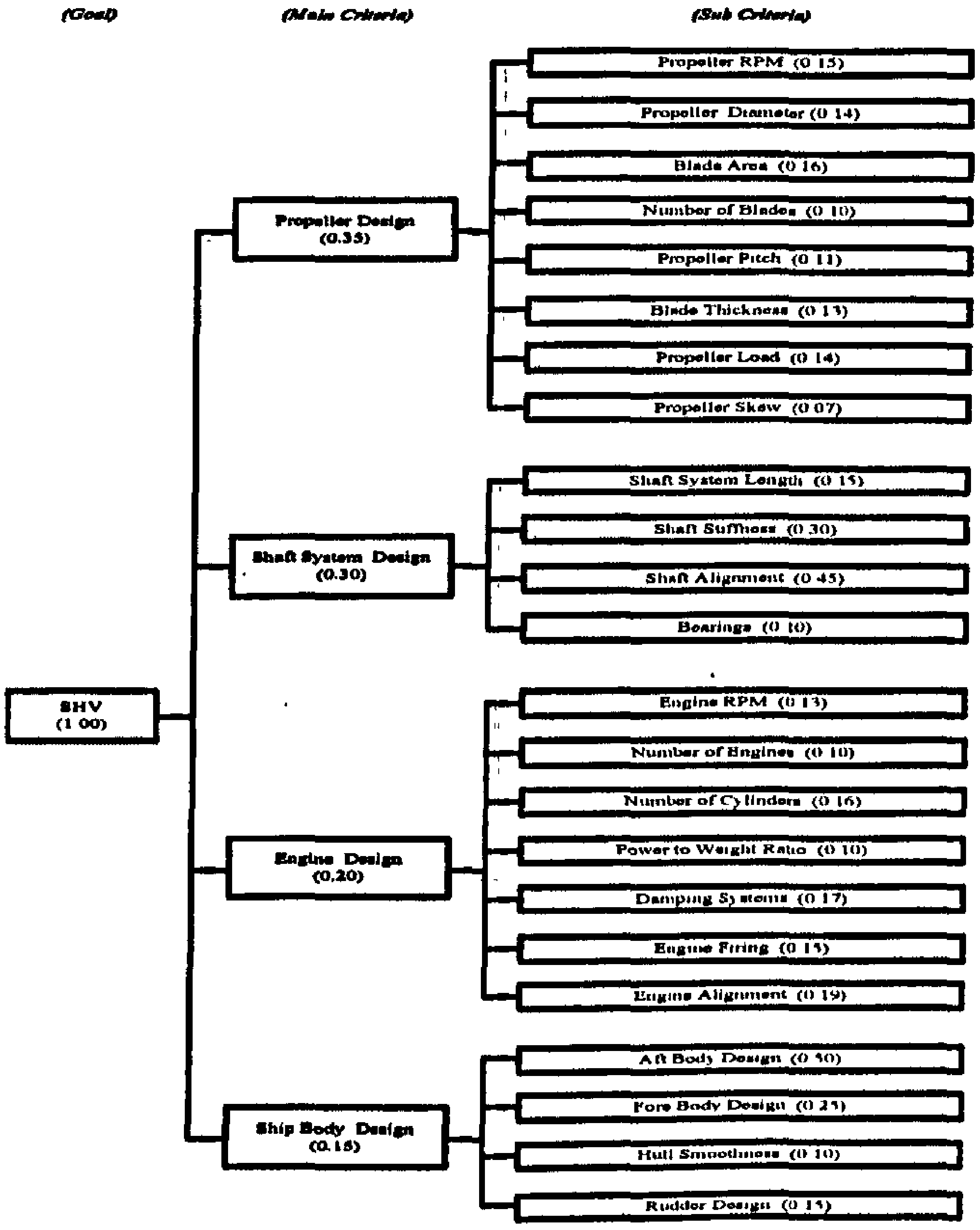


Figure 4.1: The Generic Structure of Ship Design Criteria

The weights of all the criteria are allocated based on expert judgements and literature review. By using the following linguistic terms: Excellent (EX), Very Good (VG), Good (G), Normal (N), Bad (B), and Very Bad (VB), the ship with the best design criteria in terms of risk estimation of SHV is obtained. Then the ranking of the ships is carried out. In this study three cargo ship types are considered. Those three ships are still in use and ages of them are about 12 years (built in mid 1990s). The dimensions are almost the same where the length is about 175m, breath is about 30m and gross tonnage is about 30000. All of them are ocean going ships and only a limited number of specifications of those three ships are given in Table 4.1 due to data protection purposes. Some of the data is real values and the others are obtained from expert judgements.

Table 4.1: Specifications of Ships

Quantitative Criteria	Ship 1	Ship 2	Ship 3
Propeller Design			
Propeller RPM	{125, 145}	{82, 125}	{97, 113}
Propeller Diameter (m)	{4.3}	{5.0}	{4.5}
Blade Area (m^2)	{13.5}	{18.6}	{15.1}
Number of Blades	{4}	{4}	{4}
Shaft System Design			
Shaft System Length (m)	{13}	{14}	{12}
Engine Design			
Engine RPM	{125, 145}	{82, 125}	{97, 113}
Number of Engines	{1}	{1}	{1}
Number of Cylinders	{6}	{6}	{6}

In this study four expert are employed (two from industry and two from academia). The knowledge and experience of all of them are considered as the same. Therefore, weighting of each of them will be the same. These twenty three generic ship design criteria are considered because they are regarded as the most significant criteria associated with ship design selection in terms of SHV which is obtained based on extensive discussions with the above experts. The detailed information of experts used in this chapter and dates of the meetings are given below. During the meetings, the main aims were to identify the most significant criteria to develop a ship design model on the basis of SHV and to find out the applicability of the model in real situations.

Panel of Experts:

- Dr. A. Batako: Research Fellow, General Engineering Research Institute (GERI), Liverpool John Moores University, United Kingdom.
- Dr. Z. Yang: Senior Lecturer, Liverpool John Moores University, United Kingdom.
- Mr. L.B. Godaliyadde: Ship Owner/Engineer, Rogers Agencies (Pvt) Ltd, Sri Lanka.
- Mr. R. Riahi: Senior Superintendent/Ship Design Consultant, Islamic Republic of Iran Shipping Line (IRISL), Iran.

Dates and Venues of Meetings:

- 12/12/2006: Senior Common Room, Liverpool John Moores University, United Kingdom.
- 07/02/2007: Senior Common Room, Liverpool John Moores University, United Kingdom.

Note: More extensive discussions with experts were also conducted via telephone.

4.3.1. Propeller Design

The propeller is designed primarily to ensure that a ship will be able to maintain its service speed with the lowest possible fuel consumption where vibration issues must be considered. Vibration emanating forces from the propeller are transmitted to the hull (SHV) in two ways, namely, through the shaft and bearings, and as pressure pulsations. The pressure pulsations from the propeller are usually the dominant vibration source since they are amplified 3 to 10 times due to cavitation (JISC, 2005). More information of propeller design can be found in Chapter 3.

4.3.2. Shaft System Design

As described in Chapter 3, there are three distinct modes of vibration patterns in the shaft system, each with specific sources, characteristics and consequences (Magazinovic, 2002). These three modes of shafting vibrations are torsional, axial and lateral. There are special types of couplings available to minimise torsional vibration e.g. torsionally stiff couplings (Henshall, 1996). Torsionally stiff couplings absorb shock loads and they also accommodate the misalignment.

Axial vibrations are usually the cause of SHV. However, lateral vibrations put loads on bearings and cause structural failure at the bearing and support. This can be reduced with a good shaft alignment and by stiffening the shaft system. The flexibility of dealing with shaft misalignment or vibration problems is dependent on factors such as shaft system length. More details of the shaft system can be found in Chapter 3.

4.3.3. Engine Design

There are two basic operating cycles for the internal combustion engines, the four-stroke cycle and the two stroke cycle. The two stroke engines are slow speed diesel engines (Wharton, 1991). Slow speed engines are directly connected (without a gearbox) to the propeller and they operate at a speed up to about 150 rpm although many modern engines have a speed of about 90 rpm. In this study, slow speed diesel engines are only considered, therefore, gearbox has not been included in the generic ship design criteria model (Figure 4.1). Propeller efficiency is greater at slower rotational speeds. The required power to propel the ship is usually supplied by a single engine. Therefore, such engines are normally very large in size. The large size is a disadvantage when engine alignment is considered. These engines are usually employed in cargo ship types. Two stroke engines have out of balance forces with low frequency and high amplitude and also they have very low power to weight ratio compared with medium and diesel electric engines.

4.3.4. Ship Body Design

The ship aft body should be designed to allow a good water flow to the propeller. Aft body design should be capable of producing a large clearance to the propeller as well as to the rudder in order to minimise the risk of cavitation.

The wake is not equally strong over the whole of the circular area swept out by the propeller. This means that the propeller blade is exposed to a wake of varying strength during the rotation (JISC, 2005). Usually, the wake is distributed as the blade passes the top of the circle i.e. beneath the stern post. The force on the blade then increases suddenly and a distinct pressure pulsation arises. Therefore, aft body should be designed to have a reasonable wake distribution.

Oscillations not only come from pulses from the propeller and main engines but also the effect of water striking the bow and the twisting motion caused by the sea when underway. The fore body should be designed to minimise these pulsations. When smoothness of the hull decreases, the power requirement to propel the ship should be increased to obtain a high propeller rpm. A high propeller RPM transfers a large amount of pressure pulsations to the hull surface which may lead to severe SHV occurrence.

4.4. Methodology

The following steps are developed based on the generic model (Figure 4.1) to identify the ship with the best design criteria in terms of the risk estimation results of SHV:

Step 1: Obtain data for quantitative and qualitative design criteria by using the knowledge based on literature review and expert judgements. This data is either single or interval valued.

Step 2: Propose a new approach by using continuous fuzzy sets to deal with interval quantitative criteria. Then both single and interval valued quantitative criteria are modelled by using continuous fuzzy sets. All of them are transformed to qualitative criteria with a single value of belief degree associated with each linguistic term. The normalisation and mapping is then carried out for all the transformed quantitative criteria.

Step 3: Introduce a novel approach to handle interval qualitative criteria. All the interval valued qualitative criteria are transformed to a single value of belief degree associated with each linguistic term and then normalised.

Step 4: Combine the entire normalised data of each main criterion and use the ER algorithm to synthesise all the design criteria in order to obtain risk estimation results. Finally, employ the ER based utility ranking approach to obtain a crisp value for each ship in order to rank all the ships based on their risk estimation results.

4.4.1. Triangular and Trapezoidal Membership Functions

In principle, a membership function associated with a fuzzy set $\tilde{A}$ depends not only on the concept to be represented but also on the context in which it is used (Pedrycz & Gomide, 1998). The graphs of the functions may have different shapes and may have some specific properties (e.g. continuity). Whether a particular shape is suitable or not can be determined only in the application context. In many practical instances, fuzzy sets can be represented explicitly by families of parameterised functions, the most common being:

1. Triangular Membership Function

$$\mu_{\tilde{A}}(x) = \begin{cases} 0, \text{if } x \leq a \\ \dfrac{x-a}{m-a}, \text{if } x \in \,]a, m[\\ 1, \text{if } x = m \\ \dfrac{b-x}{b-m}, \text{if } x \in \,]m, b[\\ 0, \text{if } x \geq b \end{cases}$$

where, m is a modal value where, $\mu_{\tilde{A}}(x) = 1$, a and b denote lower and upper bounds, respectively, for non-zero values of $\mu_{\tilde{A}}(x)$ shown graphically in Figure 4.2. The following can be alternatively used to represent a triangular membership function:

$\tilde{A}(x; a, m, b) = \max\{\min[(x - a)/(m - a), (b - x)/(b - m)], 0\}$

2. Trapezoidal Membership Function

$$\mu_{\tilde{A}}(x) = \begin{cases} 0, \text{if } x \leq a \\ \dfrac{x-a}{m-a}, \text{if } x \in \,]a, m[\\ 1, \text{if } x \in [m, n] \\ \dfrac{b-x}{b-n}, \text{if } x \in \,]n, b[\\ 0, \text{if } x \geq b \end{cases}$$

In this case the modal values where, $\mu_{\tilde{A}}(x) = 1$ are m and n while the lower and upper bounds are represented by a and b shown in Figure 4.3. A trapezoidal membership function can also be represented by:

$$\tilde{A}(x; a, n, b) = \max\{\min[(x - a)/(m - a), 1, (b - x)/(b - n)], 0\}$$

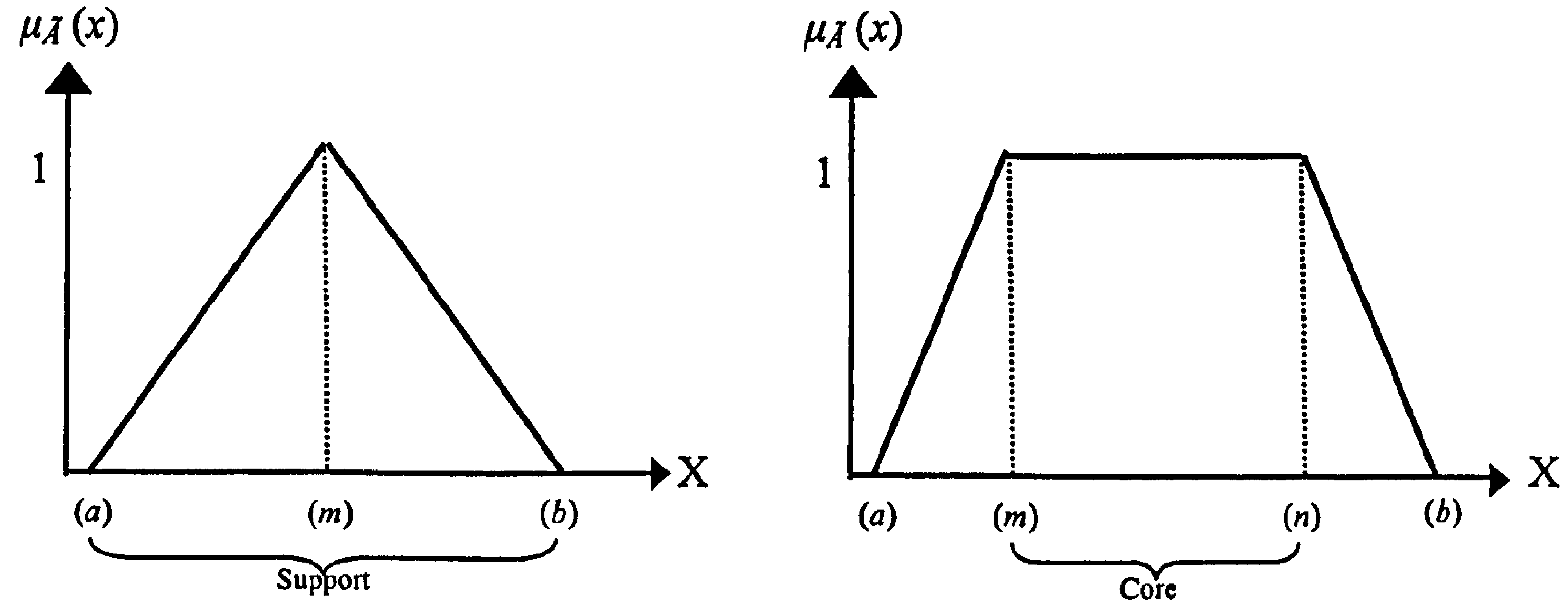


Figure 4.2: Triangular MF

Figure 4.3: Trapezoidal MF

4.4.1.1. Support and Core

1. Support

The "support" of a fuzzy set $\tilde{A}$ is denoted by Spt($\tilde{A}$) and is the set of elements of X whose degree of membership in $\tilde{A}$ is greater than 0 (Yen & Langari, 1999). The support (a, b) of $\tilde{A}$ can be represented by using a triangular membership function shown in Figure 4.2. It is formally defined as follows: Spt($\tilde{A}$)=$\{x \in X \mid \mu_{\tilde{A}}(x) > 0\}$

2. Core

The "core" of a fuzzy set $\tilde{A}$ is the set of all elements of X that exhibit a unit level of membership in $\tilde{A}$ and is denoted by Core($\tilde{A}$) (Kruse *et al.*, 1994). The core (m, n) of $\tilde{A}$ can be shown by using a trapezoidal membership function in Figure 4.3. It is formally given by: Core($\tilde{A}$) = $\{ x \in X \mid \mu_{\tilde{A}}(x) = 1 \}$

4.4.2. Continuous Fuzzy Sets

Continuous fuzzy sets are formulated by employing different kinds of membership functions. In this study continuous fuzzy sets have been used to model the quantitative criteria. The concept of a fuzzy number plays a fundamental role when formulating quantitative fuzzy variables (Klir & Yuan, 1995). These are variables whose states are fuzzy numbers. In addition, the fuzzy numbers represent linguistic concepts such as Excellent, Very Good, Good etc., as interpreted in a particular context.

However, in this study linguistic terms are represented only by using real values. Therefore, the states of each basic criterion are expressed by linguistic terms and they are interpreted by using real values (real data). The base variables are dependent on the generic quantitative criteria described in Table 4.1. An example of continuous fuzzy sets has been shown in Figure 4.4. It is based on Blade Area which is a quantitative generic design criterion of propeller design.

(VB)	(B)	(N)	(G)	(VG)	(EX)
Very Bad	Bad	Normal	Good	Very Good	Excellent
3-5	**8**	**11-13**	**15-17**	**20**	**23-25**

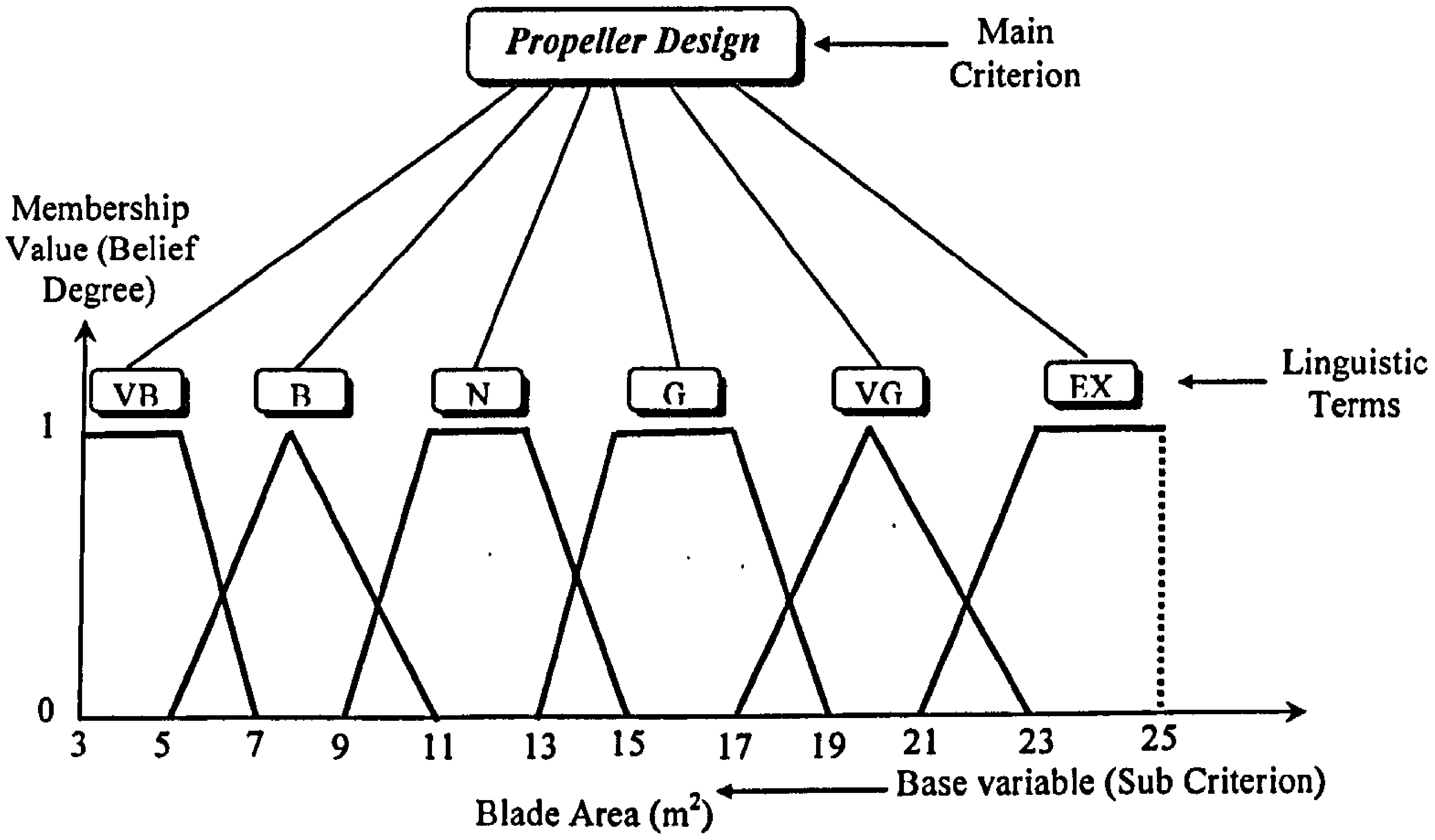


Figure 4.4: Continuous Fuzzy Sets

The associated values of each linguistic term were found based on expert judgements and the literature review. However, they may be different for different ship types. If a ship has a large blade area there will be a low level of cavitation hence low level of vibration (Section 3.3.1.3.1); therefore the propeller design should move from Very Bad (VB) to Excellent (EX) when the ship blade area increases.

It is clear that some of the values associated with the linguistic terms have intervals; that is because experts may not know the exact value. In this study a trapezoidal membership function has been used to model such kinds of values since it allows a membership value 1 (or 100% belief degree) for a range of values in the base variable. For example, if the blade area is between $11m^2$ and $13m^2$ then propeller design is Normal (N). In such a situation interval 11-13 should represent the membership value 1 under the Normal (N) linguistic term.

In Figure 4.4 continuous fuzzy sets consist of both triangular and trapezoidal MFs. In this study a triangular MF is also used because it has a smooth transition from one linguistic term to the other and also because it is suitable for representing a linguistic term with a membership value 1 for a single value in the base variable. For instance, consider the Very Good (VG) linguistic term. It has a single value for membership value 1 which means all experts have the same opinion and they are confident that if the blade area is $20m^2$ then it will be represented by the Very Good (VG) linguistic term. In that case only the value of $20m^2$ should have membership value 1. The single and interval values are modelled only by employing triangular and trapezoidal MFs since such kinds of MFs are highly applicable to deal with situations in this study compared with other available MFs.

4.4.2.1. Quantitative Data Transformation

As described in the previous section, continuous fuzzy sets are formulated to model both single and interval valued quantitative criteria. During the quantitative data transformation process, the following procedure is implemented.

i) Model the value(s) on continuous fuzzy sets and use an area method to obtain the belief degrees. By calculating the area covered by the defined triangular or trapezoidal MFs within the interval values, the relevant belief degrees associated with the linguistic terms can be estimated.

To calculate the area (A_{TG}) covered by a triangular MF within the interval values, Eq. (4.1) is used.

$$A_{TG} = \frac{1}{2} \times l_{TG} \times y_{TG} \tag{4.1}$$

where, l_{TG} and y_{TG} are the length of the base and the height of the area respectively.

Eq. (4.2) is used to calculate the area (A_{TZ}) covered by a trapezoidal MF within the interval values.

$$A_{TZ} = \frac{1}{2} \times (l_{TZ}^{1} + l_{TZ}^{2}) \times y_{TZ} \tag{4.2}$$

where, l_{TZ}^{1} is the length of the area where the membership value is equal to 1, l_{TZ}^{2} is the length of the base, and y_{TZ} is the height of the area.

The belief degrees associated with the linguistic terms can be estimated by calculating the above area. Consider the following set with belief degrees: (β') is given where each β' is obtained as the calculated area covered by a defined MF within the interval values.

{[EX, (β'_{EX})]; [VG, (β'_{VG})]; [G, (β'_{G})]; [N, (β'_{N})]; [B, (β'_{B})]; [VB, (β'_{VB})]}

The obtained set represents the belief degrees associated with each linguistic term. In this step the quantitative data has been transformed into a qualitative form. However, this procedure is not necessary for single valued quantitative criteria. In order to transform them into qualitative criteria, the procedure which is described in Section 4.4.1 can be implemented for triangular and trapezoidal MFs (traditional method). The belief degrees can then be calculated.

ii) Carry out the normalisation to obtain a real single valued belief degree for each linguistic term.

The first step of the normalisation is to take the sum of the belief degrees (β'_{s}) associated with the linguistic terms in the set. This can be done by developing the following generic algorithm:

$$\beta'_s = \sum_{X=1}^{n} \beta'_X \tag{4.3}$$

where, X represents the type of the linguistic term e.g. EX, VG etc.

The real single belief degree associated with linguistic term $X\,(\beta_X)$ can be obtained by using Eq. (4.4). This is the second step of the normalisation.

$$\beta_X = \frac{\beta'_X}{\beta'_s} \tag{4.4}$$

The normalised set is obtained as:

$$\{[\mathrm{EX}, (\beta_{EX})]; [\mathrm{VG}, (\beta_{VG})]; [\mathrm{G}, (\beta_G)]; [\mathrm{N}, (\beta_N)]; [\mathrm{B}, (\beta_B)]; [\mathrm{VB}, (\beta_{VB})]\}$$

The useful properties of this new technique are that it can be considered a logical approach when quantitative data is transformed to a qualitative form; it is possible to use this technique to estimate the belief degrees of linguistic terms which could have a wide range of quantitative intervals (e.g. propeller rpm 82-125), and extensive computations are not needed for the calculations.

4.4.3. Mapping Process

In this section a mapping process is mainly implemented to transform lower level qualitative criteria (transformed quantitative criteria) into upper level criteria. More details of the mapping process can be found in Chapter 3. By taking the lower level criterion (Sub Criterion) "Propeller RPM" in the generic model as an example, the mapping process can be introduced in the following context.

Consider the criterion "Propeller RPM (RPM)" (lower level) has its associated upper level criterion (i.e. main criterion in this generic model) "Propeller Design (PD)" in a decision making model. The upper level criterion "PD" can be expressed using such linguistic terms as "Excellent", "Very Good", "Good", "Normal", "Bad", and "Very Bad". The lower level criterion (bottom level in this generic model) "Propeller RPM" is described in terms of "Very Weak", "Weak", "Lower Medium", "Upper Medium", "Strong", and "Very Strong". The transformation from a fuzzy input to an output is shown in Figure 4.5 by using the proposed mapping process.

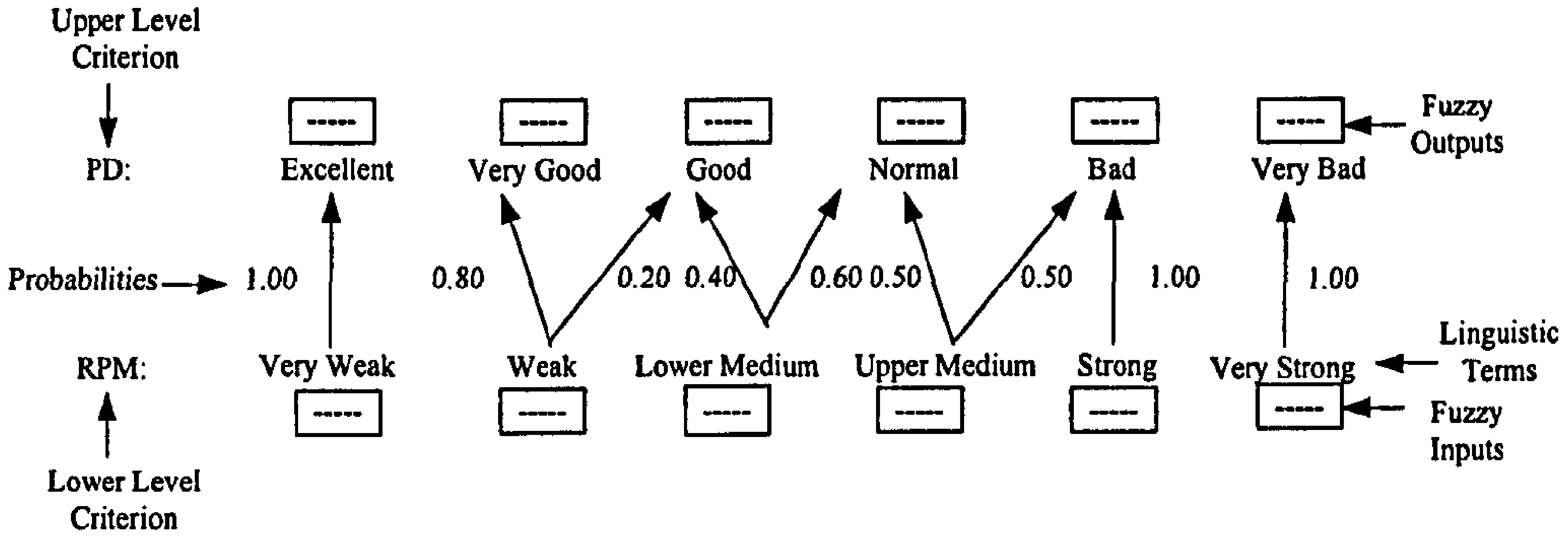


Figure 4.5: Mapping from Lower Level to Upper Level

For instance, the lower level criterion "RPM" with the "Weak" linguistic term indicates that the level of the upper level criterion "PD" is believed as 80% or 0.80 ($P_{RPM=2}{}^{PD=2}$) "Very Good" and 20% or 0.20 ($P_{RPM=2}{}^{PD=3}$) "Good". Such a mapping process can be used to transform the lower level criteria into upper level criteria given the fuzzy inputs. The transformation process and aggregation of the calculations (quantification) to complete the mapping process are illustrated as follows:

Assume that L^{RPM} (RPM = 1, 2, ..., 6) highlights the fuzzy inputs of the lower level criterion "RPM" and that U^{PD} (PD = 1, 2, ..., 6) represents the fuzzy outputs (upper level) transformed from the inputs (L^{RPM}). Then Eq. (4.5) can be constructed (similar to Section 3.4.3).

$$U^{PD} = \sum_{RPM=1}^{6} L^{RPM} P_{RPM}{}^{PD} \qquad PD = (1, 2, ..., 6) \tag{4.5}$$

where, $\sum_{PD=1}^{6} P_{RPM}{}^{PD} = 1.00$

4.4.4. Qualitative Data Transformation

When qualitative criteria are considered, three to seven linguistic terms are often used to describe a criterion (Miller, 1956; Broadbent, 1975). Rarely, one uses less than three linguistic terms since most concepts in human language consider at least the two extremes and the middle in between. On the other side, one rarely uses more than seven linguistic terms because humans interpret technical figures by using their short term memory. The human short term memory can only compute up to seven symbols at a time. Therefore, in this study, six linguistic terms (EX – VB) are used to describe qualitative criteria.

In order to process qualitative single or interval valued data the following procedure has been introduced. For instance, consider the following:

{[EX, (β_{EX1}, β_{EX2})]; [VG, (β_{VG1}, β_{VG2})]; [G, (β_{G1}, β_{G2})]; [N, (β_{N1}, β_{N2})]; [B, (β_{B1})]; [VB, (β_{VB1})]}

In this set, linguistic terms "EX", "VG", "G" and "N" have interval values (or belief degrees) e.g. β_{EX1}, β_{EX2}; β_{VG1}, β_{VG2}; linguistic terms "B" and "VB" are given single values (β_{B1} and β_{VB1}) by experts.

i) Take the mean ($\tilde{\beta}_X$) of each linguistic term in the interval.

$$\tilde{\beta}_X = \frac{\beta_t + \beta_z}{2} \tag{4.6}$$

where, β_t is the value of first belief degree in linguistic term X and β_z is the value of second belief degree in the linguistic term X.

The developed algorithm in Eq. (4.6) can be used to deal with other linguistic terms which have interval belief degrees. However, this procedure is not necessary for single valued linguistic terms. Then the following set can be obtained:

{[EX, (β'_{EX})]; [VG, (β'_{VG})]; [G, (β'_{G})]; [N, (β'_{N})]; [B, (β'_{B})]; [VB, (β'_{VB})]}

ii) Carry out the normalisation as described in Section 4.4.2.1. After completing the normalisation the following set can be obtained:

{[EX, (β_{EX})]; [VG, (β_{VG})]; [G, (β_{G})]; [N, (β_{N})]; [B, (β_{B})]; [VB, (β_{VB})]}

The range of the interval associated with a linguistic term should not be too high. The expert judgements will not be acceptable if the range of the values is too high.

In this study, the mean is taken for qualitative interval data transformation since the range of interval values is considered as small. It is also reasonable because actual value, which is given after the transformation, is in the middle of interval values and literature review shows it is logical (Wang, 2004). The useful properties of this technique are that the transformation process of interval values to a single value is straightforward and extensive computations are not needed.

4.4.5. The ER Approach

The ER approach, which was described in Section 3.4.4 of Chapter 3, has been implemented in this section. In summary, the ER approach is composed of Eq. (3.12) for information acquisition and representation, and Eq. (3.10) for weight normalisation.

4.4.6. ER Algorithm

The ER algorithm, which was explained in Section 3.4.5 of Chapter 3, has been used in this section. In summary, ER algorithm is composed of Eqs. (3.14) - (3.17) for basic probability assignments, Eqs. (3.14) – (3.26) for criteria aggregation, and Eqs. (3.25) - (3.26) for generating combined degrees of belief.

4.4.7. Expected Utility

It is difficult to select the best ship design by using belief degrees associated with linguistic terms because they are not sufficient to show the difference between the assessments. Numerical values (crisp values) may be generated from the obtained distributed assessments. Therefore, the concept of expected utility is used to obtain a crisp value for each ship in order to rank them in a prioritisation order.

Suppose the utility of an evaluation grade H_n is denoted by $u(H_n)$ and $u(H_{n+1}) > u(H_n)$ if H_{n+1} is preferred to H_n (Yang, 2001). The expected utility is calculated for the top level or general criterion ($S(E)$) which is SHV. Therefore, the utility of the general criterion can be calculated as follows:

$$u(S(E)) = \sum_{n=1}^{N} \beta_n u(H_n) \tag{4.7}$$

By using Eq. (4.8) the utility values of each linguistic term ($u(H_n)$) can be calculated:

$$u(H_n) = \frac{V_{\max} - V^n}{V_{\max} - V_{\min}} \tag{4.8}$$

where, $V_{\max}$ is the ranking value of the most preferred linguistic term (H_N), $V_{\min}$ is the ranking value of the least preferred linguistic term (H_1) and V^n is the ranking value of the linguistic term considered (H_n).

Eq. (4.7) can only be used for $\beta_H = 0$. If $\beta_H \neq 0$ (i.e. any assessment for the basic criterion is incomplete), there is a belief interval $[\beta_n, (\beta_n + \beta_H)]$, which provides the likelihood that $S(E)$ is assessed to H_n. Without loss of generality, suppose the least preferred linguistic term having the lowest utility $u(H_1)$ and the most preferred linguistic term having the highest utility $u(H_N)$. Then the minimum, maximum and average utilities of $S(E)$ are given by:

$$u_{\min}(S(E)) = \sum_{n=2}^{N} \beta_n u(H_n) + (\beta_1 + \beta_H) u(H_1) \tag{4.9}$$

$$u_{\max}(S(E)) = \sum_{n=1}^{N-1} \beta_n u(H_n) + (\beta_N + \beta_H) u(H_N) \tag{4.10}$$

$$u_{aver}(S(E)) = \frac{u_{\min}(S(E)) + u_{\max}(S(E))}{2} \tag{4.11}$$

The assessment, based on a single scale of $u(S(E))$, is obviously much easier and more intuitive for a professional decision maker to use for ranking the alternatives in question. Note that if $u(H_1) = 0$ then $u(S(E)) = u_{\min}(S(E))$. Also note that if all criteria $S(e_i)$ are complete, then $\beta_H = 0$ and $u(S(E)) = u_{\min}(S(E)) = u_{\max}(S(E)) = u_{\text{aver}}(S(E))$. It has to be made clear that the above utilities are only used for characterising an assessment, and not for criteria aggregation.

4.5. Case Study

In this case study, twenty three generic ship design criteria are taken into account and they are considered as the most significant criteria in the prediction of vibrations of a ship. The main aim of this section is to demonstrate how the proposed methodology can be applied for a ship selection problem.

4.5.1. Single and Interval Valued Generic Ship Design Criteria Modelling (*Step 1*)

In this step, data is obtained for both quantitative and qualitative generic ship design criteria described in Figure 4.1. The obtained data is single/interval valued in either a quantitative or qualitative nature. It is obtained based on expert judgements and the literature review (Table 4.1, Appendix 4.1).

Table 4.2: Single and Interval Valued Generic Ship Design Criteria

Design Criteria	*Ship 1*	*Ship 2*	*Ship 3*
Propeller Design			
Propeller RPM (*)	IV	IV	IV
Propeller Diameter (*)	SV	SV	SV
Blade Area (*)	SV	SV	SV
Number of Blades (*)	SV	SV	SV
Propeller Pitch (Δ)	SV	SV	SV
Blade Thickness (Δ)	SV/IV	SV	SV
Propeller Load (Δ)	SV/IV	SV	SV
Propeller Skew (Δ)	SV	SV	SV
Shaft System Design			
Shaft System Length (*)	SV	SV	SV
Shaft Stiffness (Δ)	SV	SV	SV/ IV
Shaft Alignment (Δ)	SV	SV	SV
Bearings (Δ)	SV	SV	SV
Engine Design			
Engine RPM (*)	IV	IV	IV
Number of Engines (*)	SV	SV	SV
Number of Cylinders (*)	SV	SV	SV
Power to Weight Ratio (Δ)	SV	SV	SV
Damping Systems (Δ)	SV	SV	SV
Engine Firing (Δ)	SV/IV	SV	IV
Engine Alignment (Δ)	SV	SV	SV
Ship Body Design			
Aft Body Design (Δ)	SV	SV	SV
Fore Body Design (Δ)	SV	SV	SV
Hull Smoothness (Δ)	SV/IV	SV/IV	SV
Rudder Design (Δ)	SV	SV	SV

(*) – Quantitative Criteria
(Δ) – Qualitative Criteria
SV – Single Valued
IV – Interval Valued
SV/IV – Combination of Single and Interval Valued

The generic ship design criteria in Table 4.2 can be considered as the bottom level criteria (Sub Criteria) in the decision making model (generic model). As shown in Table 4.2, some criteria are single valued and some criteria are described by both single and interval values. In Step 2 of the proposed methodology, continuous fuzzy sets are formulated to transform interval and single valued quantitative criteria into qualitative criteria.

4.5.2. Quantitative Interval and Single Valued Data Transformation using Continuous Fuzzy Sets (*Step 2*)

In this step, the developed approach in Section 4.4.2.1 is used to deal with quantitative interval criteria. This can be demonstrated by using the following example of propeller RPM.

The propeller RPM for Ship 2 varies in the interval of 82 and 125 as shown in Table 4.1. Firstly, these RPM values are modelled on continuous fuzzy sets to transform this interval quantitative criterion into a qualitative criterion. This can be shown in Figure 4.6:

Ship 2 = {82, 125}

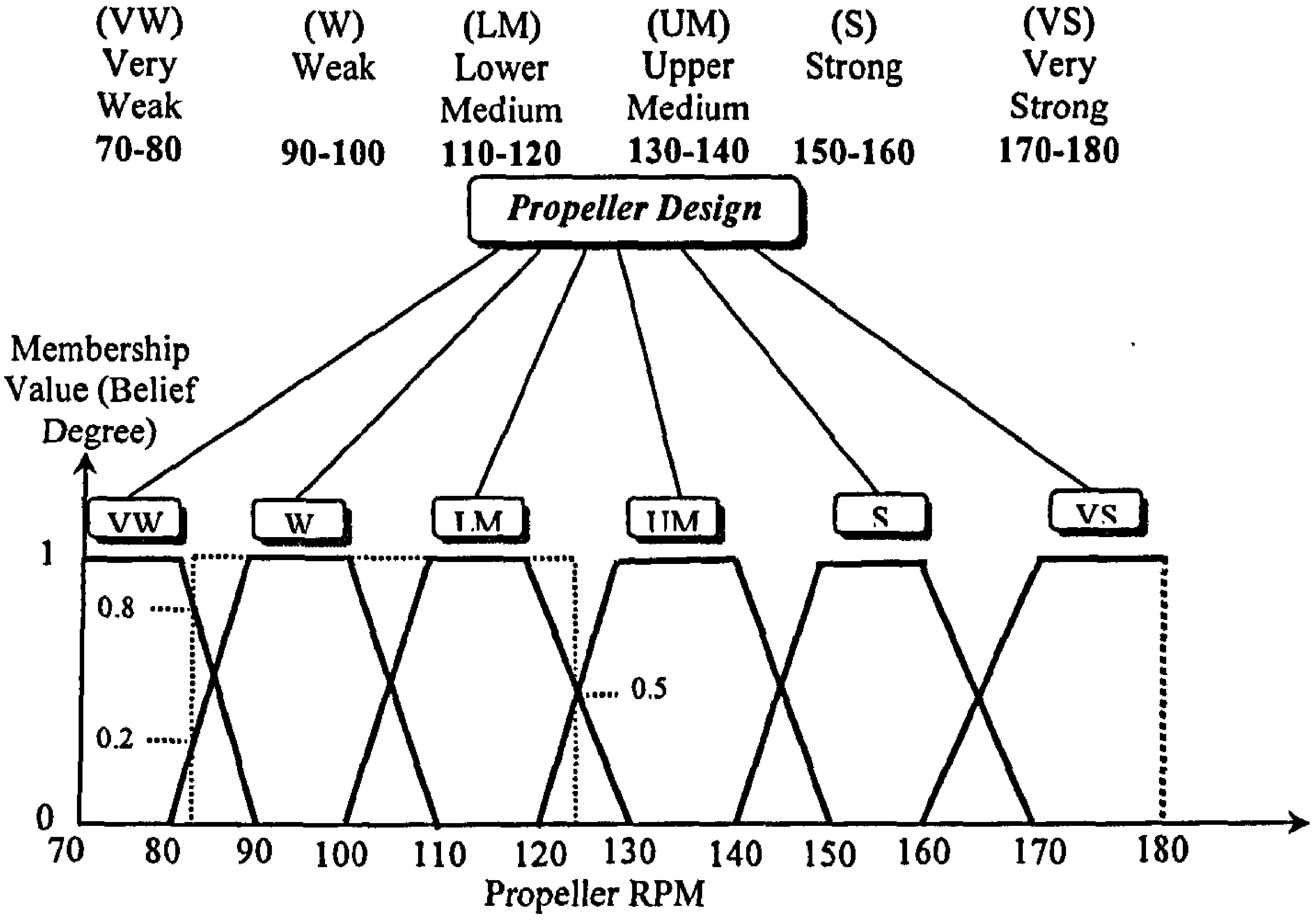


Figure 4.6: Modelling Propeller RPM of Ship 2

Secondly, the areas covered by each defined MF within the interval of 82 and 125 are calculated as follows:

$$VW = \frac{1}{2} \times 0.8 \times 8 = 3.2$$

$$W = \frac{1}{2} \times (10+30) \times 1 - \frac{1}{2} \times 2 \times 0.2 = 19.8$$

$$LM = \frac{1}{2} \times (10+30) \times 1 - \frac{1}{2} \times 5 \times 0.5 = 18.75$$

$$UM = \frac{1}{2} \times 5 \times 0.5 = 1.25$$

$$S = 0$$

$$VS = 0$$

Thirdly, the normalisation is carried out based on the above area calculations to produce the belief degrees associated with each defined linguistic term.

By using Eq. (4.3) β'_s can be calculated:

$$\beta'_s = \beta'_{VW} + \beta'_W + \beta'_{LM} + \beta'_{UM} + \beta'_S + \beta'_{VS} = 3.2 + 19.8 + 18.75 + 1.25 + 0 + 0 = 43$$

Fourthly, the real single belief degree associated with each linguistic term can be calculated by employing Eq. (4.4):

$$\beta_{VW} = \frac{\beta'_{VW}}{\beta'_s} = \frac{3.2}{43} = 0.0744 \qquad \beta_W = \frac{\beta'_W}{\beta'_s} = \frac{19.8}{43} = 0.4605$$

$$\beta_{LM} = \frac{\beta'_{LM}}{\beta'_s} = \frac{18.75}{43} = 0.4360 \qquad \beta_{UM} = \frac{\beta'_{UM}}{\beta'_s} = \frac{1.25}{43} = 0.0291$$

$$\beta_S = \frac{\beta'_S}{\beta'_s} = \frac{0}{43} = 0.0000 \qquad \beta_{VS} = \frac{\beta'_{VS}}{\beta'_s} = \frac{0}{43} = 0.0000$$

Fifthly, the belief degree associated with each linguistic term can be represented by the following set:

{[VW, (0.0744)]; [W, (0.4605)]; [LM, (0.4360)]; [UM, (0.0291)]; [S, (0)]; [VS, (0)]}

Finally, the mapping process described in Section 4.4.3 is used to transform the above into a common utility space.

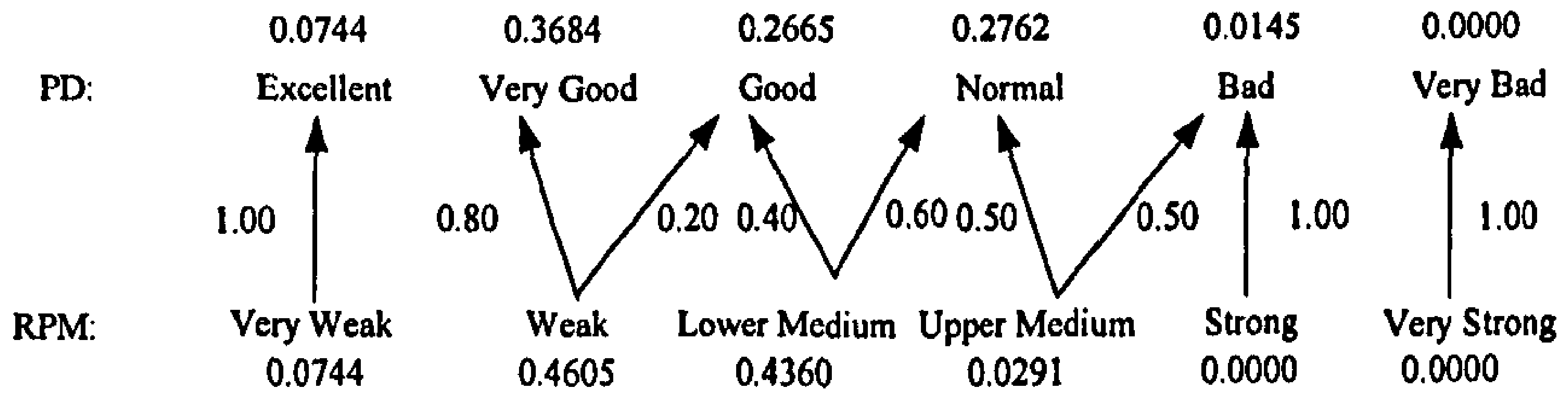


Figure 4.7: Mapping from Propeller RPM to Propeller Design

To explain this mapping process for Ship 2, a necessary fuzzy rule base has been developed (Figure 4.7).

1. If the propeller RPM is Very Weak, then the propeller design is {(Excellent, 1.00)}.
2. If the propeller RPM is Weak, then the propeller design is {(Very Good, 0.80), (Good, 0.20)}.
3. If the propeller RPM is Lower Medium, then the propeller design is {(Good, 0.40), (Normal, 0.60)}.
4. If the propeller RPM is Upper Medium, then the propeller design is {(Normal, 0.50), (Bad, 0.50)}.
5. If the propeller RPM is Strong, then the propeller design is {(Bad, 1.00)}.
6. If the propeller RPM is Very Strong, then the propeller design is {(Very Bad, 1.00)}.

After transforming criteria from a lower level into an upper level the next step is to quantify the belief degrees associated with the linguistic terms used in the upper level criterion. This is carried out by using the proposed algorithm in Eq. (4.5):

Excellent: $0.0744 \times 1.00 = 0.0744$

Very Good: $0.4605 \times 0.80 = 0.3684$

Good: $0.4605 \times 0.20 + 0.4360 \times 0.40 = 0.2665$

Normal: $0.4360 \times 0.60 + 0.0291 \times 0.50 = 0.2762$

Bad: $0.0291 \times 0.50 + 0.0000 \times 1.00 = 0.0145$

Very Bad: $0.0000 \times 1.00 = 0.0000$

∴ {[EX, (0.0744)]; [VG, (0.3684)]; [G, (0.2665)]; [N, (0.2762)]; [B, (0.0145)]; [VB, (0.0000)]}

The above set will be used in the criteria aggregation process conducted by using ER in Step 4.

Single valued quantitative criteria can be transformed by employing the procedure which has been shown in Section 4.4.1. The linguistic terms used to model the quantitative generic ship design criteria are shown in Table 4.3. The fuzzy algorithms are developed based on them.

Table 4.3: Quantitative Data Modelling Linguistic Terms

Design Criteria	Linguistic Terms					
Propeller Design						
Propeller RPM	Very Weak	Weak	Lower Medium	Upper Medium	Strong	Very Strong
Propeller Diameter	Very Low	Low	Reasonable	Frequent	High	Very High
Blade Area	Very Bad	Bad	Normal	Good	Very Good	Excellent
Number of Blades	Slightly Preferred	Moderately Preferred	Averagely Preferred	Normally Preferred	Preferred	Greatly Preferred
Shaft System Design						
Shaft System Length	Very Low	Low	Reasonable	Frequent	High	Very High
Engine Design						
Engine RPM	Very Low	Low	Reasonable	Frequent	High	Very High
Number of Engines	Unsatisfactory	Very Poor	Poor	Acceptable	Reasonably Acceptable	Satisfactory
Number of Cylinders	Slightly Preferred	Moderately Preferred	Averagely Preferred	Normally Preferred	Preferred	Greatly Preferred

All the results of the quantitative data transformation are shown in Table 4.4 and Appendix 4.2 where the results of the qualitative data transformation conducted in the next step are also presented.

Table 4.4: Results for Ship 2

Design Criteria	Excellent	Very Good	Good	Normal	Bad	Very Bad
Propeller Design						
Propeller RPM	0.0744	0.3684	0.2665	0.2762	0.0145	0.0000
Propeller Diameter	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
Blade Area	0.0000	0.7260	0.2740	0.0000	0.0000	0.0000
Number of Blades	0.0000	0.6000	0.4000	0.0000	0.0000	0.0000
Propeller Pitch	0.0000	0.0000	0.0000	0.5000	0.5000	0.0000
Blade Thickness	0.5000	0.5000	0.0000	0.0000	0.0000	0.0000
Propeller Load	0.8500	0.1500	0.0000	0.0000	0.0000	0.0000
Propeller Skew	0.0000	0.0000	0.0000	0.6000	0.4000	0.0000

Shaft System Design						
Shaft System Length	0.0000	0.0000	0.6000	0.4000	0.0000	0.0000
Shaft Stiffness	0.0000	0.0000	0.0000	0.5000	0.5000	0.0000
Shaft Alignment	0.0000	0.0000	0.0000	0.3500	0.6500	0.0000
Bearings	0.0000	0.0000	0.0000	0.7500	0.2500	0.0000
Engine Design						
Engine RPM	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
Number of Engines	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
Number of Cylinders	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
Power to Weight Ratio	0.0000	0.0000	0.0000	0.5000	0.5000	0.0000
Damping Systems	0.0000	0.0000	0.0000	0.2000	0.8000	0.0000
Engine Firing	0.0000	0.0000	0.7000	0.3000	0.0000	0.0000
Engine Alignment	0.0000	0.0000	0.0000	0.0000	0.7500	0.2500
Ship Body Design						
Aft Body Design	0.0000	0.0000	0.0000	0.0000	0.2000	0.8000
Fore Body Design	0.0000	0.0000	0.0000	0.2000	0.8000	0.0000
Hull Smoothness	0.0000	0.0000	0.0000	0.7172	0.2828	0.0000
Rudder Design	0.0000	0.0000	0.6000	0.4000	0.0000	0.0000

4.5.3. Qualitative Interval Data Transformation (*Step 3*)

The qualitative interval data is the result of experts having different views and ideas in the same situation for qualitative criteria, or the result of an expert unable to make an exact judgement for a specific case. To tackle such kinds of problems an approach proposed in Section 4.4.4 has been used.

The hull smoothness of Ship 2 is obtained based on expert judgements. Some of the values associated with the six linguistic terms are intervals (Appendix 4.1). They are transformed as the following:

{[EX, (0)]; [VG, (0)]; [G, (0)]; [N, (0.70, 0.72)]; [B, (0.28)]; [VB, (0)]}

Take the mean of the interval values for linguistic term (N) by using Eq. (4.6):

$$\beta'_N = \frac{0.70 + 0.72}{2} = 0.71$$

The normalisation is carried out for the transformed qualitative criteria as follows by using Eq. (4.3) and Eq. (4.4):

$$\beta'_s = \beta'_{EX} + \beta'_{VG} + \beta'_G + \beta'_N + \beta'_B + \beta'_{VB} = 0 + 0 + 0 + 0.71 + 0.28 + 0 = 0.99$$

$$\beta_{EX} = \frac{\beta'_{EX}}{\beta'_s} = \frac{0}{0.99} = 0.0000 \qquad \beta_{VG} = \frac{\beta'_{VG}}{\beta'_s} = \frac{0}{0.99} = 0.0000$$

$$\beta_G = \frac{\beta'_G}{\beta'_s} = \frac{0}{0.99} = 0.0000 \qquad \beta_N = \frac{\beta'_N}{\beta'_s} = \frac{0.71}{0.99} = 0.7172$$

$$\beta_B = \frac{\beta'_B}{\beta'_s} = \frac{0.28}{0.99} = 0.2828 \qquad \beta_{VB} = \frac{\beta'_{VB}}{\beta'_s} = \frac{0}{0.99} = 0.0000$$

The following set is then obtained:

{[EX, (0.0000)]; [VG, (0.0000)]; [G, (0.0000)]; [N, (0.7172)]; [B, (0.2828)]; [VB, (0.0000)]}

All the other criteria of this nature can be processed in a similar way and the results are shown in Table 4.4 and Appendix 4.2. Once the normalised estimates for all the generic ship design criteria of a ship are obtained, the next step is to combine them to obtain a single risk estimation set. In Step 4, ER is used to achieve this task.

4.5.4. Application of ER for Synthesis and ER-Based Utility Approach for Ranking (*Step 4*)

ER is used for synthesis of the generic ship design criteria. The weightings of all the criteria in Figure 4.1 are used in such synthesis.

The normalised data in Table 4.4 and Appendix 4.2 will be used to obtain the risk estimation results of each ship design in terms of SHV as shown in Table 4.5. This is carried out by employing ER (Appendices 4.3-4.7).

Table 4.5: Risk Estimation of Each Ship Design

Ship No.	Excellent	Very Good	Good	Normal	Bad	Very Bad
Ship 1	0.0000	0.0175	0.0899	0.1258	0.5032	0.2636
Ship 2	0.0650	0.1949	0.0644	0.2316	0.3056	0.1385

Ship 3	0.0000	0.0669	0.2559	0.1082	0.1141	0.4549

The ER based utility ranking approach is then used for ranking all the ships based on the risk estimation results of SHV.

The utility values associated with each linguistic term should be calculated. In this study the highest preference is given to the Excellent linguistic term and the lowest preference is given to the Very Bad linguistic term. The utility values of the linguistic terms are obtained as follows:

(EX)	(VG)	(G)	(N)	(B)	(VB)
Excellent	Very Good	Good	Normal	Bad	Very Bad
(1)	(2)	(3)	(4)	(5)	(6)

By using Eq. (4.8) the utility values of the linguistic terms are calculated as follows:

$$u(\mathrm{EX}) = \frac{6-1}{6-1} = 1.0 \qquad u(\mathrm{VG}) = \frac{6-2}{6-1} = 0.8 \qquad u(\mathrm{G}) = \frac{6-3}{6-1} = 0.6$$

$$u(\mathrm{N}) = \frac{6-4}{6-1} = 0.4 \qquad u(\mathrm{B}) = \frac{6-5}{6-1} = 0.2 \qquad u(\mathrm{VB}) = \frac{6-6}{6-1} = 0.0$$

u(EX)	u(VG)	u(G)	u(N)	u(B)	u(VB)
1.0	0.8	0.6	0.4	0.2	0.0

Since all the original assessments are complete, the expected maximum, minimum and average utilities will be the same. The expected utilities of the three ships are calculated by using Eq. (4.7) and the results are shown in Table 4.6. An example of such calculation for Ship 2 is given below.

$$u(\text{Ship 2}) = u(\mathrm{EX}) \times \beta_{EX} + u(\mathrm{VG}) \times \beta_{VG} + u(\mathrm{G}) \times \beta_{G} + u(\mathrm{N}) \times \beta_{N} + u(\mathrm{B}) \times \beta_{B} + u(\mathrm{VB}) \times \beta_{VB}$$

$$u(\text{Ship 2}) = 1.0 \times 0.0650 + 0.8 \times 0.1949 + 0.6 \times 0.0644 + 0.4 \times 0.2316 + 0.2 \times 0.3057 + 0.0 \times 0.1385$$

$$u(\text{Ship 2}) = 0.4133$$

Table 4.6: Utility and Ranking of the Three Ships

Ship No.	Ship 1	Ship 2	Ship 3
Utility	0.2189	0.4133	0.2732
Ranking	***3***	***1***	***2***

4.6. Discussion and Validation of the Model

From the obtained results it is clear that the Ship 1 is ranked last. This is because many design criteria of Ship 1 are assessed as Bad and Very Bad to a large extent. For instance, propeller pitch is assessed as Bad (60.00%) and Very Bad (40.00%), and shaft alignment is assessed as Bad (50.00%) and Very Bad (50.00%). Ship 1 has the highest number of criteria with belief degrees which are assessed as Bad and Very Bad to a large extent when compared with any other ship type. Since the highest number of design criteria of the Ship 1 is assessed to a large extent as Bad and Very Bad, the worst design should be the Ship 1. That is in harmony with the results achieved previously, as the Ship 1 has got the lowest ranking.

The propeller RPM of Ship 2 has been increased to {85, 125} from {82, 125} (Table 4.1) in order to check the sensitiveness of the model on the basis of changing of original inputs. If the model is sensitive to changes, the quality of propeller design should be reduced because when the propeller RPM is increased consequently vibration risk would be increased. Therefore, there should be a reduction of associated utility value of Ship 2 when compared with its original utility value. The achieved new results are in agreement with the changes in original inputs and they are shown in Table 4.7.

Table 4.7: New Results on the basis of Changing of Inputs

Propeller Design	Excellent	Very Good	Good	Normal	Bad	Very Bad
{82, 125} (Original)	0.1798	0.5391	0.0628	0.1336	0.0847	0.0000
{85, 125} (New)	0.1743	0.5403	0.0644	0.1360	0.0849	0.0000

The calculated utility value on the basis of new results of Ship 2 is 0.4124 which is less than the original utility value (0.4133) shown in Table 4.6. Therefore, the results obtained, using the developed approach, seem reasonable.

In this chapter the generic model was developed considering the top level as SHV and the bottom level as all the generic ship design criteria for the purpose of ship selection. Based on the results obtained it can be said that the developed generic model is well suited for a ship selection problem.

In the next chapter (Chapter 5), major causes of key failure events associated with ship propulsion system and hull (ship body) which lead to SHV are identified in terms of four risk parameters (failure likelihood, failure capability, failure recovery incapability and failure consequence probability). The majority of the failure modelling criteria are dependent on the hazard identification model of Chapter 3 (Figure 3.1) and also some of failure modelling criteria are related to this chapter (Chapter 4). In Chapter 5 risk estimation of each cause is carried out using discrete fuzzy sets and AHP, and possible Risk Control Options (RCOs) are selected for the identified causes with high risk estimation in order to manage the risk of SHV.

4.7. Conclusion

The need for safety associated with ships due to vibrations has been significantly growing over the last few years. Ship design criteria are one of the most important factors which influence the occurrence of vibration onboard ships. Ship designers always try to design ships for minimum vibrations to provide a good environment for crew and passengers. By using the developed generic model it is possible to provide a benchmark to ascertain the quality of the ship design in terms of risk estimation results of SHV. This type of benchmark would provide particularly useful information for ship designers. Furthermore, the benchmark may be used in ship classification societies as well as by buyers to judge the quality of the design when purchasing ships.

The four step methodology proposed in this chapter provides a subjective decision making approach for organisations involved in ship vibration problems. Step 1 highlights the single/interval valued quantitative and qualitative criteria in the generic model. The approach developed in Steps 2 and 3 gives a subjective way to handle interval/single valued quantitative and qualitative data. In the final step

(Step 4) ER is used for synthesis of all the normalised generic ship design criteria, and the ER based utility ranking approach is used for ranking ships based on the risk estimation results of SHV. The proposed methodology can be used for ship selection, design options selection, and many more.

Chapter 5 – A Subjective Risk Management Approach for Modelling of Failures Onboard Ships

SUMMARY

Performance degradations (failures) of onboard ships have a significant contribution to Ship Hull Vibration (SHV) which may lead to marine accidents. Due to the complexity of risks of SHV, conventional Quantitative Risk Assessment (QRA) techniques may not often be capable of providing sufficient risk management information to minimise the risks of SHV. In this study a subjective novel approach is developed by combining discrete fuzzy sets with Analytical Hierarchy Process (AHP) to deal with management of SHV induced risks. The causes of each failure event are compared with each other in terms of failure likelihood, failure capability, failure recovery incapability and failure consequence probability to achieve the relative importance and overall risk estimation of each cause. Finally, relevant Risk Control Options (RCOs) are introduced and the effectiveness of each Risk Control Option (RCO) is evaluated to minimise the risks of major causes which create SHV. The results of this chapter reveal that the marriage of discrete fuzzy sets and AHP is capable of producing the information to manage the risks of SHV.

5.1. Introduction

Vibrations induced by failures have played a crucial role in major marine accidents, for instance "Esso Mersey", "Constant Faith", "Britannia Conquest", "Green Lily", and "Elegance" to name a few (MAIB, 1990-2008). "MT Esso Mersey" was a steel hull, single screw motor tanker with gross tonnage of 11,898. The vessel operated in the 'clean oil' trade round the UK coast and European continent. An explosion occurred in this vessel on 4th September 1991. The accident was attributed to vibration induced by failure of one of the cargo pumps, leading to the leakage of cargo through the top mechanical seal and eventual ignition by contact between the drive shaft and the shaft guard. The explosion passed up through the pump room, burst into the cargo control room and through the forward starboard door at the poop deck level. This incident resulted in the loss of two lives.

"MV Green Lily" was a Bahamian registered 3624 gross tonnage, single engine, refrigerated general cargo vessel built in 1978. On 19th November 1997 a sea water supply line fractured in the engine room. The flooding was controlled, however, suddenly, the main engine stopped. The accident report shows an "L" shaped pipe section had two potential high risk areas of weakness. The weaker one was due to erosion/corrosion and other one because of condensation/water etc dropping down from pipes and floor plates above the pipe. Once this had developed, it led to heavy vibrations. Those vibrations contributed to the sudden failure, causing the initial flooding and loss of the vessel. Serious accidents, caused by failures onboard at sea over the last few years, highlight the need for more research to identify the possible Risk Control Options (RCOs) to minimise the risks of ship vibrations.

In this study five major failure events, namely, propeller failure, shafting failure, thrust block failure, engine component failure and hull failure, are identified based on expert judgements and literature review. These are classified under failure likelihood, failure capability, failure recovery incapability and failure consequence probability risk parameters. Possible causes of each failure event are discussed in Level 4 (bottom level) of the developed hierarchical structure. A pairwise comparison is conducted in terms of failure likelihood, failure capability, failure recovery incapability and failure consequence probability.

An Analytical Hierarchy Process (AHP) method is implemented because it is a comprehensive framework which is designed to cope with intuitive, rational, and irrational data when dealing with multi-objective, multi-criterion and multi-actor decisions with and without certainty for any number of alternatives (Harker & Vargas, 1987). It is a method for deriving ratio scales used to integrate the elements of any problem. It organises the basic rationality by breaking down a problem into its smaller constituent parts and then calls for simple pairwise comparison judgements to develop priorities in hierarchy.

The failure data of propulsion system components and hull may not always available, and its collection is time consuming and expensive as well as dependent on many uncertainties. Consequently, the data may not be well suited for dealing with SHV problems in situations having a high level of uncertainty. One realistic way of handling such situations is to use linguistic assessment. Fuzzy set theory is well suited to modelling subjective linguistic variables and dealing with discrete problems (Wang *et al.,* 1996). Therefore, in this study, discrete fuzzy sets are combined with AHP. More information of fuzzy set theory can be found in Chapter 2.

The main aim of this chapter is to study possible RCOs to reduce the risks of SHV by identifying the possible failure events and their major causes. In order to achieve the aim, this study proposes a new method using AHP and discrete fuzzy sets. The new method is demonstrated with a case study based on a hierarchical structure constructed for modelling of failures onboard.

5.2. Background

5.2.1. Analytical Hierarchy Process

AHP was developed by Satty and it is designed to solve complex multi-criteria decision problems (Anderson *et al.*, 2003; Satty, 1980). AHP requires the decision maker to supply judgments (expert judgments) about the relative importance of each criterion and then specify a preference for each decision alternative using each criterion. AHP is especially appropriate for complex decisions which involve the comparison of decision criteria that are difficult to quantify (Pillay & Wang, 2003). It is based on the assumption that when faced with a complex decision the natural human reaction is to cluster the decision criteria according to their common characteristics.

Since AHP was introduced nearly three decades ago, it has found many useful applications. These include maritime applications (Brown & Haugene, 1998; Lim *et al.*, 2004; Teng & Jaramillo, 2005; Ugboma *et al.*, 2006), financial and business applications (Ayag, 2005; Madu *et al.*, 1991; Stewart *et al.*, 2002), risk and safety assessment (Sii *et al.*, 2001; Sii & Wang, 2003; Ung *et al.*, 2006), industrial engineering applications (Chan *et al.*, 2000; Lee *et al.*, 1999; Lee *et al.*, 2001; Yang *et al.*, 2003), transportation systems (Arslan & Khisty, 2005; Lambert *et al.*, 2006; Shang *et al.*, 2004), military applications (Cheng, 1997; Cheng *et al.*, 1999), location selection (Kuo *et al.*, 2002; Xie *et al.*, 2006) and many more. This is because AHP has several useful characteristics (Anderson *et al.*, 2003; Kumar & Ganesh, 1996):

- AHP can handle situations in which the unique subjective judgements of the individual decision maker constitute an important part of the decision making process.

- Relative ease with which it handles multiple criteria.
- AHP is easier to understand and it can effectively handle both qualitative and quantitative data.

Generally, AHP comprises the following four steps (Drake, 1998): selection of criteria, assessment of the relative importance of these criteria using pairwise comparisons, assessment of each alternative relative to each other on the basis of each selection criteria using the pairwise comparison technique, and combination of the ratings synthesised in the previous steps to obtain an overall relative rating for each alternative respectively. AHP is capable of breaking down a decision into smaller parts, proceeding from the goal to main criteria to sub-criteria down to the alternative courses of action. Decision makers then make simple pairwise comparison judgements throughout the hierarchy (model) to arrive at overall priorities for the alternatives.

SHV can be named as a serious issue in shipboard environment. Therefore, it is necessary to study RCOs to minimise the risks of SHV. Although the potential of discrete fuzzy sets and AHP for application in the shipping industry is recognised, it has not been applied to risk management of ship vibration. A possible methodology is proposed in the following sections in order to demonstrate the applicability of discrete fuzzy sets and AHP for the risk management of SHV.

5.3. Modelling of Failures

In this study performance degradations of components are considered as "failures". Figure 5.1 is the AHP structure developed for failure modelling. The Goal (top level) in the AHP structure contains SHV. The elements in Level 2 are set to be failure likelihood, failure capability, failure recovery incapability and failure consequence probability. Level 3 elements contain propeller failure, shafting failure, thrust block failure, engine component failure and hull failure. Each failure event in Level 3 is investigated based on its associated causes given in Level 4 and listed in Table 5.1. These causes are chosen because they are regarded as the most significant ones associated with major failure events which lead to SHV. The selection of such failures and causes is conducted based on extensive discussions with experts in the area and the study of SHV related marine accident data (MDS, 1992-2007).

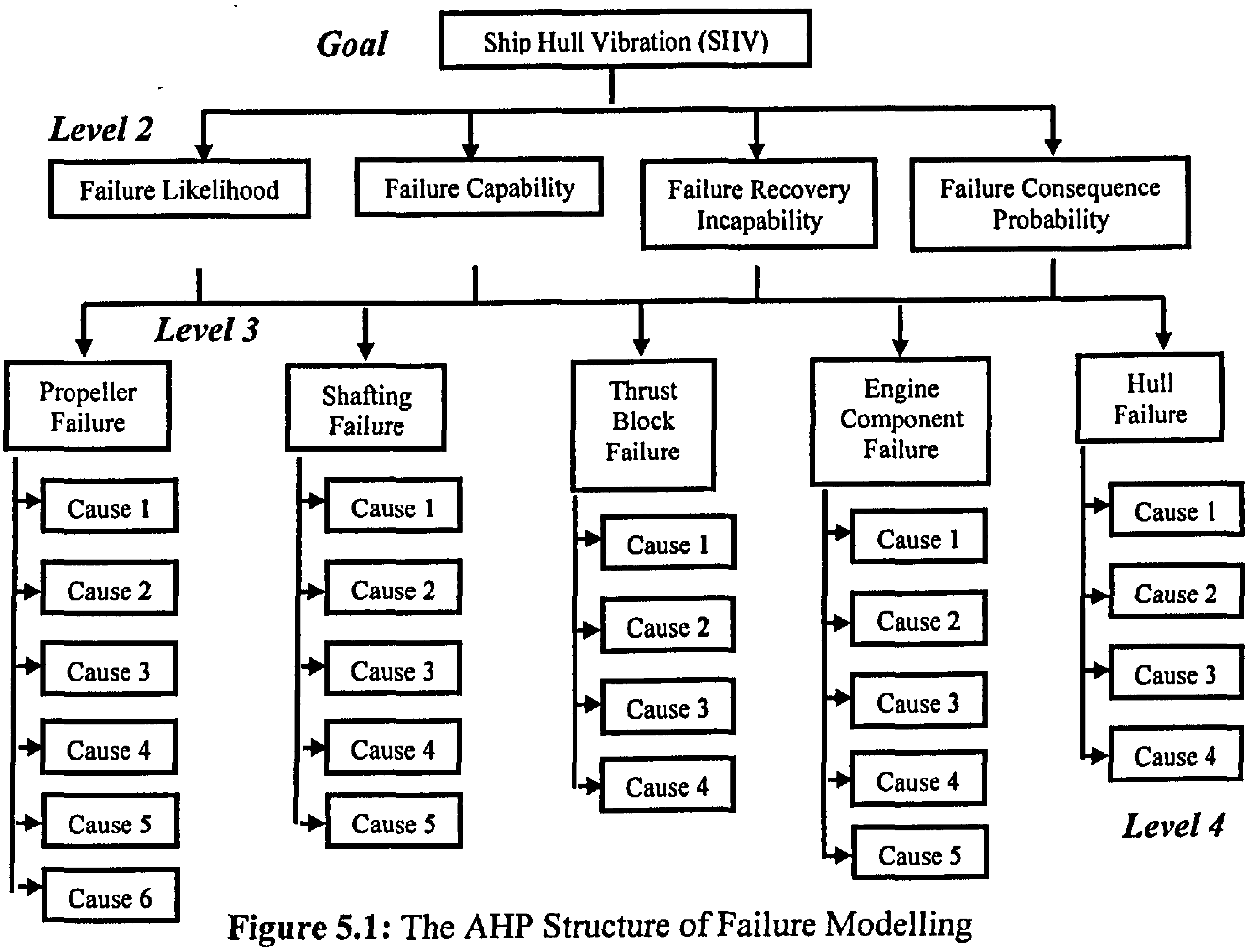


Figure 5.1: The AHP Structure of Failure Modelling

Table 5.1 consists of causes of each failure event. The data is obtained based on a fishing vessel. It is an ocean going ship built in 1983, which is currently in service. The ship dimensions are 50.3 m in length, 9.8 m in breadth and 722 in gross tonnage.

Table 5.1: Causes of Failures

Failure Type	Cause No.	Cause
Propeller Failure	1	Back bubble cavitation
	2	Sheet cavitation
	3	Cloud cavitation
	4	Tip/hub vortex cavitation
	5	Propeller-hull vortex cavitation
	6	Physical damages
Shafting Failure	1	Misalignment
	2	Bearing failure
	3	Torque variations

	4	Crankshaft deflection
	5	Shaft whirling
Thrust Block Failure	1	Deformation from the thrust load
	2	Thrust block misalignment
	3	Thrust block rocking
	4	Excessive thrust block wear
Engine Component Failure	1	Component wear
	2	Out of balance forces
	3	Incorrect power balance
	4	Variable gas pressures
	5	Engine misalignment
Hull Failure	1	Sagging & hogging of the hull due to sea conditions
	2	Ship loading & discharging
	3	Corrosion
	4	Grounding

The detailed information of experts used in this chapter and dates of the meetings are given below. During the meetings, the main aims were to identify the most significant criteria to develop a model to highlight the failures on the basis of SHV and to find out the applicability of the model in real situations.

Panel of Experts:

- Dr. A. Batako: Research Fellow, General Engineering Research Institute (GERI), Liverpool John Moores University, United Kingdom.
- Mr. G. Phylip-Jones: Senior Lecturer, Liverpool John Moores University, United Kingdom.
- Mr. K.M. Wijegoonewardane: Consultant/Chief Engineer, Lakcey Shipping (Pvt) Ltd, Sri Lanka.
- Mr. R. Riahi: Senior Superintendent/Ship Design Consultant, Islamic Republic of Iran Shipping Line (IRISL), Iran.

Dates and Venues of Meetings:

- 14/05/2007: Albert Dock, Liverpool, United Kingdom.

- 16/08/2007: Senior Common Room, Liverpool John Moores University, United Kingdom.

Note: More extensive discussions with experts were also conducted via telephone.

5.3.1. Propeller Failure

Cavitation is a major source of propeller failure (JISC, 2005); this leads to unbalanced forces generating on the propeller blades. When the propeller rotates these unbalanced forces give extra movements of blades resulting in propeller induced vibrations. The propeller cavitation depends on such factors as propeller design criteria, pressure variations, wake variations, angle of attack and thrust variations. Various forms of cavitation can occur on propeller blades and some of them are more harmful than others.

When water flows over the suction side of an aerofoil the velocity rises, pressure falls and bubble cavitation may occur at the maximum section thickness (Brownlie, 1998). The bubbles grow, travel with the water flow, and then quickly reduce in size. The greater the thickness/chord ratio of the section, the greater the maximum pressure drop and the more likely that back bubble cavitation will form. One way of avoiding this form of cavitation is to increase the chord length of the section, thus reducing the thickness/chord ratio. Section camber also affects the pressure distribution over the suction face and therefore affects the onset of back bubble cavitation. Reducing the section camber will also reduce the likelihood of back bubble cavitation.

The wake variations are as important as the pressure variations. During the initial ship design it is important to select a slow propeller speed and large diameter, not only to give an efficient propulsion system but also to avoid cavitation problems (Brownlie, 1998). The design should optimise the wake field, minimising the variations between maximum and minimum wake fractions and avoiding sudden velocity changes. Hull appendages, such as bossings, must be carefully designed to obtain uniform wake distribution. It is necessary to have large fore and aft bossing clearances (Todd, 1961). That not only controls the vibration but also reduces the bearing forces from the propeller by decreasing the bossing force directly.

Since the propeller works in a non-uniform flow, the angle of attack of each blade section varies circumferentially (Gabriel & Atlar, 1998). A periodic change in angle of attack gives rise to unsteady blade forces. This leads in turn to undesirable propeller excited vibrations and induced ship hull pressures of an unsteady nature. When the flow past the blade section is at a large positive angle of attack, there is a steep drop in pressure just behind the leading edge on the suction face (Brownlie, 1998). If this drop in pressure is greater than the static water pressure, sheet cavitation will occur on the back of the propeller. The flow separates from the blade surface and a fixed pocket of water vapour and gases form. Sheet cavitation may appear when the flow passes the blade at a negative angle of attack.

Sheet cavitation can break down, either on or off the blade, forming cloud cavitation consisting of a large number of very small bubbles appearing as a mist (Brownlie, 1998). Cloud cavitation may also occur when a blade emerges from a wake peak giving a localised short term increase in loading.

The tip/hub vortex cavitation results from a high specific thrust loading of the propeller in combination with the wake peak and the high loading of the blade tips (Holtrop & Valkhof, 2003). Unstable, fluctuating and irregular behaviour of the tip/hub vortex cavitation can lead to a wide spread distribution of high energy pressure levels on the hull.

Another form of cavitation which can be troublesome, despite occurring fairly infrequently, is propeller-hull vortex cavitation (Brownlie, 1998). This phenomenon can take several forms. It is usually recognised as a vortex in the flow, or possibly two or three vortices emanating from a small localised region on the ship's stern and extending towards the propeller, made visible by a hollow cavitating core.

Physical damages due to collision with small rocks and floating debris raise the number of out of balance forces on the propeller blades. There are situations where propellers have lost some parts of the blades. Sometimes there will be severe vibrations due to consequences of blade damages.

5.3.2. Shafting Failure

The description of misalignment and bearing failure can be found in Chapters 3 and 4. Shaft torque variations can cause severe damage to the shafting system. These torque variations are caused by pitching movements of the ship and also from variation of torque from the engine. In rough weather conditions especially, shaft torque variations reach the maximum level. One of the causes of torsional vibration is the crankshaft/connecting rod mechanism creating varying torque in the crankshaft (Woodyard, 2004; Anon, 1989). The excitation of torsional vibration is the result of those variations. More information can be obtained by referring to Chapter 3.

High deck temperatures in the tropics or low sea temperatures can cause differential expansion and hogging of the hull (McGeorge, 1995). Also, wave loading may cause hull sagging and hogging. These types of changes can alter crankshaft deflection.

Shaft whirling is caused mainly due to lack of support from the bearings. This could lead to out of balance forces generating in the shafting system. Sometimes there will be secondary effects such as bending of the shafting.

5.3.3. Thrust Block Failure

Thrust block failures are mainly caused by deformation from the thrust load, thrust block misalignment, thrust block rocking and excessive thrust block wear. Thrust load is not always constant and in some situations it varies rapidly, hence causing deformation of the thrust block.

Thrust block misalignment can generate vibration in the whole ship transmission system. Production of out of balance forces due to misalignment leads to failure of the thrust block while creating vibrations.

Axial vibration of the shaft system caused by slackening of the propeller blade load as it turns in the stern frame or by the splay of diesel engine crankwebs, is normally damped by the thrust block (McGeorge, 1995). Serious axial vibration problems have sometimes caused thrust block rock, panting of the tank top and structural damage. Due to thrust block rock there will be further vibration problems.

Excessive thrust block wear is another problem in sea going vessels. Maintenance activities should be carried out to minimise the vibration problems. Thrust block wear not only causes severe vibrations but also other operational problems such as poor performance of the shafting and propeller system.

5.3.4. Engine Component Failure

Maintenance activities should be carried out on time in order to replace worn engine components. Worn engine components are highly likely to produce out of balance forces responsible for vibrations.

Information on out of balance forces and incorrect power balance can be found in Chapter 3. One of the causes for torsional vibration is the varying gas pressures in the cylinders during the working cycle. This gives torsional excitation of the engine rotating parts. This vibration causes extra stresses, which could result in serious damages in the engine rotating parts and even fracture of engine components (Magazinovic, 2002).

Great care should be paid to keep the correct engine alignment. The engine alignment could change regularly. If there is an engine misalignment, it can cause severe damage to the engine, associated equipment and hull structures while producing vibrations.

5.3.5. Hull Failure

Sea, loading and deck temperature variations can cause sagging and hogging of the hull (McGeorge, 1995). In some vessels, sagging and hogging have caused large fatigue cracks on the hull. Fatigue cracks may weaken the hull material which could increase the risk of SHV.

A ship's loading or ballast condition, which changes the hull shape to an unusual degree, could result in higher temperatures in bearings due to uneven load distribution. Experiences have shown that incorrect cargo loading, discharging procedures and resultant excessive hull stresses could actually break a ship into two parts (McGeorge, 1995).

Ship hull is exposed to salt water. Due to chemical reaction between steel and salt water there will be corrosion on the hull surface after some period of time. Corrosion weakens the hull material and consequently hull vibration risk may increase.

Grounding results in damage of the hull and production of heavy SHV. Since the ship body contacts with the ground, sometimes it changes the hull shape, as a consequence bending moments are applied on the ship.

The causes of hull failure, such as sagging and hogging of the hull due to sea conditions, ship loading and discharging and grounding, could lead to serious problems like engine and shaft misalignment. However, those problems depend on the magnitude of the failure.

5.4. Methodology

The following steps with respect to Figure 5.1 are developed in order to obtain the effectiveness of each RCO to minimise the risks of SHV:

Step 1: Model the linguistic terms by using discrete fuzzy sets to describe the relationship between the criteria in each level.

Step 2: Calculate the numerical values of seven linguistic terms to obtain their numerical relationship and carry out the normalisation.

Step 3: Carry out the pairwise comparisons between failure likelihood, failure capability, failure recovery incapability and failure consequence probability by using normalised values of linguistic terms. Based on normalised values, calculate the relative importance of each criterion in Level 2.

Step 4: Calculate the weighting vectors of the criteria in Level 2 after the calculation of relative importance.

Step 5: Conduct the pairwise comparisons of failure events identified in Level 3 in terms of failure likelihood, failure capability, failure recovery incapability and failure consequence probability. Then obtain the normalised weighting vectors of each failure event by employing the calculated weighting vectors of Level 2.

Step 6: Carry out the pairwise comparisons of the causes in Level 4 in terms of failure likelihood, failure capability, failure recovery incapability and failure consequence probability. Then estimate the risk of each cause (normalised weighting vectors) by using the results obtained in Level 3.

Step 7: Estimate the overall risk of each cause in terms of failure likelihood, failure capability, failure recovery incapability and failure consequence probability and select the causes with high risk estimation which create SHV.

Step 8: Identify suitable RCOs to minimise the causes with high risk estimation, assess their effectiveness and list the preference of them.

5.4.1. Calculation of Numerical Values and Normalisation

Suppose there are seven linguistic terms used in the discrete fuzzy sets. They are named as Equally (EQ), Slightly (SL), Moderately (MO), Fairly (FA), Strongly (ST), Very Strongly (VS) and Extremely (EX) (Table 5.2). The membership values associated with 'y' for each discrete fuzzy set are assessed using '*x*' where 'y' stands for categories y_1 (lowest importance) to y_7 (highest importance). Table 5.2 was originally obtained from (Wang *et al.*, 1995; Wang *et al.*, 1996; Wang, 2000; Yang, 2005) and used in the Case Study (Section 5.5) of this chapter. However, in this section symbols *x* and y are used to represent membership values and categories and to keep the methodology as generic.

Table 5.2: An Example of Discrete Fuzzy Sets

Linguistic Terms	y_1	y_2	y_3	y_4	y_5	y_6	y_7
Equally (EQ)	x_{EQ1}	x_{EQ2}	x_{EQ3}	x_{EQ4}	x_{EQ5}	x_{EQ6}	x_{EQ7}
Slightly (SL)	x_{SL1}	x_{SL2}	x_{SL3}	x_{SL4}	x_{SL5}	x_{SL6}	x_{SL7}
Moderately (MO)	x_{MO1}	x_{MO2}	x_{MO3}	x_{MO4}	x_{MO5}	x_{MO6}	x_{MO7}
Fairly (FA)	x_{FA1}	x_{FA2}	x_{FA3}	x_{FA4}	x_{FA5}	x_{FA6}	x_{FA7}
Strongly (ST)	x_{ST1}	x_{ST2}	x_{ST3}	x_{ST4}	x_{ST5}	x_{ST6}	x_{ST7}
Very Strongly (VS)	x_{VS1}	x_{VS2}	x_{VS3}	x_{VS4}	x_{VS5}	x_{VS6}	x_{VS7}
Extremely (EX)	x_{EX1}	x_{EX2}	x_{EX3}	x_{EX4}	x_{EX5}	x_{EX6}	x_{EX7}

For linguistic term EQ, numerical value k_{EQ}' can be calculated as follows:

$$k_{\mathrm{EQ}}' = \left[\frac{x_{\mathrm{EQ1}}}{x_{\mathrm{EQ1}} + \dots + x_{\mathrm{EQ7}}}\right] \times \mathrm{y}_1 + \left[\frac{x_{\mathrm{EQ2}}}{x_{\mathrm{EQ1}} + \dots + x_{\mathrm{EQ7}}}\right] \times \mathrm{y}_2 + \dots + \left[\frac{x_{\mathrm{EQ7}}}{x_{\mathrm{EQ1}} + \dots + x_{\mathrm{EQ7}}}\right] \times \mathrm{y}_7$$

The calculated k_{EQ}' is the associated original value (numerical value) of the linguistic term EQ. This procedure can be used to calculate the numerical values of the other six linguistic terms. The following generic Eq. (5.1) is constructed to estimate the numerical values of the linguistic terms in the discrete fuzzy sets.

$$k_X' = \sum_{b=1}^{n} \left\{ \left[\frac{x_b}{\sum_{b=1}^{n} x_b} \right] \times \mathrm{y}_b \right\} \tag{5.1}$$

where, X is the type of the linguistic term, k_X' is the original value (numerical value) of the linguistic term X, b is the element belonging to category 'y' of linguistic term X and n is the number of elements belonging to all the categories (y_1 to y_7) of linguistic term X.

The obtained numerical values for the seven linguistic terms are k_{EQ}', k_{SL}', k_{MO}', ..., k_{EX}'. Then normalised values can be calculated. Suppose EQ should have the highest value which is 1. The normalisation is carried out as follows:

$$\left[k_{\mathrm{EQ}}\, k_{\mathrm{SL}}\, k_{\mathrm{MO}} \dots k_{\mathrm{EX}}\right] = \left[\frac{k_{\mathrm{EQ}}'}{k_{\mathrm{EQ}}'} \frac{k_{\mathrm{SL}}'}{k_{\mathrm{EQ}}'} \frac{k_{\mathrm{MO}}'}{k_{\mathrm{EQ}}'} \dots \frac{k_{\mathrm{EX}}'}{k_{\mathrm{EQ}}'}\right]$$

Eq. (5.2) is developed to obtain the normalisation for the situations where a selected linguistic term takes the maximum value 1. Then the normalised value of k_X' (k_X) can be calculated.

$$k_X = \frac{k_X'}{k_b'} \tag{5.2}$$

where, k_b' is the numerical value of the linguistic term which should have the normalised value 1 (highest value).

5.4.2. Calculation of Relative Importance

The relative importance of the criteria should be carried out after the pairwise comparison process. This is achieved by taking into account k_X from Eq. (5.2) and constructing generic Eq. (5.3).

$$N_I = \sum_{X=1}^{n} \beta_X \times k_X \tag{5.3}$$

where, N_I is the relative importance of the criteria, β_X is the belief degree associated with the linguistic term X (e.g. 0.5 EQ, 0.5 SL).

5.4.3. Weighting Vector and Normalised Weighting Vector Calculation

After the calculation of relative importance, the fuzzy pairwise comparison matrix is converted into a single-value comparison matrix. Suppose the quantified judgement on pairs of criteria C_i and C_j are represented by a $n \times n$ single-value comparison matrix A (Pillay & Wang, 2003).

$$A = (a_{ij}) = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ . & . & \cdots & . \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \tag{5.4}$$

where, a_{ij} is the relative importance of criteria C_i and C_j.

The weighting vector of the single-value comparison matrix provides the priority ordering (weight), and the weighting value is a measure of consistency. To find the priority vector or the weight of each factor included in the priority ranking analysis, the weighting vector corresponding to the maximum weighting value is to be determined from matrix analysis.

In mathematical terms, the principal weighting vector is computed, and when normalised becomes the vector of priorities (weights). To reduce the excessive computing time needed to solve the problem exactly and due to the results of complex numbers, a good estimate of that vector can be obtained by dividing the elements of each column in the comparison matrix by the sum of that column (i.e. normalise the column) (Ung *et al.*, 2006). The elements in each resulting row are added and the sum is divided by the number of the elements in the row. This is a process of averaging over the normalised columns. Mathematically w_1 is calculated using Eq. (5.5):

$$w_1 = \frac{1}{n}\left[\left(\frac{a_{11}}{\sum_{i=1}^{n} a_{i1}}\right) + \left(\frac{a_{12}}{\sum_{i=1}^{n} a_{i2}}\right) + \ldots \left(\frac{a_{1n}}{\sum_{i=1}^{n} a_{in}}\right)\right] \tag{5.5}$$

where, w_1 is the weighting vector of element 1 of the pairwise comparison matrix.

The mathematical expression of the synthesisation is shown in Eq. (5.6).

$$w_k = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}} \qquad (k = 1,2,\ldots\ldots,n) \tag{5.6}$$

where, a_{ij} is the entry of row i and column j in a comparison matrix of order n and w_k is the weighting vector of a specific element k in the pairwise comparison matrix.

When numerous pairwise comparisons are evaluated, perfect consistency is difficult to achieve. In fact, some degree of inconsistency could be expected to exist in almost any set of pairwise comparisons. The AHP method provides a measure of the consistency for pairwise comparisons by introducing a consistency ratio (Anderson *et al.*, 2003). The ratio is designed in such a way that a value greater than 0.10 indicates an inconsistency in the pairwise judgements in question, meaning that the comparisons will have to be revaluated. The comparisons will be considered reasonable only if the consistency ratio is equal to or less than 0.10. An approximation of the ratio can be obtained using the algorithm described in Eq. (5.7):

$$CR = \frac{CI}{RI} \tag{5.7}$$

where, CR is the consistency ratio, and RI is the random index for the matrix size, n. The value of RI depends on the number of items being compared and is given in Table 5.3, and CI is the consistency index that can be obtained from Eq. (5.8).

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{5.8}$$

where, $\lambda_{\max}$ is the maximum weighting value of a $n \times n$ comparison matrix A. $\lambda_{\max}$ is calculated using Eq. (5.9).

$$\lambda_{\max} = \frac{\sum_{j=1}^{n} \frac{\sum_{k=1}^{n} w_k a_{jk}}{w_j}}{n} \tag{5.9}$$

Table 5.3: Average Random Index (RI) Values

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

where, n is the size of pairwise comparison matrix.

The normalised weighting vectors need to be calculated for lower level criteria after the weighting vector calculation. The similar procedure is implemented for the weighting vector calculation of the lower level criteria. Then the Normalised Weighting Vector (*NVW*) of each criterion is obtained by multiplying the weighting vectors of relevant associated upper level criterion.

5.4.4. Assessment of the Effectiveness of Each RCO

The matrices will be developed by using discrete fuzzy sets. After the calculation of importance, the effectiveness of each RCO for the identified major causes (causes with high risk estimation) in terms of failure likelihood, failure capability, failure recovery incapability and failure consequence probability will be estimated. The matrices will consequently be normalised to achieve the overall effectiveness of each identified RCO to minimise the risks by employing constructed Eq. (5.10):

$$NVE_{ij} = \frac{IE_{ij}}{\sum_{j=1}^{n} IE_{ij}} \cdot NVW_i \tag{5.10}$$

where, NVE_{ij} is the normalised value of the effectiveness index applied on RCO j to major cause i, NVW_i is the normalised weighting vector of major cause i in terms of failure likelihood or failure consequence probability or failure capability or failure recovery incapability, and IE_{ij} is the importance of the effectiveness index applied on RCO j to major cause i.

Each RCO is associated with four effectiveness indices evaluated with respect to failure likelihood, failure consequence probability, failure capability and failure recovery incapability. The total effectiveness of a specific RCO to a specific major cause is obtained by calculating the summation of these four indices. Suppose there are K major causes incorporated to produce SHV. The total effectiveness of a specific RCO j is acquired by modifying NVE_{ij} of Eq. (5.10) to represent failure likelihood, failure consequence probability, failure capability and failure recovery incapability and constructing new Eq. (5.11).

$$TE_{RCO_j} = \sum_{i=1}^{K} NEL_{ij} + \sum_{i=1}^{K} NEP_{ij} + \sum_{i=1}^{K} NEC_{ij} + \sum_{i=1}^{K} NEI_{ij} \tag{5.11}$$

where, TE_{RCO_j} is the total effectiveness of the RCO_j, NEL_{ij} is the normalised effectiveness index imposed on the RCO j to the i^{th} major cause in terms of failure likelihood, NEP_{ij} is the normalised effectiveness index imposed on the RCO j to the i^{th} major cause in terms of failure consequence probability, NEC_{ij} is the normalised effectiveness index imposed on the RCO j to the i^{th} major cause in terms of failure capability, and NEI_{ij} is the normalised effectiveness index imposed on the RCO j to the i^{th} major cause in terms of failure recovery incapability.

The normalised total effectiveness of each RCO can be calculated by developing Eq. (5.12).

$$NTE_{RCO_j} = \frac{TE_{RCO_j}}{\sum_{j=1}^{J} TE_{RCO_j}} \tag{5.12}$$

where, NTE_{RCO_j} is the normalised total effectiveness of RCO_j, J is the number of RCOs.

By using this technique, it is possible to estimate the effectiveness of RCOs to minimise the risk of each major cause; this can be said to be the major advantage of this developed technique. This technique is also suitable for applications where there are subjective judgements available.

5.5. Case Study

Referring to the AHP structure of failure modelling, it can be said that five failure events (Level 3) have great impact on causing SHV. The main aim of this section is to demonstrate how the proposed methodology can be applied to evaluate RCOs to minimise the risks of SHV. This can be achieved by using the following steps. The data is obtained based on four experts in the area (two from industry and two from academia) based on a fishing vessel (Section 5.1).

5.5.1. Modelling of Linguistic Terms (*Step 1*)

Seven linguistic terms are adopted to describe the relative importance of the criteria in each level. They are, namely, Equally (EQ), Slightly (SL), Moderately (MO), Fairly (FA), Strongly (ST), Very Strongly (VS) and Extremely (EX). Table 5.4 describes the definitions of the linguistic terms when applied in a pairwise comparison matrix.

Table 5.4: The Definitions of Linguistic Terms Describing the Relative Importance

Linguistic Terms	Definition
Equally (EQ)	Both equally important

Slightly (SL)	Left slightly less important than top
Moderately (MO)	Left moderately less important than top
Fairly (FA)	Left fairly less important than top
Strongly (ST)	Left strongly less important than top
Very Strongly (VS)	Left very strongly less important than top
Extremely (EX)	Left extremely less important than top

These seven linguistic terms are modelled by using discrete fuzzy sets. There are seven categories in the discrete fuzzy sets table and their importance values range from 0 to 1. The modelling process is shown in Table 5.5.

Table 5.5: Modelling of Linguistic Terms using Discrete Fuzzy Sets

Linguistic Terms	**0**	**1/6**	**1/3**	**1/2**	**2/3**	**5/6**	**1**
Equally (EQ)	0	0	0	0	0	0.25	1
Slightly (SL)	0	0	0	0	0.75	1	0.25
Moderately (MO)	0	0	0	0.75	1	0.25	0
Fairly (FA)	0	0	0.5	1	0.5	0	0
Strongly (ST)	0	0.25	1	0.75	0	0	0
Very Strongly (VS)	0.25	1	0.75	0	0	0	0
Extremely (EX)	1	0.25	0	0	0	0	0

The linguistic terms modelled by discrete fuzzy sets will be applied to determine the relative importance of the risk parameters of failure likelihood, failure capability, failure recovery incapability and failure consequence probability. They will also be employed to describe the relationship between the criteria in each of Levels 3 and 4 in terms of the four risk parameters defined.

5.5.2. Calculation of Numerical Relationship between Each Linguistic Term (*Step 2*)

The numerical relationship of each linguistic term is achieved by inputting the data in Table 5.5 to the developed generic algorithm in Eq. (5.1).

$$k_{EQ}' = \left(\frac{0.25}{0.25+1}\right)\times\frac{5}{6}+\left(\frac{1}{0.25+1}\right)\times 1 = 0.967$$

$$k_{SL}' = \left(\frac{0.75}{0.75+1+0.25}\right)\times\frac{2}{3}+\left(\frac{1}{0.75+1+0.25}\right)\times\frac{5}{6}+\left(\frac{0.25}{0.75+1+0.25}\right)\times 1 = 0.792$$

$$k_{MO}' = \left(\frac{0.75}{0.75+1+0.25}\right)\times\frac{1}{2}+\left(\frac{1}{0.75+1+0.25}\right)\times\frac{2}{3}+\left(\frac{0.25}{0.75+1+0.25}\right)\times\frac{5}{6} = 0.625$$

$$k_{FA}' = \left(\frac{0.5}{0.5+1+0.5}\right)\times\frac{1}{3}+\left(\frac{1}{0.5+1+0.5}\right)\times\frac{1}{2}+\left(\frac{0.5}{0.5+1+0.5}\right)\times\frac{2}{3} = 0.500$$

$$k_{ST}' = \left(\frac{0.25}{0.25+1+0.75}\right)\times\frac{1}{6}+\left(\frac{1}{0.25+1+0.75}\right)\times\frac{1}{3}+\left(\frac{0.75}{0.25+1+0.75}\right)\times\frac{1}{2} = 0.375$$

$$k_{VS}' = \left(\frac{0.25}{0.25+1+0.75}\right)\times 0+\left(\frac{1}{0.25+1+0.75}\right)\times\frac{1}{6}+\left(\frac{0.75}{0.25+1+0.75}\right)\times\frac{1}{3} = 0.208$$

$$k_{EX}' = \left(\frac{1}{1+0.25}\right)\times 0+\left(\frac{0.25}{1+0.25}\right)\times\frac{1}{6} = 0.033$$

Normalisation is carried out to obtain the normalised numerical relationship of each linguistic term. This can be achieved by using Eq. (5.2).

$$[\; k_{EQ} \quad k_{SL} \quad k_{MO} \quad k_{FA} \quad k_{ST} \quad k_{VS} \quad k_{EX} \;]$$

$$= \left[\frac{0.967}{0.967} \quad \frac{0.792}{0.967} \quad \frac{0.625}{0.967} \quad \frac{0.500}{0.967} \quad \frac{0.375}{0.967} \quad \frac{0.208}{0.967} \quad \frac{0.033}{0.967}\right]$$

$$= [\; 1.00 \quad 0.82 \quad 0.65 \quad 0.52 \quad 0.39 \quad 0.22 \quad 0.03 \;]$$

Table 5.6: Normalised Numerical Values

k_{EQ}	k_{SL}	k_{MO}	k_{FA}	k_{ST}	k_{VS}	k_{EX}
1.00	0.82	0.65	0.52	0.39	0.22	0.03

Linguistic term EQ has the highest normalised numerical value and linguistic term EX has the lowest numerical value (Table 5.6). These normalised numerical values are employed for the pairwise comparison of the four risk parameters. This is carried out in Step 3.

5.5.3. Calculation of the Relative Importance of Failure Likelihood, Failure Capability, Failure Recovery Incapability and Failure Consequence Probability (*Step 3*)

The relative importance of failure likelihood, failure capability, failure recovery incapability and failure consequence probability is obtained by using the normalised numerical values of linguistic terms. It is noted that the risk parameter to be compared with the others is the one with the least relative importance which is obtained based on expert judgements. Tables 5.7, 5.8 and 5.9 show the pairwise comparisons between the four risk parameters (Level 2) by using fuzzy set theory.

Table 5.7: The Pairwise Comparisons of Failure Recovery Incapability, Failure Likelihood, Failure Capability and Failure Consequence Probability

	Failure Likelihood	**Failure Capability**	**Failure Recovery Incapability**	**Failure Consequence Probability**
Failure Recovery Incapability	0.5 FA 0.5 ST	0.6 SL 0.4 MO	1.0 EQ	0.3 VS 0.7 EX

Table 5.8: The Pairwise Comparisons of Failure Capability, Failure Likelihood and Failure Consequence Probability

	Failure Likelihood	**Failure Capability**	**Failure Consequence Probability**
Failure Capability	0.2 MO 0.8 FA	1.0 EQ	0.45 ST 0.55 VS

Table 5.9: The Pairwise Comparisons of Failure Likelihood and Failure Consequence Probability

	Failure Likelihood	**Failure Consequence Probability**
Failure Likelihood	1.0 EQ	0.25 SL

		0.75 MO

The calculation of relative importance of each risk parameter can be carried out by using Eq. (5.3). This is conducted to convert fuzzy expressions in the pairwise comparisons in Tables 5.7, 5.8 and 5.9 to a single crisp value. The importance of fuzzy expression 0.6 SL 0.4 MO in Table 5.7 can be calculated as follows:

$$N_{IC} = 0.6 \times 0.82 + 0.4 \times 0.65 = 0.752$$

By using the same procedure crisp importance values can be obtained for each comparison of risk parameters. They have been given in Tables 5.10, 5.11 and 5.12.

Table 5.10: The Crisp Importance Values of Failure Recovery Incapability, Failure Likelihood, Failure Capability and Failure Consequence Probability

	Failure Likelihood	**Failure Capability**	**Failure Recovery Incapability**	**Failure Consequence Probability**
Failure Recovery Incapability	0.455	0.752	1.000	0.087

Table 5.11: The Crisp Importance Values of Failure Capability, Failure Likelihood and Failure Consequence Probability

	Failure Likelihood	**Failure Capability**	**Failure Consequence Probability**
Failure Capability	0.546	1.000	0.297

Table 5.12: The Crisp Importance Values of Failure Likelihood and Failure Consequence Probability

	Failure Likelihood	**Failure Consequence Probability**
Failure Likelihood	1.000	0.693

5.5.4. Weighting Vector Calculation of Failure Likelihood, Failure Capability, Failure Recovery Incapability and Failure Consequence Probability (*Step 4*)

Since there are four risk parameters which are evaluated in this model, a 4 × 4 pairwise comparison matrix is constructed. *A(ILCP)* is the pairwise matrix with the crisp importance values which expresses the quantified judgement with regard to the relative importance of failure likelihood, failure capability, failure recovery incapability and failure consequence probability.

$$A(ILCP) = \begin{array}{c} \\ I \\ L \\ C \\ P \end{array} \begin{array}{c} \begin{array}{cccc} I & L & C & P \end{array} \\ \begin{bmatrix} 1.000 & 0.455 & 0.752 & 0.087 \\ 2.198 & 1.000 & 1.832 & 0.693 \\ 1.330 & 0.546 & 1.000 & 0.297 \\ 11.494 & 1.443 & 3.367 & 1.000 \end{bmatrix} \end{array}$$

where, *I* is the failure recovery incapability, *L* is the failure likelihood, *C* is the failure capability and *P* is the failure consequence probability.

The weighting vector representing the priority of each risk parameter in the pairwise comparison matrix, in terms of its contribution to the overall risk, is achieved by using Eq. (5.6):

$$w_1 = \frac{1}{4}\sum_{j=1}^{4}\frac{a_{1j}}{\sum_{i=1}^{4} a_{ij}} = \frac{1}{4}\times\begin{bmatrix}\left(\dfrac{1.000}{1.000+2.198+1.330+11.494}\right)+\left(\dfrac{0.455}{0.455+1.000+0.546+1.443}\right)+ \\ \left(\dfrac{0.752}{0.752+1.832+1.000+3.367}\right)+\left(\dfrac{0.087}{0.087+0.693+0.297+1.000}\right)\end{bmatrix}$$

$$w_1 = 0.0860$$

$$w_2 = \frac{1}{4}\sum_{j=1}^{4}\frac{a_{2j}}{\sum_{i=1}^{4} a_{ij}} = \frac{1}{4}\times\begin{bmatrix}\left(\dfrac{2.198}{1.000+2.198+1.330+11.494}\right)+\left(\dfrac{1.000}{0.455+1.000+0.546+1.443}\right)+ \\ \left(\dfrac{1.832}{0.752+1.832+1.000+3.367}\right)+\left(\dfrac{0.693}{0.087+0.693+0.297+1.000}\right)\end{bmatrix}$$

$$w_2 = 0.2563$$

$$w_3 = \frac{1}{4}\sum_{j=1}^{4}\frac{a_{3j}}{\sum_{i=1}^{4}a_{ij}} = \frac{1}{4}\times\left[\begin{array}{l}\left(\frac{1.330}{1.000+2.198+1.330+11.494}\right)+\left(\frac{0.546}{0.455+1.000+0.546+1.443}\right)+\\ \left(\frac{1.000}{0.752+1.832+1.000+3.367}\right)+\left(\frac{0.297}{0.087+0.693+0.297+1.000}\right)\end{array}\right]$$

$$w_3 = 0.1325$$

$$w_4 = \frac{1}{4}\sum_{j=1}^{4}\frac{a_{4j}}{\sum_{i=1}^{4}a_{ij}} = \frac{1}{4}\times\left[\begin{array}{l}\left(\frac{11.494}{1.000+2.198+1.330+11.494}\right)+\left(\frac{1.443}{0.455+1.000+0.546+1.443}\right)+\\ \left(\frac{3.367}{0.752+1.832+1.000+3.367}\right)+\left(\frac{1.000}{0.087+0.693+0.297+1.000}\right)\end{array}\right]$$

$$w_4 = 0.5252$$

The weighting vector matrix of the Level 2, *W(ILCP)* can be shown as follows:

$$W(ILCP) = \begin{array}{c} I \\ L \\ C \\ P \end{array}\begin{bmatrix} 0.0860 \\ 0.2563 \\ 0.1325 \\ 0.5252 \end{bmatrix}$$

It is necessary to check if the pairwise comparison of the four risk parameters achieves the required consistency. This is carried out as follows:

Firstly $\lambda_{\max}$ is calculated using Eq. (5.9).

$$\lambda_{\max} = \frac{4.045+4.105+4.096+4.436}{4} = 4.171$$

Secondly Consistency Index *(CI)* is obtained using Eq. (5.8).

$$CI = \frac{4.171-4}{4-1} = 0.057$$

Finally Consistency Ratio *(CR)* is calculated employing Eq. (5.7) and Table 5.3.

$$CR = \frac{0.057}{0.90} = 0.063$$

Since the obtained *CR* value is less than 0.10, it can be said that the pairwise comparisons have achieved the consistency.

5.5.5. Pairwise Comparison and Normalised Weighting Vector Calculation of All Failure Events in terms of Failure Likelihood, Failure Capability, Failure Recovery Incapability and Failure Consequence Probability (*Step 5*)

In this step failure likelihood, failure capability, failure recovery incapability and failure consequence probability of Level 3 will be evaluated. To achieve this task the procedure which was implemented in Steps 3-4 will be repeated. Tables 5.13-5.16 show the fuzzy pairwise comparisons of the failure events (Level 3) in terms of failure likelihood risk parameter.

Table 5.13: The Pairwise Comparisons between the Thrust Block Failure and Propeller Failure, Shafting Failure, Engine Component Failure and Hull Failure

	Propeller Failure	Shafting Failure	Thrust Block Failure	Engine Component Failure	Hull Failure
Thrust Block Failure	0.8 EX 0.2 VS	0.5 VS 0.5 ST	1.0 EQ	0.3 VS 0.7 ST	0.4 FA 0.6 MO

Table 5.14: The Pairwise Comparisons between the Hull Failure and Propeller Failure, Shafting Failure and Engine Component Failure

	Propeller Failure	Shafting Failure	Engine Component Failure	Hull Failure
Hull Failure	0.6 EX 0.4 VS	0.4 VS 0.6 ST	0.7 ST 0.3 FA	1.0 EQ

Table 5.15: The Pairwise Comparisons between the Engine Component Failure and Propeller Failure and Shafting Failure

	Propeller Failure	Shafting Failure	Engine Component Failure
Engine Component Failure	0.35 EX 0.65 VS	0.95 ST 0.05 FA	1.0 EQ

Table 5.16: The Pairwise Comparisons between the Shafting Failure and Propeller Failure

	Propeller Failure	Shafting Failure
Shafting Failure	0.5 FA 0.5 MO	1.0 EQ

Subsequently, the fuzzy pairwise comparisons described in Tables 5.13-5.16 will be used to obtain the importance of each failure event in terms of failure likelihood. This is achieved by using Eq. (5.3) and given in Tables 5.17-5.20.

Table 5.17: The Crisp Importance Values of Pairwise Comparisons between the Thrust Block Failure and Propeller Failure, Shafting Failure, Engine Component Failure and Hull Failure

	Propeller Failure	Shafting Failure	Thrust Block Failure	Engine Component Failure	Hull Failure
Thrust Block Failure	0.068	0.305	1.000	0.339	0.598

Table 5.18: The Crisp Importance Values of Pairwise Comparisons between the Hull Failure and Propeller Failure, Shafting Failure and Engine Component Failure

	Propeller Failure	Shafting Failure	Engine Component Failure	Hull Failure
Hull Failure	0.106	0.322	0.429	1.000

Table 5.19: The Crisp Importance Values of Pairwise Comparisons between the Engine Component Failure and Propeller Failure and Shafting Failure

	Propeller Failure	Shafting Failure	Engine Component Failure
Engine Component Failure	0.154	0.397	1.000

Table 5.20: The Crisp Importance Values of Pairwise Comparisons between the Shafting Failure and Propeller Failure

	Propeller Failure	Shafting Failure
Shafting Failure	0.585	1.000

Therefore, the pairwise comparison matrix can be developed as follows:

$$A(LF) = \begin{array}{c} \\ PF \\ SF \\ TBF \\ ECF \\ HF \end{array} \begin{array}{c} \begin{array}{ccccc} PF & SF & TBF & ECF & HF \end{array} \\ \begin{bmatrix} 1.000 & 1.709 & 14.706 & 6.494 & 9.434 \\ 0.585 & 1.000 & 3.279 & 2.519 & 3.106 \\ 0.068 & 0.305 & 1.000 & 0.339 & 0.598 \\ 0.154 & 0.397 & 2.950 & 1.000 & 2.331 \\ 0.106 & 0.322 & 1.672 & 0.429 & 1.000 \end{bmatrix} \end{array}$$

where, *A(LF)* is the pairwise comparison matrix of the failure events in Level 3 in terms of failure likelihood, PF is the propeller failure, SF is the shafting failure, TBF is the thrust block failure, ECF is the engine component failure and HF is the hull failure.

The weighting vector *W(LF)* and normalised weighting vector *W(NLF)* matrices of the failure events in Level 3 in terms of failure likelihood can be obtained by:

$$W(LF) = \begin{array}{c} PF \\ SF \\ TBF \\ ECF \\ HF \end{array} \begin{bmatrix} 0.5558 \\ 0.2270 \\ 0.0455 \\ 0.1092 \\ 0.0626 \end{bmatrix} \qquad W(NLF) = W(LF) \times 0.2563 = \begin{array}{c} PF \\ SF \\ TBF \\ ECF \\ HF \end{array} \begin{bmatrix} 0.1424 \\ 0.0582 \\ 0.0117 \\ 0.0280 \\ 0.0160 \end{bmatrix}$$

Table 5.21: The Weighting Vectors and Normalised Weighting Vectors of Each Failure Event in Terms of Failure Likelihood

Failure Event	Weighting Vector	Normalised Weighting Vector
Propeller Failure	0.5558	0.1424
Shafting Failure	0.2270	0.0582
Thrust Block Failure	0.0455	0.0117

Engine Component Failure	0.1092	0.0280
Hull Failure	0.0626	0.0160

It can be seen from Tables 5.17-5.21 and *W(NLF)* that the less important failure events described by the linguistic terms have lower normalised weighting vectors. This is consistent with the expert judgements. In order to find out whether the pairwise comparisons of the failure events achieve the acceptable consistency, *CR* is obtained as in Step 4 using Eqs. (5.7), (5.8) and (5.9) and Table 5.3.

$$\lambda_{\max} = \frac{5.240 + 5.158 + 4.991 + 5.173 + 5.072}{5} = 5.127$$

$$CI = \frac{5.127 - 5}{5 - 1} = 0.032$$

$$CR = \frac{0.032}{1.12} = 0.028$$

Since the obtained *CR* value is less than 0.10, the pairwise comparisons have achieved the consistency.

The pairwise comparisons of the failure events in terms of failure capability, failure recovery incapability and failure consequence probability (Level 3) are carried out in a similar way. Tables 5.22-5.24 show the results, and the crisp importance values of the fuzzy pairwise comparisons of the failure events are shown in Appendices 5.1, 5.2 and 5.3.

Table 5.22: The Weighting Vectors and Normalised Weighting Vectors of Each Failure Event in Terms of Failure Capability

Failure Event	Weighting Vector	Normalised Weighting Vector
Propeller Failure	0.1029	0.0136
Shafting Failure	0.1630	0.0216
Thrust Block Failure	0.0772	0.0102
Engine Component Failure	0.2411	0.0319
Hull Failure	0.4158	0.0551

Table 5.23: The Weighting Vectors and Normalised Weighting Vectors of Each Failure Event in Terms of Failure Recovery Incapability

Failure Event	Weighting Vector	Normalised Weighting Vector
Propeller Failure	0.4569	0.0393
Shafting Failure	0.0904	0.0078
Thrust Block Failure	0.0655	0.0056
Engine Component Failure	0.1631	0.0140
Hull Failure	0.2241	0.0193

Table 5.24: The Weighting Vectors and Normalised Weighting Vectors of Each Failure Event in Terms of Failure Consequence Probability

Failure Event	Weighting Vector	Normalised Weighting Vector
Propeller Failure	0.4801	0.2522
Shafting Failure	0.1447	0.0760
Thrust Block Failure	0.0591	0.0311
Engine Component Failure	0.2287	0.1201
Hull Failure	0.0873	0.0459

5.5.6. Pairwise Comparison and Normalised Weighting Vector Calculation of All Causes in terms of Failure Likelihood, Failure Capability, Failure Recovery Incapability and Failure Consequence Probability (*Step 6*)

Criteria in Level 4 can be assessed by using the same procedure which was employed in Step 5. Table 5.25 shows the fuzzy pairwise comparisons between the causes in the propeller failure event in terms of failure likelihood. The crisp importance values of such pairwise comparisons for the propeller failure event are given in Table 5.26. The crisp importance values of the causes for all the other failure events are presented in Appendix 5.4.

Table 5.25: The Pairwise Comparisons between the Cloud Cavitation and Back Bubble Cavitation, Sheet Cavitation, Tip/Hub Vortex Cavitation, Propeller-Hull Vortex Cavitation and Physical Damages

	Back Bubble Cavitation	Sheet Cavitation	Cloud Cavitation	Tip/Hub Vortex Cavitation	Propeller-Hull Vortex Cavitation	Physical Damages
Cloud Cavitation	0.25 MO 0.75 SL	0.9 MO 0.1 SL	1.0 EQ	0.35 EX 0.65 VS	0.4 VS 0.6 ST	0.7 FA 0.3 MO

Table 5.26: The Crisp Importance Values of Pairwise Comparisons between the Cloud Cavitation and Back Bubble Cavitation, Sheet Cavitation, Tip/Hub Vortex Cavitation, Propeller-Hull Vortex Cavitation and Physical Damages

	Back Bubble Cavitation	Sheet Cavitation	Cloud Cavitation	Tip/Hub Vortex Cavitation	Propeller-Hull Vortex Cavitation	Physical Damages
Cloud Cavitation	0.778	0.667	1.000	0.154	0.322	0.559

The pairwise comparison matrix showing the quantified relationship between the causes in the propeller failure event is developed as indicated in *A(PFL)*. Then the weighting vector *W(PFL)* and normalised weighting vector *W(NPFL)* can be obtained.

$$A(PFL) = \begin{array}{c} \\ BBC \\ SC \\ CC \\ TVC \\ PVC \\ PD \end{array} \begin{array}{c} \begin{array}{cccccc} BBC & SC & CC & TVC & PVC & PD \end{array} \\ \begin{bmatrix} 1.000 & 0.735 & 1.285 & 0.201 & 0.356 & 0.579 \\ 1.361 & 1.000 & 1.499 & 0.305 & 0.442 & 0.795 \\ 0.778 & 0.667 & 1.000 & 0.154 & 0.322 & 0.559 \\ 4.975 & 3.279 & 6.494 & 1.000 & 1.898 & 2.404 \\ 2.809 & 2.262 & 3.106 & 0.527 & 1.000 & 1.876 \\ 1.727 & 1.258 & 1.789 & 0.416 & 0.533 & 1.000 \end{bmatrix} \end{array}$$

$$W(PFL) = \begin{array}{c} BBC \\ SC \\ CC \\ TVC \\ PVC \\ PD \end{array} \begin{bmatrix} 0.0799 \\ 0.1066 \\ 0.0679 \\ 0.3853 \\ 0.2258 \\ 0.1345 \end{bmatrix} \quad W(NPFL) = W(PFL) \times 0.1424 = \begin{array}{c} BBC \\ SC \\ CC \\ TVC \\ PVC \\ PD \end{array} \begin{bmatrix} 0.0114 \\ 0.0152 \\ 0.0097 \\ 0.0549 \\ 0.0322 \\ 0.0192 \end{bmatrix}$$

where, BBC is the back bubble cavitation, SC is the sheet cavitation, CC is the cloud cavitation, TVC is the tip/hub vortex cavitation, PVC is the propeller/hull vortex cavitation, and PD is the physical damages.

The quantified pairwise comparisons and their weighting vectors between the causes in the remaining four failure events can be obtained in a similar way. The weighting vectors and normalised weighting vectors of the causes in terms of failure likelihood of each failure event are shown in Table 5.27.

Table 5.27: The Weighting Vectors and Normalised Weighting Vectors of Causes in Failure Events in Terms of Failure Likelihood

Failures	Cause No.	Weighting Vector	Normalised Weighting Vector
Propeller Failure	1	0.0799	0.0114
	2	0.1066	0.0152
	3	0.0679	0.0097
	4	0.3853	0.0549
	5	0.2258	0.0322
	6	0.1345	0.0192
Shafting Failure	1	0.4956	0.0288
	2	0.0505	0.0029
	3	0.2525	0.0147
	4	0.1283	0.0075
	5	0.0730	0.0042
Thrust Block Failure	1	0.1413	0.0016
	2	0.4081	0.0048
	3	0.2654	0.0031
	4	0.1852	0.0022
Engine Component Failure	1	0.0709	0.0020
	2	0.3941	0.0110

	3	0.1123	0.0031
	4	0.1640	0.0046
	5	0.2587	0.0072
Hull Failure	1	0.6152	0.0099
	2	0.1042	0.0017
	3	0.2241	0.0036
	4	0.0564	0.0009

The weighting vectors and normalised weighting vectors of the causes in terms of failure capability, failure recovery incapability and failure consequence probability are obtained by employing the same procedure. The crisp importance values of the causes of the failure events in terms of failure capability, failure recovery incapability and failure consequence probability are shown in Appendices 5.5-5.7. The corresponding weighting vectors and normalised weighting vectors are given in Tables 5.28-5.30.

Table 5.28: The Weighting Vectors and Normalised Weighting Vectors of Causes in Failure Events in Terms of Failure Capability

Failures	Cause No.	Weighting Vector	Normalised Weighting Vector
Propeller Failure	1	0.0752	0.0010
	2	0.0987	0.0013
	3	0.0603	0.0008
	4	0.1878	0.0026
	5	0.1518	0.0021
	6	0.4262	0.0058
Shafting Failure	1	0.1709	0.0037
	2	0.0506	0.0011
	3	0.2856	0.0062
	4	0.0954	0.0021
	5	0.3974	0.0086
Thrust Block Failure	1	0.0694	0.0007
	2	0.2766	0.0028
	3	0.5376	0.0055
	4	0.1164	0.0012
Engine Component Failure	1	0.0560	0.0018
	2	0.2384	0.0076
	3	0.4665	0.0149

	4	0.0891	0.0028
	5	0.1500	0.0048
Hull Failure	1	0.2863	0.0158
	2	0.4659	0.0257
	3	0.0903	0.0050
	4	0.1575	0.0087

Table 5.29: The Weighting Vectors and Normalised Weighting Vectors of Causes in Failure Events in Terms of Failure Recovery Incapability

Failures	Cause No.	Weighting Vector	Normalised Weighting Vector
Propeller Failure	1	0.0867	0.0034
	2	0.1224	0.0048
	3	0.0699	0.0027
	4	0.1625	0.0064
	5	0.2204	0.0087
	6	0.3380	0.0133
Shafting Failure	1	0.1471	0.0011
	2	0.0947	0.0007
	3	0.4272	0.0033
	4	0.0629	0.0005
	5	0.2682	0.0021
Thrust Block Failure	1	0.1125	0.0006
	2	0.2718	0.0015
	3	0.5420	0.0031
	4	0.0738	0.0004
Engine Component Failure	1	0.0637	0.0009
	2	0.2494	0.0035
	3	0.1007	0.0014
	4	0.1568	0.0022
	5	0.4294	0.0060
Hull Failure	1	0.1504	0.0029
	2	0.4840	0.0093
	3	0.0760	0.0015
	4	0.2895	0.0056

Table 5.30: The Weighting Vectors and Normalised Weighting Vectors of Causes in Failure Events in Terms of Failure Consequence Probability

Failures	Cause No.	Weighting Vector	Normalised Weighting Vector
Propeller Failure	1	0.0818	0.0206
	2	0.1081	0.0273
	3	0.0689	0.0174
	4	0.3760	0.0948
	5	0.2293	0.0578
	6	0.1359	0.0343
Shafting Failure	1	0.4935	0.0375
	2	0.0496	0.0038
	3	0.2550	0.0194
	4	0.1278	0.0097
	5	0.0741	0.0056
Thrust Block Failure	1	0.1412	0.0044
	2	0.4054	0.0126
	3	0.2686	0.0083
	4	0.1848	0.0057
Engine Component Failure	1	0.0719	0.0086
	2	0.3844	0.0462
	3	0.1162	0.0140
	4	0.1663	0.0200
	5	0.2612	0.0314
Hull Failure	1	0.6136	0.0281
	2	0.1023	0.0047
	3	0.2262	0.0104
	4	0.0580	0.0027

5.5.7. Estimation of Overall Risk of Each Cause in terms of Failure Likelihood, Failure Capability, Failure Recovery Incapability and Failure Consequence Probability *(Step 7)*

In this step the overall risk of each cause is estimated in terms of failure likelihood, failure capability, failure recovery incapability and failure consequence probability. Such overall risk is estimated by adding the normalised weighting vectors of each cause in terms of the four risk parameters as described in Tables

5.27-5.30. The risk ranking for all the causes is obtained based on the overall risk estimation of each cause shown in Table 5.31.

Table 5.31: Overall Risk Estimation and Risk Ranking of Each Cause

Failures	Cause No.	L	C	I	P	Overall Risk	Risk Rank
Propeller Failure	1	0.0114	0.0010	0.0034	0.0206	0.0364	11
	2	0.0152	0.0013	0.0048	0.0273	0.0486	08
	3	0.0097	0.0008	0.0027	0.0174	0.0306	13
	4	0.0549	0.0026	0.0064	0.0948	0.1587	01
	5	0.0322	0.0021	0.0087	0.0578	0.1008	02
	6	0.0192	0.0058	0.0133	0.0343	0.0726	03
Shafting Failure	1	0.0288	0.0037	0.0011	0.0375	0.0711	04
	2	0.0029	0.0011	0.0007	0.0038	0.0085	23
	3	0.0147	0.0062	0.0033	0.0194	0.0436	09
	4	0.0075	0.0021	0.0005	0.0097	0.0198	19
	5	0.0042	0.0086	0.0021	0.0056	0.0204	17
Thrust Block Failure	1	0.0016	0.0007	0.0006	0.0044	0.0073	24
	2	0.0048	0.0028	0.0015	0.0126	0.0217	15
	3	0.0031	0.0055	0.0031	0.0083	0.0199	18
	4	0.0022	0.0012	0.0004	0.0057	0.0095	22
Engine Component Failure	1	0.0020	0.0018	0.0009	0.0086	0.0133	21
	2	0.0110	0.0076	0.0035	0.0462	0.0683	05
	3	0.0031	0.0149	0.0014	0.0140	0.0334	12
	4	0.0046	0.0028	0.0022	0.0200	0.0296	14
	5	0.0072	0.0048	0.0060	0.0314	0.0494	07
Hull Failure	1	0.0099	0.0158	0.0029	0.0281	0.0567	06
	2	0.0017	0.0257	0.0093	0.0047	0.0414	10
	3	0.0036	0.0050	0.0015	0.0104	0.0205	16
	4	0.0009	0.0087	0.0056	0.0027	0.0179	20

It is obvious from the results that causes 4, 5, 6 of the propeller failure, cause 1 of the shafting system, cause 2 of the engine component failure and cause 1 of the hull failure are the major contributors to SHV. This is because the overall risk estimates of those causes, in terms of the four risk parameters, are relatively or extremely higher than the others. Also the summation of risk estimates of those causes is 0.5282 which accounts for more than 50% of the total risk of all the causes. To minimise those six causes appropriate RCOs should be studied; this is done in the next step.

5.5.8. Identification of RCOs, Calculation of their Effectiveness and List of Preferences (*Step 8*)

Five RCOs are studied to minimise the risks of major causes. Table 5.32 shows the identified RCOs.

Table 5.32: Risk Control Options

RCO No.	Types of RCOs
1	Regular inspection
2	Carry out maintenance activities
3	Minimise causes by design and manufacture
4	Use detuners or dampers or anti vibration systems
5	Install warning devices (audio and visual alarms, indications, etc.)

The effectiveness of each RCO is assessed by using discrete fuzzy sets. The seven linguistic terms explaining the levels of the effectiveness have been obtained. They are, namely, Completely Effective (CE), Greatly Effective (GE), Averagely Effective (AE), Effective (EF), Moderately Effective (ME), Slightly Effective (SE), and Least Effective (LE). Their definitions are shown in Table 5.33.

Table 5.33: The Definitions of Linguistic Terms Describing the Levels of Effectiveness

Linguistic Terms	**Definition**
Completely Effective (CE)	The RCO used is completely effective in reduction of risks
Greatly Effective (GE)	The RCO used is greatly effective in reduction of risks
Averagely Effective (AE)	The RCO used is averagely effective in reduction of risks
Effective (EF)	The RCO used is effective in reduction of risks
Moderately Effective (ME)	The RCO used is moderately effective in reduction of risks
Slightly Effective (SE)	The RCO used is slightly effective in reduction of risks
Least Effective (LE)	The RCO used is least effective in reduction of risks

The seven linguistic terms are modelled by using discrete fuzzy sets. The modelling process is shown in Table 5.34.

Table 5.34: Modelling of Linguistic Terms using Discrete Fuzzy Sets

Linguistic Terms	**0**	**1/6**	**1/3**	**1/2**	**2/3**	**5/6**	**1**
Completely Effective (CE)	0	0	0	0	0	0.25	1
Greatly Effective (GE)	0	0	0	0	0.75	1	0.25
Averagely Effective (AE)	0	0	0	0.75	1	0.25	0
Effective (EF)	0	0	0.5	1	0.5	0	0
Moderately Effective (ME)	0	0.25	1	0.75	0	0	0
Slightly Effective (SE)	0.25	1	0.75	0	0	0	0
Least Effective (LE)	1	0.25	0	0	0	0	0

The numerical relationship between the linguistic terms is obtained by inputting the data in Table 5.34 to Eq. (5.1). The normalised numerical values are calculated by using Eq. (5.2) and shown in Table 5.35.

Table 5.35: Normalised Numerical Values

k_{CE}	k_{GE}	k_{AE}	k_{EF}	k_{ME}	k_{SE}	k_{LE}
1.00	0.82	0.65	0.52	0.39	0.22	0.03

These numerical values are used to calculate the effectiveness of each RCO. The assessment process is started by analysing the RCO effectiveness on the major causes of propeller failure in terms of the failure likelihood risk parameter. Table 5.36 presents the fuzzy expressions describing the level of effectiveness of each RCO, based on expert judgements, in terms of failure likelihood for the three identified major causes of propeller failure.

Table 5.36: Fuzzy Expressions Describing the Level of Effectiveness of Each RCO in Terms of Failure Likelihood of Propeller Failure

Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Cause 4	0.6 GE 0.4 AE	0.95 GE 0.05 AE	1.0 CE	0.2 SE 0.8 LE	1.0 LE
Cause 5	0.6 GE 0.4 AE	0.95 GE 0.05 AE	1.0 CE	0.2 SE 0.8 LE	1.0 LE
Cause 6	0.7 AE	0.9 GE	0.85 GE	1.0 LE	1.0 LE

	0.3 EF	0.1 AE	0.15 AE		

By using Eq. (5.3) the crisp importance value (or effectiveness) of each RCO can be calculated for all the six causes under consideration. Such values are shown in Table 5.37 for the three causes of propeller failure and Appendix 5.8 for the other three causes.

Table 5.37: Crisp Importance Values of RCOs for the Three Causes of Propeller Failure

Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Cause 4	0.752	0.812	1.000	0.068	0.030
Cause 5	0.752	0.812	1.000	0.068	0.030
Cause 6	0.611	0.803	0.795	0.030	1.000

The quantified data in Table 5.37 and Appendix 5.8 is converted into normalised results by using Eq. (5.10). Each value of NVW_i in Eq. (5.10) is obtained from Table 5.31. The normalised results of the effectiveness of each RCO in terms of failure likelihood are shown in Table 5.38.

Table 5.38: Normalised Results of Effectiveness of Each RCO in Terms of Failure Likelihood

Failure Type	Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Propeller Failure	4	0.0155	0.0167	0.0206	0.0014	0.0006
	5	0.0091	0.0098	0.0121	0.0008	0.0004
	6	0.0036	0.0048	0.0047	0.0002	0.0059
Shafting Failure	1	0.0066	0.0066	0.0066	0.0038	0.0053
Engine Component Failure	2	0.0028	0.0028	0.0028	0.0019	0.0008
Hull Failure	1	0.0031	0.0020	0.0044	0.0001	0.0004

The same procedure has been implemented separately for failure consequence probability, failure capability and failure recovery incapability, to calculate the normalised results of effectiveness of each RCO for the six causes under consideration. They are shown in Appendices 5.9-5.12.

The rankings of the RCOs are obtained based on the normalised results of their effectiveness in terms of the four risk parameters (Table 5.38 and Appendix 5.12). The total effectiveness of each RCO in terms of failure likelihood, failure capability, failure recovery incapability and failure consequence probability is calculated by using Eq. (5.11). The normalised total effectiveness of each RCO can be calculated by employing Eq. (5.12) and the results are shown in Table 5.39. For example 4.06% in Table 5.39 shows the effectiveness of RCO 1 to reduce failure likelihood and 26.39% shows the normalised total effectiveness of RCO 1. The preferences (rankings) of RCOs are listed in Table 5.39.

Table 5.39: Normalised Total Effectiveness of Each RCO and Rankings

	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Failure Likelihood	4.06%	4.27%	5.11%	0.82%	1.34%
Failure Consequence Probability	1.03%	0.99%	1.32%	0.21%	0.21%
Failure Capability	0.95%	1.24%	1.19%	0.12%	0.09%
Failure Recovery Incapability	7.90%	8.07%	9.81%	1.74%	2.35%
Total Effectiveness	13.94%	14.57%	17.43%	2.89%	3.99%
Normalised Total Effectiveness	**26.39%**	**27.59%**	**33.00%**	**5.47%**	**7.55%**
Ranking	***3***	***2***	***1***	***5***	***4***

5.6. Discussion and Validation of the Model

Based on the results shown in Table 5.39 it can be seen that the best RCO to reduce failure likelihood, failure capability, failure recovery incapability and failure consequence probability of the six major causes is RCO 3 (minimise the causes by design and manufacture). This is followed by RCO 2 (carry out maintenance activities), RCO 1 (regular inspection), RCO 5 (install warning devices) and RCO 4 (use detuners or dampers or anti vibration systems) respectively.

The effectiveness of RCO 3 in terms of failure likelihood, failure capability, failure recovery incapability and failure consequence probability is assessed to have a comparatively very large value (Table 5.36 and Appendices 5.8-5.12). For instance, the effectiveness of RCO 3 is assessed as (1.0 CE), (1.0 CE) and (0.85 GE 0.15 AE) for causes 4, 5 and 6 of propeller failure in terms of failure likelihood (Table 5.36). However, the effectiveness of RCO 4 is assessed to a comparatively very small amount by experts (Table 5.36 and Appendices 5.8-5.12). For instance, the effectiveness of RCO 4 is assessed as (0.2 SE 0.8 LE), (0.2 SE 0.8 LE) and (1.0 LE) for causes 4, 5 and 6 of propeller failure in terms of failure likelihood (Table 5.36). Thus RCO 3 is assessed as the most effective and RCO 4 is assessed as the least effective by experts compared with all other RCOs considered, in terms of failure likelihood, failure capability, failure recovery incapability and failure consequence probability. They are in harmony with the results achieved finally in Table 5.39 as RCO 3 is ranked as the most effective RCO and RCO 4 is ranked as the least effective RCO.

The results obtained by using a combination of AHP and discrete fuzzy sets can help facilitate risk management of SHV. The most effective RCO is determined through RCO selection. Chosen alternatives, which make up the most effective RCO, are then subjected to cost benefit assessment to select the most desirable alternative.

It is clear that SHV mainly comes from the propulsion system (propeller system and machinery) as described in Section 3.3 of Chapter 3. It is also clear that in this study RCO 3 (minimise causes by design and manufacture) is the most effective, as it has achieved the best ranking during the RCO selection. Therefore, in the next chapter (Chapter 6) cost benefit assessment of ten alternatives of propulsion system design and manufacture is carried out to select the most economical propulsion system with consideration of vibration characteristics. The cost benefit assessment is conducted by combining Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) with fuzzy sets.

5.7. Conclusion

The failures of hull, propeller systems and machinery, onboard ships lead to the occurrence of SHV. These failures originate from different causes and their importance could differ. The developed novel approach using both AHP and discrete fuzzy sets establishes the importance of each cause and failure event in terms of failure likelihood, failure capability, failure recovery incapability and failure consequence probability. RCOs are studied for the causes with relatively or extremely high risk estimation. This is followed by the selection of the best RCO.

This chapter provides a subjective risk management approach for ship designers, ship classification societies and other organisations involved in ship vibrations. The method enables them to identify the suitable RCOs by modelling the possible failures onboard. The results of this chapter provide useful information for the shipping industry in order to prevent or reduce the major causes of SHV by selecting suitable RCOs.

Chapter 6 – A Subjective Cost Benefit Analysis Approach for Modelling Ship Propulsion Systems

SUMMARY

A ship propulsion system is the major contributor to the occurrence of Ship Hull Vibration (SHV) which could easily lead to marine tragedies. A hierarchical structure for modelling propulsion systems is developed using a subjective novel cost benefit criteria analysis approach to select the most economical propulsion system with the consideration of vibration characteristics. The weights of all the criteria are estimated by utilising Analytical Hierarchy Process (AHP) technique. All the quantitative criteria in the hierarchy are converted into the qualitative criteria. Membership Functions (MFs) of continuous fuzzy sets are employed to estimate the fuzzy performance ratings of all the criteria. By taking into account fuzzy performance ratings of all the criteria, a fuzzy TOPSIS decision matrix is constructed. Finally, the most economical propulsion system, with consideration of vibration characteristics, is selected using the fuzzy TOPSIS method. The results of this chapter reveal that the fuzzy TOPSIS is suitable for propulsion systems selection.

6.1. Introduction

The selection of an appropriate propulsion plant is one of the most important decisions a ship designer or ship owner has to make in the process of designing or purchasing a ship. It will influence the reputation of ship designers and profits of ship owners during the ship's operational life. Traditionally, most ship owners look for a propulsion system which could give relatively low expenses in order to make high profits. However, when vibration problems emerge, this selection process would become more complex. Vibration problems in modern ships have increased with the complexity of the structure and associated equipment. Many maritime casualties have occurred as a direct result of high vibration levels (Chapters 3, 4 & 5).

The propulsion system, consisting of ship propeller system and machinery, is the major contributor to SHV. In this chapter ten propulsion systems are considered in order to select the most economical propulsion system. They are classified under eight generic cost benefit criteria in the hierarchical structure (Figure 6.1). However, in this study, the propulsion system vibration characteristics are considered to be the major priority during the selection process.

The Analytical Hierarchy Process (AHP) is utilised to allocate the weights in a hierarchy. Membership Functions (MFs) of continuous fuzzy sets are used to estimate the fuzzy performance ratings of all the cost benefit criteria in the hierarchical structure. More information of fuzzy logic can be found in Chapter 2.

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is employed since it is among the most cited Multiple Criteria Group Decision Making (MCGDM) techniques in the way it approaches the selection issue (Bottani & Antonio, 2006). TOPSIS is based on the logical consideration that the most suitable solution should be closest to the positive ideal solution and farthest from the negative ideal solution. TOPSIS is one of the most suitable techniques for cost benefit analysis, therefore, in this study, TOPSIS is combined with fuzzy sets (fuzzy TOPSIS) to achieve the aim, which is to select the most economical propulsion system under uncertainties when considering vibration characteristics.

In order to achieve the aim, this chapter describes the estimation of weights of the criteria in the hierarchical structure by using AHP, models the annual operating expenses and transforms the quantitative criteria into qualitative criteria by developing a novel approach, obtains fuzzy performance ratings of all the criteria, develops the fuzzy TOPSIS decision matrix, and shows the normalisation and weighting of the matrix. The chapter then determines the fuzzy negative and positive ideal reference points and calculates the distance to each propulsion system, and finally ranks the propulsion systems by estimating the closeness coefficient. This methodology is demonstrated through a case study.

6.2. Background

6.2.1. TOPSIS

Yoon and Hwang developed the TOPSIS method based upon the concept that the chosen alternative should have the shortest distance from the positive ideal solution and the farthest from the negative ideal solution (Hwang & Yoon, 1981). The linear weighting technique with TOPSIS was first proposed in its crisp version by Chen and Hwang in 1992 based on their previous work conducted in

1981 (Chen & Hwang, 1992). Its general extension for group decision making problems under fuzzy environment was published by Chen, (2000).

In TOPSIS, cost criteria are defined as the most desirable candidate scoring at the lowest and benefit criteria are described as if the more desirable the candidate, the higher its score verses this criterion (Bottani & Antonio, 2006; Wang & Chang, 2007). This method works well for multi-tier hierarchies and better than other techniques such as AHP. The TOPSIS approach is adopted in this study since the logic of TOPSIS is rational and understandable, the computation processes are straightforward, the concept permits the pursuit of the best alternatives for each criterion depicted in a simple mathematical form and the importance weights are incorporated into the comparison procedures.

Since TOPSIS was introduced nearly three decades ago, it has been employed in many applications. These include selection of grippers in flexible manufacturing (Olson, 2004), financial investment in advanced manufacturing systems, in an application of selecting robotic process (Parken & Wu, 1999; Bhangale *et al.*, 2004; Kahraman *et al.*, 2007), the comparison of company performances, aircraft selection (Wang & Chang, 2007), logistics services (Bottani & Antonio, 2006), risk assessment (Chen *et al.*, 2001; Wang & Elhag, 2006), management systems (Sobczak & Berry, 2007) and many more. This is because TOPSIS has several useful characteristics:

- TOPSIS ranks different alternatives measuring their relative distances to ideal positive and negative solutions, then providing a meaningful performance measurement for each candidate.
- In TOPSIS, weights and ratings can be directly assigned by decision makers. The feature is extremely useful in case of shallow and wide decisional hierarchies like the one considered in this study, since it eliminates the need for cumbersome pairwise comparisons and makes the practical application of the methodology straightforward.
- The TOPSIS approach has been proven to be robust in dealing with MCGDM problems.

TOPSIS also has positive characteristics compared with other MCGDM methods. They are that the performance is only slightly affected by the number of alternatives and rank discrepancies are amplified to a lesser extent for increasing values of the number of alternatives and the number of criteria. It has been proved to be one of the best methods in addressing rank reversal issue which is the change in the ranking of alternatives when a non optimal alternative is introduced; this consistency feature is largely appreciated in practical applications.

6.3. Propulsion Systems Modelling

A two level generic structure of propulsion systems modelling (Figure 6.1) is developed to select the most economical propulsion system for a ship (Appendix 6.1). In this study ten types of propulsion systems are considered namely, 2 Heater Cycle Steam Turbine (2ST), 4 Heater Cycle Steam Turbine (4ST), Reheat Cycle Steam Turbine (RST), Medium Speed Diesel (MSD), Slow Speed Diesel (SSD), Heavy Duty Gas Turbine (HDGT), Aircraft Derivative Gas Turbine (ADGT), Heavy Duty Gas Turbine with Helper Turbine (HDGTH), Heavy Duty Gas Turbine with STAG Cycle (HDGTS) and Aircraft Gas Turbine STAG Plant (AGTSC). They are classified under the following eight cost benefit criteria: Vibration Characteristics (VIB), Annual Capital Charge (ACC), Fuel Oil Costs (FOC), Maintenance and Repair Costs (M&R), Lubricating Oil Costs (LOC), Insurance Costs (IC), Crew Costs (CC) and Reliability (REL).

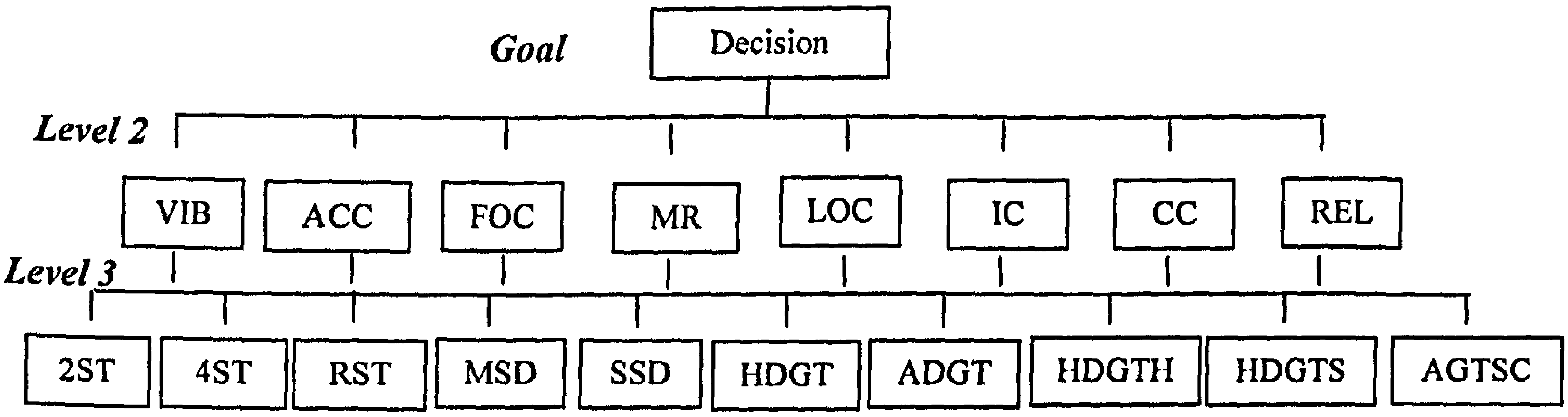


Figure 6.1: Hierarchy of Propulsion Systems Modelling

In this study these eight cost benefit criteria are chosen because they are regarded as the most significant criteria associated with propulsion systems selection based on extensive discussions with experts in the area. The descriptions of all propulsion systems (plants) are obtained from Wang (1995). The power development of each propulsion system is 20000 kW.

The detailed information of experts used in this chapter and dates of the meetings are given below. During the meetings, the main aims were to identify the most significant criteria to develop a model to select a propulsion system based on decision makers' requirement and to find out the applicability of the model in real situations.

Panel of Experts:

- Professor J. Wang: Professor of Marine Technology, Liverpool John Moores University, United Kingdom.
- Dr. Z. Yang: Senior Lecturer, Liverpool John Moores University, United Kingdom.
- Mr. U. Udo: Lube Analyst/Engineer, Shell Marine, London, United Kingdom.
- Mr. R. Riahi: Senior Superintendent/Ship Design Consultant, Islamic Republic of Iran Shipping Line (IRISL), Iran.

Dates and Venues of Meetings:

- 29/11/2007: Albert Dock, Liverpool, United Kingdom.
- 04/03/2008: Albert Dock, Liverpool, United Kingdom.

Note: More extensive discussions with experts were also conducted via telephone.

6.3.1. Steam Turbine Plants

In this study three separate steam plants are investigated. They are, namely, 2 Heater Cycle Steam Turbine (2ST), 4 Heater Cycle Steam Turbine (4ST) and Reheat Cycle Steam Turbine (RST). All those steam plants are equipped with a cross-compound double reduction geared turbine, boiler plant, one turbo-generator and two diesel generators. A reversible double reduction gear converts the high turbine rotor speeds to a propeller shaft speed low enough to drive the Fixed Pitch Propeller (FPP) efficiently. The plants operate on IFO 380 oil at sea and manoeuvring. These plants have much better vibration characteristics and reliability than MSD and SSD plants.

6.3.2. Medium Speed Diesel Plant

The Medium Speed Diesel (MSD) plant included in this study has two unidirectional MSD engines coupled to a single FPP via a reversible reduction gear. The engines operate on IFO 380 oil. The electrical generating plant consists of two auxiliary diesel-driven sets and one shaft-driven main generator. A waste heat boiler to supply steam for fuel oil heating, domestic heating and distilling plant operation, and an oil fired auxiliary boiler are included in the plant. This plant has better vibration characteristics than a corresponding SSD plant in general; although its reliability is lower.

6.3.3. Slow Speed Diesel Plant

The Slow Speed Diesel (SSD) plant is considered as a direct reversible diesel engine coupled to a FPP. The electrical generating plant has three suitably sized diesel driven generators. The main engine works on IFO 380 fuel, while the diesel generators operate on Marine Diesel Oil (MDO). A waste-heat boiler of sufficient size to supply steam for fuel oil heating, domestic heating and distilling plant operation, and an oil fired boiler are included in the plant. This plant has the worst vibration characteristics compared with all other plants but its reliability is usually better than MSD.

6.3.4. Heavy Duty Gas Turbine Plant

The Heavy Duty Gas Turbine (HDGT) plant consists of a single HDGT fitted with a regenerator driving a Controllable Pitch Propeller (CPP) through a non-reversing reduction gear. The plant is fitted with the following: electrical generating plant consisting of two diesel driven auxiliary generators and one gear driven main generator, waste-heat boiler of sufficient size to supply steam for domestic heating and distilling plant operation, and an oil fired auxiliary boiler. This plant uses distillate fuel only. HDGT plant has better vibration characteristics than steam plants. Its reliability is much higher than that of SSD and lower than that of steam plants (Wang, 1995) because SSD plant has many components compared with the components of HDGT. However, in steam plants associated components are less than that of HDGT; hence steam plants are more reliable than HDGT plants.

6.3.5. Aircraft Derivative Gas Turbine Plant

The Aircraft Derivative Gas Turbine (ADGT) plant consists of a single aircraft-type gas turbine driving a CPP through a non-reversing reduction gear. The plant is also fitted with the following: electrical generating plant consisting of two suitably sized diesel driven auxiliary generators and one gear driven main generator, oil fired auxiliary boiler, waste heat boiler of sufficient size to supply steam for domestic heating and distilling plant. ADGT burns distillate fuel only. ADGT has the best vibration characteristics compared with other plants and its reliability is almost similar to that of HDGT.

6.3.6. Combined Gas Turbine and Steam Turbine Plants

All the combined Steam Turbine And Gas (STAG) plants contain the following major components apart from the main prime mover: electrical generating plant, consisting of one steam turbine-driven main generator and one diesel-driven auxiliary generator, and waste-heat boiler capable of extracting the optimum amount of energy from the turbine exhaust gases and also capable of being oil fired. All these plants are fitted with CPP. Three of these plants investigated in this study are: Heavy Duty Gas Turbine with Helper Turbine (HDGTH), Heavy Duty Gas Turbine with STAG Cycle (HDGTS) and Aircraft Gas Turbine STAG Plant (AGTSC). All the combined STAG plants use a turbo generator for their main source of electrical power. The plants have oil fired, steam generators for the supply of "in-port" steam. The vibration characteristics of these plants are worse than that of HDGT and their reliability is lower than that of HDGT.

6.4. Methodology

The following steps are developed, based on the hierarchical structure (Figure 6.1) in order to select the most economical propulsion plant in terms of the eight cost benefit criteria.

Step 1: Estimate the weights of the cost benefit criteria in the hierarchical structure (Figure 6.1) by using AHP.

Step 2: Model the annual expenses cost criteria of Figure 6.1, and transform the quantitative annual expenses cost criteria into qualitative criteria by developing a novel approach.

Step 3: Construct triangular MFs of continuous fuzzy sets to estimate the fuzzy performance ratings of all the qualitative cost benefit criteria in a fuzzy decision matrix which is developed on the basis of fuzzy TOPSIS.

Step 4: Normalise the fuzzy decision matrix for the cost benefit criteria and establish the weighted normalised fuzzy decision matrix by multiplying the normalised fuzzy index values by weights.

Step 5: Determine the fuzzy positive and negative ideal reference points by employing the weighted normalised values. Then calculate the distance from each propulsion system to Fuzzy Positive Ideal Reference Point (FPIRP) and Fuzzy Negative Ideal Reference Point (FNIRP) by taking into account the obtained fuzzy positive and negative ideal reference points.

Step 6: Achieve the closeness coefficient by using FPIRP and FNIRP values. Based on the closeness coefficient, carry out the ranking of the ten propulsion systems in the hierarchical structure.

6.4.1. Weighting Vector and Normalised Weighting Vector Calculation

The weighting vector and normalised weighting vector calculation can be performed by using an AHP method which has been described in Section 5.4.3 in Chapter 5. The Eqs. (5.4) – (5.9) of Section 5.4.3 have been used in this chapter (Chapter 6) and Table 5.3 has also been implemented.

6.4.2. Quantitative Data Transformation Technique

In this study a novel approach is developed to transfer the quantitative criteria (annual expenses cost criteria) into qualitative criteria. For example, consider the following five MDO costs (US$ per tonne) in five countries (MER, 2007): 530, 605, 626, 558 and 705. The prices have to be represented by qualitative criteria and by using Very Good (VG), Good (G), Average (A), Poor (P) and Very Poor (VP) linguistic terms,

The value of 530 should be the most economical and 705 the least economical. Therefore, the value of 530 is allocated to VG and the price of 705 is given to VP. The values associated with the other linguistic terms can be calculated as follows:

$$A = \frac{530+705}{2} = 617.50$$

$$\mathrm{G} = \frac{\left(\frac{530+705}{2}\right)+530}{2} = 573.75$$

$$\mathrm{P} = \frac{\left(\frac{530+705}{2}\right)+705}{2} = 661.25$$

VG	G	A	P	VP
530.00	573.75	617.50	661.25	705.00

Such calculated values represent the reference point of each linguistic term. The following three generic algorithms can be developed for the calculation process.

$$\mathrm{A} = \frac{Min + Max}{2} \tag{6.1}$$

$$\mathrm{G} = \frac{\left(\frac{Min + Max}{2}\right) + Min}{2} \tag{6.2}$$

$$\mathrm{P} = \frac{\left(\frac{Min + Max}{2}\right) + Max}{2} \tag{6.3}$$

where, *Min* is the minimum value and *Max* is the maximum value.

Eq. (6.4) is constructed to suit any type of situation. By using this equation the linear distance between two neighbouring linguistic terms can be estimated. According to this method the distance equally distributes between the linguistic terms. This can be used for distance modelling of any number of linguistic terms and any type of linguistic terms.

$$S = \frac{V_{\max} - V_{\min}}{(n-1)} \tag{6.4}$$

where, S is the distance between two neighbouring linguistic terms, $V_{\max}$ is the maximum value, $V_{\min}$ is the minimum value and n is the number of the linguistic terms.

The quantitative data transformation can be carried out by using the distance approach. For example, consider the transformation of value 626 and calculation of the belief degrees (β) associated with the linguistic terms. The value of 626 is between A and P linguistic terms. Therefore, it should be represented by linguistic terms A and P after the transformation.

The distance from linguistic term A to 626 is 8.5 (626 – 617.50) and the distance from linguistic term P to 626 is 35.25 (661.25 – 626). It is obvious that high β value should be associated with linguistic term A while low β value should be associated with linguistic term P. The calculation can be done as follows:

$$\beta_A = \frac{35.25}{8.5+35.25} = 0.8057 \qquad \beta_P = \frac{8.5}{8.5+35.25} = 0.1943$$

In this case 80.57% belief degree belongs to linguistic term A and 19.43% to linguistic term P. The generic algorithm shown in Eq. (6.5) can be developed to deal with such situations as the above.

$$\beta = \frac{D}{D_Y + D_Z} \tag{6.5}$$

where, D_Y is the distance from the value of the previous linguistic term (Y) to the actual value, D_Z is the distance from the value of the next linguistic term (Z) to the actual value, D is either D_Y or D_Z, and β is the belief degree of either linguistic term Y or Z.

6.4.3. Operations of Membership Functions

Let G and H be two triangular fuzzy numbers parameterized by the triplet (g_1, g_2, g_3) and (h_1, h_2, h_3) respectively (Figure 6.2). Then the operational laws of these two triangular fuzzy numbers are as follows (Wang & Chang, 2007):

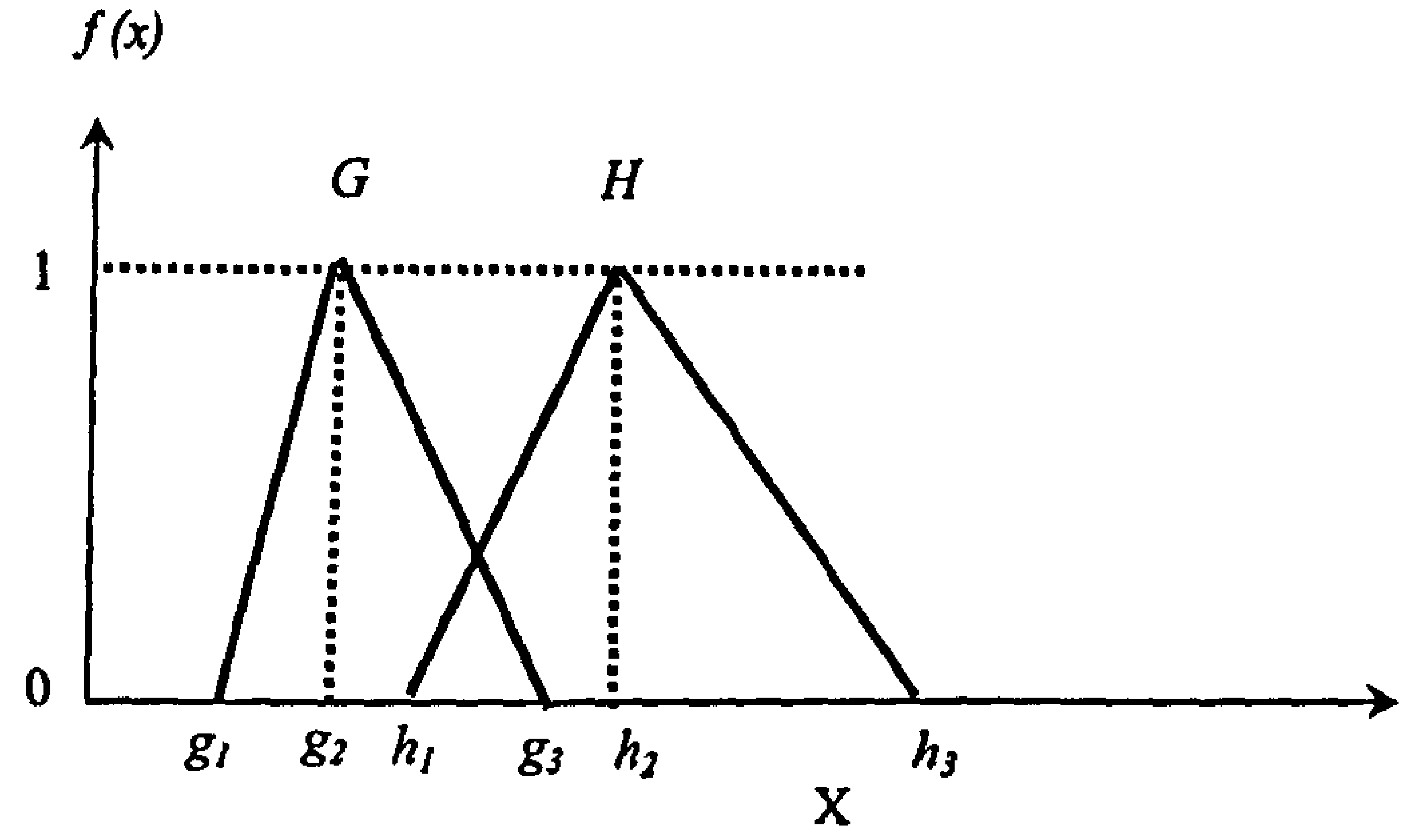


Figure 6.2: MFs for Triangular Fuzzy Numbers

$$G + H = (g_1, g_2, g_3) + (h_1, h_2, h_3) = (g_1 + h_1, g_2 + h_2, g_3 + h_3) \quad (6.6)$$

$$G - H = (g_1, g_2, g_3) - (h_1, h_2, h_3) = (g_1 - h_3, g_2 - h_2, g_3 - h_1) \quad (6.7)$$

$$G \times H = (g_1, g_2, g_3) \times (h_1, h_2, h_3) = (g_1h_1, g_2h_2, g_3h_3) \quad (6.8)$$

$$G \div H = (g_1, g_2, g_3) \div (h_1, h_2, h_3) = \left(\frac{g_1}{h_3}, \frac{g_2}{h_2}, \frac{g_3}{h_1}\right) \quad (6.9)$$

6.4.3.1. Establishment of Triangular Membership Functions

Triangular MFs are adopted for linguistic terms to estimate the fuzzy performance ratings of the criteria. A triangular MF has a smooth transition from one linguistic term to the other. The membership values for each linguistic term are estimated between 0 and 1 [0, 1].

In this study four experts are employed, each expert being asked to estimate the proposition 'x belongs to $\tilde{A}$'. Consider $\tilde{A}$ is a fuzzy set on X that represents a linguistic term associated with a given category and $e_k(x)$ is a value within a certain range in X i.e. $e_k(x) \in X$ (Klir & Yuan, 1995). In this research X is described as 0-10 categories. On occasions where there are n experts and each of them has equal importance, Eq. (6.10) is used:

$$\tilde{A}(x) = \frac{\sum_{k=1}^{n} e_k(x)}{n} \tag{6.10}$$

where, $\tilde{A}(x)$ is the final value of the category when membership value equals 1 after the judgements of n experts are synthesised and $e_k(x)$ is the value allocated by the k^{th} expert $k \in n$.

In situations where the experts have different importance (W_k), Eq. (6.10) can be modified as follows:

$$\tilde{A}(x) = \sum_{k=1}^{n} W_k \times e_k(x) \tag{6.11}$$

$$\sum_{k=1}^{n} W_k = 1 \tag{6.12}$$

6.4.4. Fuzzy TOPSIS

The TOPSIS MCGDM method is used to obtain the rankings of all the propulsion systems under consideration and it is described in detail in the following sections. In this study qualitative criteria are considered to be fuzzy variables, represented by triangular fuzzy numbers (g, h, p).

6.4.4.1. Construction of Fuzzy Decision Matrix

Given m alternatives, n criteria and k decision makers, a typical fuzzy MCGDM problem can be represented in a matrix format as shown in Eq. (6.13) (Bottani & Antonio, 2006; Wang & Chang, 2007):

$$R_k = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \end{array} \quad q = 1, 2, \ldots., m; \quad z = 1, 2, \ldots., n \tag{6.13}$$

where, $A_1, A_2, \ldots, A_m$ are the alternatives to be chosen, $C_1, C_2, \ldots, C_n$ define the evaluation criteria, r_{qz} represents the rating of the alternative A_q with respect to criterion C_z.

In this study expert judgments are used to estimate the values of qualitative criteria. Since expert judgments toward propulsion systems selection vary with their experience and knowledge, the method of average value is implemented to obtain the fuzzy performance ratings r_{qz}. The four experts appointed in this research are considered to have equal knowledge and experience in the subject area. Eq. (6.14) is developed to combine the expert judgements in order to obtain reasonable results.

$$r_{qz} = \frac{1}{k}\sum_{t=1}^{k}(\beta_{qz}{}^{t} . r_{qz}{}^{t}) \tag{6.14}$$

where, $(\beta_{qz}{}^{t} . r_{qz}{}^{t})$ is the product of the belief degrees and ratings of alternative A_q with respect to criterion C_z estimated by the t^{th} expert and $r_{qz}{}^{t} = (g_{qz}{}^{t}, h_{qz}{}^{t}, p_{qz}{}^{t})$.

6.4.4.2. Fuzzy Decision Matrix Normalisation

All the triangular fuzzy data in the decision matrix is normalised to eliminate irregularities with different measurement units and scales in the TOPSIS MCGDM problem. The normalisation has two other main aims namely, to compare heterogeneous criteria and to ensure that triangular fuzzy numbers all range within the interval [0, 1] (Wang & Chang, 2007). In this study, linear scales transform normalisation function is employed to normalise the criteria.

In the normalisation process, Eq. (6.16) is used for both the benefit and cost criteria. If $\widetilde{R}$ defines the normalised fuzzy decision matrix then

$$\widetilde{R} = [\widetilde{r}_{qz}] \quad q = 1, 2, \ldots, m; \quad z = 1, 2, \ldots, n \tag{6.15}$$

$$\widetilde{r}_{qz} = \frac{r_{qz}}{p_z^{+}} = \left(\frac{g_{qz}}{p_z^{+}}, \frac{h_{qz}}{p_z^{+}}, \frac{p_{qz}}{p_z^{+}}\right) z \in \mathrm{B} \,\&\, \mathrm{C} \tag{6.16}$$

$$p_z^{+} = \max_{q} p_{qz} \tag{6.17}$$

where, B is benefit criteria and C is cost criteria.

6.4.4.3. Development of Weighted Normalised Fuzzy Decision Matrix

By taking into account the allocated weight (w_z) of each criterion, the weighted normalised decision matrix can be computed by multiplying the importance weights of the evaluation criteria and the values in $\widetilde{R}$. The weighted normalised fuzzy decision matrix V is denoted as:

$$V = [v_{qz}] \quad q = 1, 2, \ldots., m; \quad z = 1, 2, \ldots., n \tag{6.18}$$

$$v_{qz} = \widetilde{r}_{qz} \times w_z \tag{6.19}$$

where, w_z is the weight of criterion C_z.

6.4.4.4. Obtaining the FPIRP and FNIRP

In order to obtain FPIRP (A^+) and FNIRP (A^-), the following Eqs. (6.20), (6.21), (6.22) and (6.23) are employed:

$$A^+ = \left(v_1^+, v_2^+, \ldots., v_n^+\right) \tag{6.20}$$

$$A^- = \left(v_1^-, v_2^-, \ldots., v_n^-\right) \tag{6.21}$$

where,

$$v_z^+ = (1,1,1)\, z \in \mathrm{B,C} \quad z = 1, 2, \ldots., n \tag{6.22}$$

$$v_z^- = (0,0,0)\, z \in \mathrm{B,C} \quad z = 1, 2, \ldots., n \tag{6.23}$$

6.4.4.5. Calculation of the Distances of Each Alternative to FPIRP and FNIRP

The distance of each alternative to the FPIRP and FNIRP can be computed as follows:

$$d_q^+ = \sum_{z=1}^{n} d(v_{qz}, v_z^+) = \sum_{z=1}^{n} \sqrt{\frac{1}{3} \cdot \left[\left(g_{qz} - g_z^+\right)^2 + \left(h_{qz} - h_z^+\right)^2 + \left(p_{qz} - p_z^+\right)^2 \right]} \qquad (6.24)$$

$$d_q^- = \sum_{z=1}^{n} d(v_{qz}, v_z^-) = \sum_{z=1}^{n} \sqrt{\frac{1}{3} \cdot \left[\left(g_{qz} - g_z^-\right)^2 + \left(h_{qz} - h_z^-\right)^2 + \left(p_{qz} - p_z^-\right)^2 \right]} \qquad (6.25)$$

where, d_q^+ denotes the distance of alternative A_q from FPIRP and d_q^- is the distance of alternative A_q from FNIRP.

The calculated d_q^+ and d_q^- values can be used to obtain the Closeness Coefficient (CC_q) of each alternative for ranking purposes.

6.4.4.6. Calculation of the Closeness Coefficient and Ranking of the Alternatives

The ranking of the alternatives can be determined after the CC_q is obtained. This allows the decision makers to choose the most rational alternative. CC_q can be calculated by using Eq. (6.26).

$$CC_q = \frac{d_q^-}{d_q^+ + d_q^-} \quad q = 1, 2, \ldots., m \qquad (6.26)$$

CC_q is equal to 0 if and only if $d_q^- = 0$ or $A_q = A^-$. $CC_q = 1$ when $d_q^+ = 0$ or $A_q = A^+$. As a result, the best alternative is the one with the value of CC_q closest to 1.

6.5. Case Study

The main aim of this section is to demonstrate how the proposed methodology can be applied to carry out cost benefit analysis in order to select the most economical propulsion system with the consideration of vibration. The selected propulsion system will be applied to a real ship (Appendix 6.1) with significant attention paid to vibration problems.

6.5.1. Estimating the Weights of Criteria using AHP (*Step 1*)

AHP has been used to estimate the weights of all the cost benefit criteria in Figure 6.1. In the hierarchical structure, apart from VIB and REL criteria, the remainder can be considered as annual expenses. The annual expenses criteria are classified under the Expenses (EXP) Main Criterion (Figure 6.3).

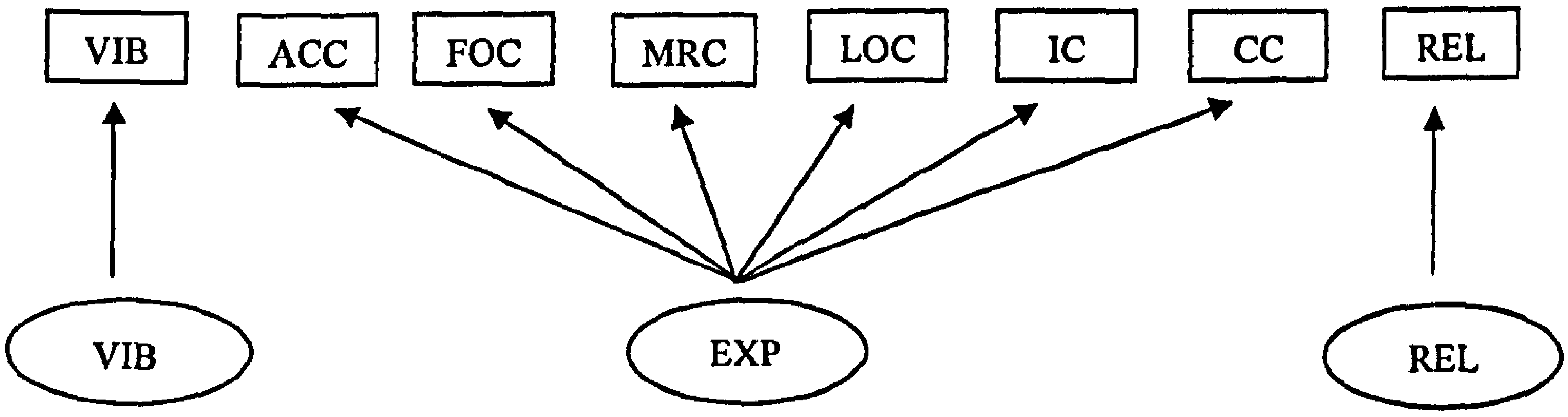


Figure 6.3: Hierarchy for Weight Estimation

Table 6.1 has been created to show lower level and upper level criteria in the hierarchy.

Table 6.1: Lower Level and Upper Level Criteria

Lower Level Criteria	Upper Level Criteria
VIB	VIB
EXP	ACC
	FOC
	MRC
	LOC
	IC
	CC
REL	REL

It is noted that the criterion to compare with others is taken as REL since it is considered to be of the least relative importance based on expert judgements. Tables 6.2 and 6.3 show the crisp importance values after the pairwise comparisons between the three criteria.

Table 6.2: The Crisp Importance Values of REL and EXP and VIB

	VIB	EXP	REL
REL	0.600	0.800	1.000

Table 6.3: The Crisp Importance Values of EXP and VIB

	VIB	EXP
EXP	0.700	1.000

A 3 × 3 pairwise comparison matrix is developed to obtain the weights of the three criteria. *A(RVE)* is the pairwise comparison matrix expressing the quantified judgement with regard to the relative importance of VIB, EXP and REL.

$$A(RVE) = \begin{array}{c} \\ R \\ V \\ E \end{array} \begin{array}{c} \begin{array}{ccc} R & V & E \end{array} \\ \begin{bmatrix} 1.000 & 0.600 & 0.800 \\ 1.667 & 1.000 & 1.429 \\ 1.250 & 0.700 & 1.000 \end{bmatrix} \end{array}$$

where, *R*, *V* and *E* stand for REL, VIB and EXP respectively.

The weighting vector representing the priority of each criterion in the pairwise comparison matrix is obtained by using Eq. (5.6):

$$w_1 = \frac{1}{3}\sum_{j=1}^{3}\frac{a_{1j}}{\sum_{i=1}^{3}a_{ij}} = \frac{1}{3}\times\left[\left(\frac{1.000}{1.000+1.667+1.250}\right)+\left(\frac{0.600}{0.600+1.000+0.700}\right)+\left(\frac{0.800}{0.800+1.429+1.000}\right)\right]$$

$$w_1 = 0.2547$$

$$w_2 = \frac{1}{3}\sum_{j=1}^{3}\frac{a_{1j}}{\sum_{i=1}^{3}a_{ij}} = \frac{1}{3}\times\left[\left(\frac{1.667}{1.000+1.667+1.250}\right)+\left(\frac{1.000}{0.600+1.000+0.700}\right)+\left(\frac{1.429}{0.800+1.429+1.000}\right)\right]$$

$$w_2 = 0.4343$$

$$w_3 = \frac{1}{3}\sum_{j=1}^{3}\frac{a_{ij}}{\sum_{i=1}^{3}a_{ij}} = \frac{1}{3}\times\left[\left(\frac{1.250}{1.000+1.667+1.250}\right)+\left(\frac{0.700}{0.600+1.000+0.700}\right)+\left(\frac{1.000}{0.800+1.429+1.000}\right)\right]$$

$$w_3 = 0.3110$$

The weighting vector *W(RVE)* can be shown as follows:

$$W(RVE) = \begin{array}{c} R \\ V \\ E \end{array}\begin{bmatrix} 0.2547 \\ 0.4343 \\ 0.3110 \end{bmatrix}$$

It is necessary to check that the pairwise comparisons of the three criteria achieve the required consistency. This is carried out as follows:

Firstly, $\lambda_{\max}$ is calculated using Eq. (5.9).

$$\lambda_{\max} = \frac{2.999+3.001+3.001}{3} = 3.001$$

Secondly, Consistency Index *(CI)* is obtained using Eq. (5.8).

$$CI = \frac{3.001-3}{3-1} = 0.001$$

Finally, Consistency Ratio *(CR)* is calculated employing Eq. (5.7) and Table 5.3.

$$CR = \frac{0.001}{0.58} = 0.002$$

Since the derived *CR* value is less than 0.10, it can be said that the pairwise comparisons are consistent.

The weights (normalised weighting vectors) of annual expenses criteria of the EXP Main Criterion can be calculated after obtaining the weighting vectors of VIB, EXP and REL. The pairwise comparisons can be conducted in a similar way; the crisp importance values are shown in Appendix 6.2. The weighting vectors (*W(EC)*) and the normalised weighting vectors (*W(NEC)*) of annual expenses criteria are obtained as follows:

$$W(EC) = \begin{array}{r}LOC\\ACC\\FOC\\CC\\MRC\\IC\end{array}\begin{bmatrix}0.0726\\0.2395\\0.3091\\0.1249\\0.0925\\0.1614\end{bmatrix} \qquad W(NEC) = W(EC) \times 0.3110 = \begin{array}{r}LOC\\ACC\\FOC\\CC\\MRC\\IC\end{array}\begin{bmatrix}0.0226\\0.0745\\0.0961\\0.0388\\0.0288\\0.0502\end{bmatrix}$$

Table 6.4: The *W(EC)* and *W(NEC)* of the Associated Criteria of EXP

Criterion	*W(EC)*	*W(NEC)*
ACC	0.2395	0.0745
FOC	0.3091	0.0961
MRC	0.0925	0.0288
LOC	0.0726	0.0226
IC	0.1614	0.0502
CC	0.1249	0.0388

The *W(NEC)* values in Table 6.4 represent the weightings of the associated criteria of the EXP Main Criterion. Figure 6.3 can be modelled by using the calculated weighting (*w*) values. All the weightings of the criteria in the decision making hierarchy are shown in Figure 6.4.

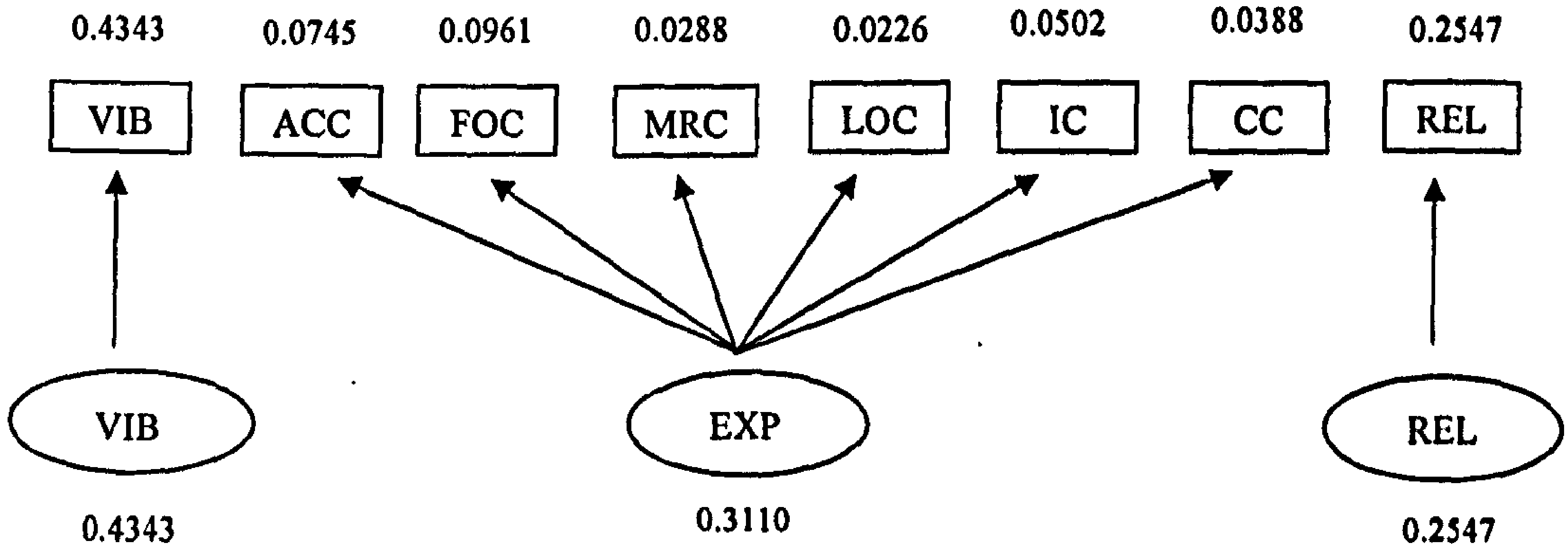


Figure 6.4: Hierarchy with Weightings

6.5.2. Modelling of Annual Expenses Cost Criteria and Transformation into Qualitative Criteria (*Step 2*)

In this section those associated with the EXP Main Criterion in Figure 6.4 are modelled. The annual expenses of all the plants are based on real values for a shaft power of 20000 kW. Such values are with units of US$ and shown in Table 6.5.

Table 6.5: Modelled Annual Expenses for Ten Propulsion Systems

	ACC × 10^5	FOC × 10^5	MRC ×10^5	LOC × 10^5	IC × 10^5	CC × 10^5
2ST	36.435	122.616	3.330	1.413	09.794	8.100
4ST	37.746	119.267	3.692	1.413	10.147	8.100
RST	38.386	105.870	4.055	1.413	10.319	8.100
MSD	33.307	076.300	7.261	5.386	08.953	6.720
SSD	35.537	073.761	5.599	4.427	09.553	6.180
HDGT	31.966	123.768	7.097	1.413	08.593	6.300
ADGT	29.668	230.767	8.755	0.875	07.975	6.300
HDGTH	42.209	106.651	7.097	1.413	11.347	7.500
HDGTS	43.989	106.651	6.470	1.413	11.825	7.500
AGTSC	36.476	192.371	9.417	0.906	09.805	7.500

All the annual expenses (quantitative criteria) are converted into qualitative criteria. The novel approach developed in this study is employed in the transformation process. All the qualitative criteria are represented by using such linguistic terms as Very Good (VG), Good (G), Average (A), Poor (P) and Very Poor (VP). The transformation process can be shown by using an example of ACC of 2ST.

The highest ACC value is 43.989 and the lowest ACC value is 29.668 (Table 6.5); these two values are allocated to linguistic terms VP and VG respectively as described in Section 6.4.2. All the values associated with the five given linguistic terms can be estimated by using Eqs. (6.1), (6.2) and (6.3) or Eq. (6.4) and shown as follows:

VG	G	A	P	VP
29.668	33.248	36.829	40.409	43.989

The ACC value of the 2ST propulsion system is 36.435, which is in between the values associated with linguistic terms G and A. The distances between the ACC value and the associated values of linguistic terms G and A are calculated by using Eq. (6.5). Then the belief degrees associated with linguistic terms G and A for the ACC value of 36.435 are estimated.

$D_G = 36.435 - 33.248 = 3.187$
$D_A = 36.829 - 36.435 = 0.394$

$$\beta_G = \frac{0.394}{(3.187 + 0.394)} = 0.1100 \qquad \beta_A = \frac{3.187}{(3.187 + 0.394)} = 0.8900$$

Table 6.6: Transformed Annual Expenses for Ten Propulsion Systems

	ACC	FOC	MRC	LOC	IC	CC
2ST	(G, 0.1100; A, 0.8900)	(G, 0.7553; A, 0.2447)	(VG, 1.0000)	(VG, 0.5230; G, 0.4770)	(G, 0.1102; A, 0.8898)	(VP, 1.0000)
4ST	(A, 0.7439; P, 0.2561)	(G, 0.8407; A, 0.1593)	(VG, 0.7622; G, 0.2378)	(VG, 0.5230; G, 0.4770)	(A, 0.7435; P, 0.2565)	(VP, 1.0000)
RST	(A, 0.5651; P, 0.4349)	(VG, 0.1820; G, 0.8180)	(VG, 0.5237; G, 0.4763)	(VG, 0.5230; G, 0.4770)	(A, 0.5649; P, 0.4351)	(VP, 1.0000)
MSD	(G, 0.9835; A, 0.0165)	(VG, 0.9353; G, 0.0647)	(A, 0.4168; P, 0.5832)	(VP, 1.0000)	(G, 0.9844; A, 0.0156)	(G, 0.8750; A, 0.1250)
SSD	(G, 0.3608; A, 0.6392)	(VG, 1.0000)	(G, 0.5092; A, 0.4908)	(P, 0.8502; VP, 0.1498)	(G, 0.3607; A, 0.6393)	(VG, 1.0000)
HDGT	(VG, 0.3581; G, 0.6419)	(G, 0.7260; A, 0.2740)	(A, 0.5247; P, 0.4753)	(VG, 0.5230; G, 0.4770)	(VG, 0.3583; G, 0.6417)	(VG, 0.7500; G, 0.2500)
ADGT	(VG, 1.0000)	(VP, 1.0000)	(P, 0.4350; VP, 0.5650)	(VG, 1.0000)	(VG, 1.0000)	(VG, 0.7500; G, 0.2500)
HDGTH	(P, 0.4972; VP, 0.5028)	(VG, 0.1621; G, 0.8379)	(A, 0.5247; P, 0.4753)	(VG, 0.5230; G, 0.4770)	(P, 0.4969; VP, 0.5031)	(A, 0.2500; P, 0.7500)
HDGTS	(VP, 1.0000)	(VG, 0.1621; G, 0.8379)	(A, 0.9369; P, 0.0631)	(VG, 0.5230; G, 0.4770)	(VP, 1.0000)	(A, 0.2500; P, 0.7500)
AGTSC	(G, 0.0986; A, 0.9014)	(P, 0.9782; VP, 0.0218)	(VP, 1.0000)	(VG, 0.9725; G, 0.0275)	(G, 0.0988; A, 0.9012)	(A, 0.2500; P, 0.7500)

All the transformed annual expenses values of the ten propulsion systems in Table 6.6 will be used to estimate the fuzzy performance ratings of the criteria; this will be conducted in Step 3. Also the complete TOPSIS decision matrix will be developed by adding the data of the criteria VIB and REL obtained based on expert judgements.

6.5.3. Determination of Fuzzy Performance Ratings of the Cost Benefit Criteria (*Step 3*)

The MFs of the five defined linguistic terms (VG, G, A, P and VP) are developed based on expert judgements in order to obtain fuzzy performance ratings of the cost benefit criteria. In this study four experts are employed (two from industry and two from academia) and each expert has equal knowledge and experience in the field. Therefore, the weighting of each expert (W_k) is considered as the same. By using Eq. (6.10) MFs are developed; this can be highlighted through an example of linguistic term P.

$$\tilde{A}(x)_P = \frac{\sum_{k=1}^{4}(3.00+3.25+3.00+2.75)}{4} = 3.00$$

The calculated value (3.00) which represents linguistic term P is the membership value equal to 1. By using the same procedure, the MFs for all the other linguistic terms can be obtained. After calculating all MFs, they are represented in Figure 6.5.

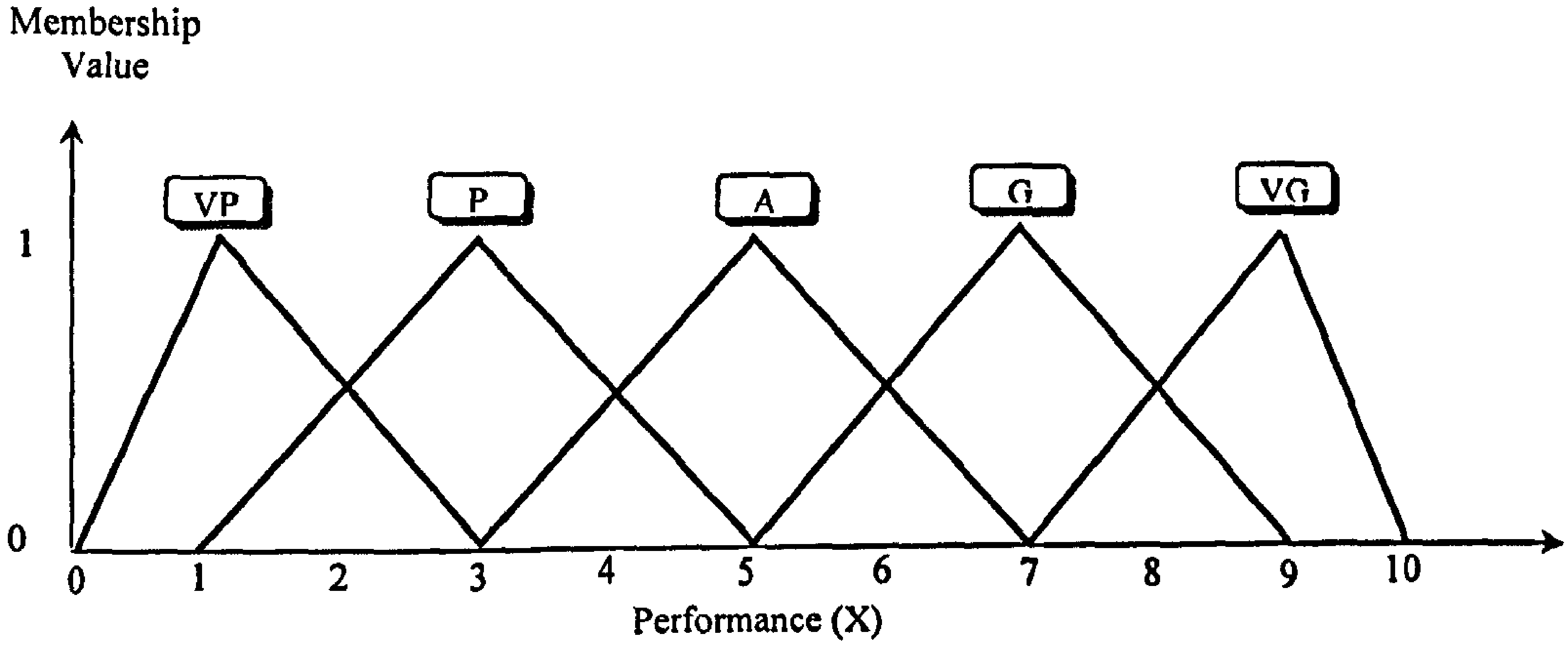


Figure 6.5: MFs for Determination of Fuzzy Performance Ratings of Criteria

Table 6.7 shows the associated triangular fuzzy number values of linguistic terms. The lowest triangular fuzzy number values (performance ratings) are represented by linguistic term VP and the highest triangular fuzzy number values are represented by linguistic term VG.

Table 6.7: Associated Triangular Fuzzy Numbers of Linguistic Terms

Linguistic Term	Associated Triangular Fuzzy Number
Very Poor (VP)	(0, 1, 3)
Poor (P)	(1, 3, 5)
Average (A)	(3, 5, 7)
Good (G)	(5, 7, 9)

Very Good (VG)	(7, 9, 10)

The fuzzy TOPSIS matrix is developed based on the fuzzy performance ratings of all the criteria. The obtained fuzzy performance ratings highlight all the criteria as benefit criteria. All the cost criteria are changed to benefit criteria by using this approach. From now on, all the criteria can be considered as benefit criteria (common utility space). All the fuzzy performance ratings of the EXP criteria (transferred quantitative criteria) are estimated by using the following approach; this is explained by using an example of ACC of 2ST. In order to perform the calculations Eq. (6.6) is used.

$$\begin{aligned} r_{12} &= 0.1100 \times (5, 7, 9) + 0.8900 \times (3, 5, 7) \\ &= (0.5500, 0.7700, 0.9900) + (2.6700, 4.4500, 6.2300) \\ &= (3.2200, 5.2200, 7.2200) \end{aligned}$$

In this study the judgements of the four experts are implemented to estimate the values of the original qualitative criteria. This is explained through an example of VIB of 2ST and Table 6.8 shows the judgments of the four experts. Eqs. (6.6) and (6.14) are used to synthesise those judgements and to estimate the triangular fuzzy numbers.

Table 6.8: Expert Judgements for VIB of 2ST

Expert No.	1	2	3	4
Belief Degree	(VG, 0.5; G, 0.5)	(VG, 0.3; G, 0.7)	(VG, 0.7; G, 0.3)	(VG, 0.8; G, 0.2)

$$r_{11} = \frac{1}{4}\left\{\begin{matrix}[0.5(7,9,10) + 0.5(5,7,9)] + [0.3(7,9,10) + 0.7(5,7,9)] + [0.7(7,9,10) + 0.3(5,7,9)] \\ [0.8(7,9,10) + 0.2(5,7,9)]\end{matrix}\right\}$$

$$r_{11} = \frac{1}{4}\left\{\begin{matrix}[(3.5,4.5,5.0) + (2.5,3.5,4.5)] + [(2.1,2.7,3.0) + (3.5,4.9,6.3)] + [(4.9,6.3,7.0) + (1.5,2.1,2.7)] \\ [(5.6,7.2,8.0) + (1.0,1.4,1.8)]\end{matrix}\right\}$$

$$r_{11} = \frac{1}{4}\{(24.6, 32.6, 38.3)\}$$

$$r_{11} = (6.1500, 8.1500, 9.5800)$$

The fuzzy TOPSIS matrix, including all the fuzzy performance ratings for each of the propulsion systems under consideration, is obtained and shown in Table 6.9.

Table 6.9: The Fuzzy TOPSIS Decision Matrix

	VIB $^{(C)}$	ACC $^{(C)}$	FOC $^{(C)}$	MRC $^{(C)}$	LOC $^{(C)}$	IC $^{(C)}$	CC $^{(C)}$	REL $^{(B)}$
2ST	(6.1500, 8.1500, 9.5800)	(3.2200, 5.2200, 7.2200)	(4.5100, 6.5100, 8.5100)	(7.0000, 9.0000, 10.0000)	(6.0500, 8.0500, 9.5200)	(3.2200, 5.2200, 7.2200)	(0.0000, 1.0000, 3.0000)	(6.2000, 8.2000, 9.6000)
4ST	(4.8500, 6.8500, 8.8300)	(2.5000, 4.5000, 6.5000)	(4.6800, 6.6800, 8.6800)	(6.5200, 8.5200, 9.7600)	(6.0500, 8.0500, 9.5200)	(2.4900, 4.4900, 6.4900)	(0.0000, 1.0000, 3.0000)	(4.7000, 6.7000, 8.7000)
RST	(3.5000, 5.5000, 7.5000)	(2.1300, 4.1300, 6.1300)	(5.3600, 7.3600, 9.1800)	(6.0600, 8.0600, 9.5300)	(6.0500, 8.0500, 9.5200)	(2.1300, 4.1300, 6.1300)	(0.0000, 1.0000, 3.0000)	(3.4500, 5.4500, 7.4500)
MSD	(3.0500, 5.0500, 7.0500)	(4.9700, 6.9700, 8.9700)	(6.8700, 8.8700, 9.9400)	(1.8300, 3.8300, 5.8300)	(0.0000, 1.0000, 3.0000)	(4.9700, 6.9700, 8.9700)	(4.7500, 6.7500, 8.7500)	(0.3300, 1.6500, 3.6500)
SSD	(0.1000, 1.2000, 3.2000)	(3.7200, 5.7200, 7.7200)	(7.0000, 9.0000, 10.0000)	(4.0200, 6.0200, 8.0200)	(0.8500, 2.7000, 4.7000)	(3.7200, 5.7200, 7.7200)	(7.0000, 9.0000, 10.0000)	(0.8800, 2.6500, 4.6500)
HDGT	(6.8500, 8.8500, 9.9300)	(5.7200, 7.7200, 9.3600)	(4.4500, 6.4500, 8.4500)	(2.0500, 4.0500, 6.0500)	(6.0500, 8.0500, 9.5200)	(5.7200, 7.7200, 9.3600)	(6.5000, 8.5000, 9.7500)	(3.3500, 5.3500, 7.3500)
ADGT	(6.9000, 8.9000, 9.9500)	(7.0000, 9.0000, 10.0000)	(0.0000, 1.0000, 3.0000)	(0.4400, 1.8700, 3.8700)	(7.0000, 9.0000, 10.0000)	(7.0000, 9.0000, 10.0000)	(6.5000, 8.5000, 9.7500)	(3.1500, 5.1500, 7.1500)
HDGTH	(4.7000, 6.7000, 8.7000)	(0.5000, 1.9900, 3.9900)	(5.3200, 7.3200, 9.1600)	(2.0500, 4.0500, 6.0500)	(6.0500, 8.0500, 9.5200)	(0.5000, 1.9900, 3.9900)	(1.5000, 3.5000, 5.5000)	(3.0000, 5.0000, 7.0000)
HDGTS	(4.6000, 6.6000, 8.6000)	(0.0000, 1.0000, 3.0000)	(5.3200, 7.3200, 9.1600)	(2.8700, 4.8700, 6.8700)	(6.0500, 8.0500, 9.5200)	(0.0000, 1.0000, 3.0000)	(1.5000, 3.5000, 5.5000)	(2.9000, 4.9000, 6.9000)
AGTSC	(3.8000, 5.8000, 7.8000)	(3.2000, 5.2000, 7.2000)	(0.9800, 2.9600, 4.9600)	(0.0000, 1.0000, 3.0000)	(6.9500, 8.9500, 9.9800)	(3.2000, 5.2000, 7.2000)	(1.5000, 3.5000, 5.5000)	(2.8000, 4.8000, 6.8000)

The developed fuzzy decision matrix (Table 6.9) includes eight criteria and ten alternatives. There are seven cost criteria and the only one benefit criterion is REL. In this study VIB is considered as a cost criterion in the fuzzy TOPSIS decision matrix, since when vibration increases, the economy of the ship decreases.

However, all the cost criteria are transformed into benefit criteria as described earlier.

6.5.4. Normalisation of Fuzzy Decision Matrix (*Step 4*)

In this step the normalisation is carried out for the fuzzy decision matrix shown in Table 6.9. Linear scale transform functions are used to ensure that the normalised triangular fuzzy numbers are included in the range of [0, 1]. Based on the technique, the cost benefit criteria are normalised by taking the maximum fuzzy number of all the alternatives and then dividing all the alternatives by the chosen maximum fuzzy number. Eq. (6.16) is employed to normalise all the criteria. For example, the normalisation can be shown as follows by using VIB of 2ST.

$$\tilde{r}_{11} = \frac{r_{11}}{9.95} = \left(\frac{6.1500}{9.9500}, \frac{8.1500}{9.9500}, \frac{9.5800}{9.9500}\right) = (0.6181, 0.8191, 0.9628)$$

The procedure which was discussed previously is used for the normalisation of all the criteria. All the normalised data are shown in Table 6.10.

Table 6.10: The Normalised Fuzzy Decision Matrix

	VIB $^{(C)}$	ACC $^{(C)}$	FOC $^{(C)}$	MRC $^{(C)}$	LOC $^{(C)}$	IC $^{(C)}$	CC $^{(C)}$	REL $^{(B)}$
2ST	(0.6181, 0.8191, 0.9628)	(0.3220, 0.5220, 0.7220)	(0.4510, 0.6510, 0.8510)	(0.7000, 0.9000, 1.0000)	(0.6050, 0.8050, 0.9520)	(0.3220, 0.5220, 0.7220)	(0.0000, 0.1000, 0.3000)	(0.6458, 0.8542, 1.0000)
4ST	(0.4874, 0.6884, 0.8874)	(0.2500, 0.4500, 0.6500)	(0.4680, 0.6680, 0.8680)	(0.6520, 0.8520, 0.9760)	(0.6050, 0.8050, 0.9520)	(0.2490, 0.4490, 0.6490)	(0.0000, 0.1000, 0.3000)	(0.4896, 0.6979, 0.9063)
RST	(0.3518, 0.5528, 0.7538)	(0.2130, 0.4130, 0.6130)	(0.5360, 0.7360, 0.9180)	(0.6060, 0.8060, 0.9530)	(0.6050, 0.8050, 0.9520)	(0.2130, 0.4130, 0.6130)	(0.0000, 0.1000, 0.3000)	(0.3594, 0.5677, 0.7760)
MSD	(0.3065, 0.5075, 0.7085)	(0.4970, 0.6970, 0.8970)	(0.6870, 0.8870, 0.9940)	(0.1830, 0.3830, 0.5830)	(0.0000, 0.1000, 0.3000)	(0.4970, 0.6970, 0.8970)	(0.4750, 0.6750, 0.8750)	(0.1042, 0.1719, 0.3802)
SSD	(0.0101, 0.1206, 0.3216)	(0.3720, 0.5720, 0.7720)	(0.7000, 0.9000, 1.0000)	(0.4020, 0.6020, 0.8020)	(0.0850, 0.2700, 0.4700)	(0.3720, 0.5720, 0.7720)	(0.7000, 0.9000, 1.0000)	(0.1146, 0.2760, 0.4844)
HDGT	(0.6884, 0.8894, 0.9980)	(0.5720, 0.7720, 0.9360)	(0.4450, 0.6450, 0.8450)	(0.2050, 0.4050, 0.6050)	(0.6050, 0.8050, 0.9520)	(0.5720, 0.7720, 0.9360)	(0.6500, 0.8500, 0.9750)	(0.3490, 0.5573, 0.7656)
ADGT	(0.6935,	(0.7000,	(0.0000,	(0.0440,	(0.7000,	(0.7000,	(0.6500,	(0.3281,

	0.8945, 1.0000)	0.9000, 1.0000)	0.1000, 0.3000)	0.1870, 0.3870)	0.9000, 1.0000)	0.9000, 1.0000)	0.8500, 0.9750)	0.5365, 0.7448)
HDGTH	(0.4724, 0.6734, 0.8744)	(0.5000, 0.1990, 0.3990)	(0.5320, 0.7320, 0.9160)	(0.2050, 0.4050, 0.6050)	(0.6050, 0.8050, 0.9520)	(0.1500, 0.1990, 0.3990)	(0.1500, 0.3500, 0.5500)	(0.3125, 0.5208, 0.7292)
HDGTS	(0.4623, 0.6633, 0.8643)	(0.0000, 0.1000, 0.3000)	(0.5320, 0.7320, 0.9160)	(0.2870, 0.4870, 0.6870)	(0.6050, 0.8050, 0.9520)	(0.0000, 0.1000, 0.3000)	(0.1500, 0.3500, 0.5500)	(0.3021, 0.5104, 0.7188)
AGTSC	(0.3819, 0.5829, 0.7839)	(0.3200, 0.5200, 0.7200)	(0.0980, 0.2960, 0.4960)	(0.0000, 0.1000, 0.3000)	(0.6950, 0.8950, 0.9980)	(0.3200, 0.5200, 0.7200)	(0.1500, 0.3500, 0.5500)	(0.2917, 0.5000, 0.7083)

The weights of each criterion are then taken into account and the weighted normalised fuzzy decision matrix is developed by employing Eq. (6.19). For instance, the weighted normalised triangular fuzzy numbers of VIB of 2ST are obtained as follows:

$$v_{11} = (0.6181, 0.8191, 0.9628) \times 0.4343 = (0.2684, 0.3557, 0.4181)$$

The weighted normalised fuzzy decision matrix is shown in Table 6.11.

Table 6.11: The Weighted Normalised Fuzzy Decision Matrix

	VIB $^{(C)}$	ACC $^{(C)}$	FOC $^{(C)}$	MRC $^{(C)}$	LOC $^{(C)}$	IC $^{(C)}$	CC $^{(C)}$	REL $^{(B)}$
2ST	(0.2684, 0.3557, 0.4181)	(0.0240, 0.0389, 0.0537)	(0.0433, 0.0626, 0.0818)	(0.0202, 0.0259, 0.0288)	(0.0137, 0.0182, 0.0215)	(0.0162, 0.0262, 0.0362)	(0.0000, 0.0039, 0.0116)	(0.1645, 0.2176, 0.2547)
4ST	(0.2117, 0.2990, 0.3854)	(0.0186, 0.0335, 0.0484)	(0.0450, 0.0642, 0.0834)	(0.0188, 0.0245, 0.0281)	(0.0137, 0.0182, 0.0215)	(0.0125, 0.0225, 0.0326)	(0.0000, 0.0039, 0.0116)	(0.1246, 0.1778, 0.2308)
RST	(0.1528, 0.2401, 0.3274)	(0.0159, 0.0308, 0.0457)	(0.0515, 0.0707, 0.0882)	(0.0175, 0.0232, 0.0274)	(0.0137, 0.0182, 0.0215)	(0.0107, 0.0207, 0.0308)	(0.0000, 0.0039, 0.0116)	(0.0915, 0.1446, 0.1977)
MSD	(0.1331, 0.2204, 0.3077)	(0.0370, 0.0519, 0.0668)	(0.0660, 0.0852, 0.0955)	(0.0053, 0.0110, 0.0168)	(0.0000, 0.0023, 0.0068)	(0.0249, 0.0350, 0.0450)	(0.0184, 0.0262, 0.0340)	(0.0265, 0.0437, 0.0968)
SSD	(0.0044, 0.0524, 0.1397)	(0.0277, 0.0426, 0.0575)	(0.0673, 0.0865, 0.0961)	(0.0116, 0.0173, 0.0231)	(0.0019, 0.0061, 0.0106)	(0.0187, 0.0287, 0.0388)	(0.0272, 0.0349, 0.0388)	(0.0292, 0.0702, 0.1234)
HDGT	(0.2990, 0.3893, 0.4334)	(0.0426, 0.0575, 0.0697)	(0.0428, 0.0620, 0.0812)	(0.0059, 0.0117, 0.0174)	(0.0137, 0.0182, 0.0215)	(0.0287, 0.0388, 0.0470)	(0.0252, 0.0330, 0.0378)	(0.0888, 0.1419, 0.1950)

ADGT	(0.3012, 0.3880, 0.4343)	(0.0521, 0.0671, 0.0745)	(0.0000, 0.0096, 0.0288)	(0.0013, 0.0054, 0.0111)	(0.0158, 0.0203, 0.0206)	(0.0351, 0.0452, 0.0502)	(0.0252, 0.0330, 0.0378)	(0.0836, 0.1366, 0.1897)
HDGTH	(0.2052, 0.2925, 0.3798)	(0.0373, 0.0148, 0.0297)	(0.0511, 0.0703, 0.0880)	(0.0059, 0.0117, 0.0174)	(0.0137, 0.0182, 0.0215)	(0.0075, 0.0100, 0.0200)	(0.0058, 0.0136, 0.0213)	(0.0796, 0.1327, 0.1858)
HDGTS	(0.2008, 0.2881, 0.3754)	(0.0000, 0.0075, 0.0224)	(0.0511, 0.0703, 0.0880)	(0.0083, 0.0140, 0.0198)	(0.0137, 0.0182, 0.0215)	(0.0000, 0.0050, 0.0151)	(0.0058, 0.0136, 0.0213)	(0.0769, 0.1300, 0.1831)
AGTSC	(0.1659, 0.2532, 0.3404)	(0.0238, 0.0387, 0.0536)	(0.0094, 0.0284, 0.0477)	(0.0000, 0.0029, 0.0086)	(0.0157, 0.0202, 0.0226)	(0.0161, 0.0261, 0.0361)	(0.0058, 0.0136, 0.0213)	(0.0743, 0.1274, 0.1804)

6.5.5. Obtaining FPIRP and FNIRP of Each Alternative (*Step 5*)

In this step first of all the fuzzy positive and negative ideal reference points are estimated for each alternative. Eqs. (6.20), (6.21), (6.22) and (6.23) are employed to obtain the fuzzy positive and negative ideal reference points.

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

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

The distances from each propulsion system to FPIRP and FNIRP are calculated for all the alternatives by employing Eqs. (6.24) and (6.25) respectively. An example has been shown to highlight the calculation process for the 2ST propulsion system and all the results are shown in Table 6.12.

$$d_1^{+} = \left\{ \begin{array}{l} \sqrt{\frac{1}{3}\left[(0.2684-1)^2+(0.3557-1)^2+(0.4181-1)^2\right]}+\sqrt{\frac{1}{3}\left[(0.0240-1)^2+(0.0389-1)^2+(0.0537-1)^2\right]}+ \\ \sqrt{\frac{1}{3}\left[(0.0433-1)^2+(0.0626-1)^2+(0.0818-1)^2\right]}+\sqrt{\frac{1}{3}\left[(0.0202-1)^2+(0.0259-1)^2+(0.0288-1)^2\right]}+ \\ \sqrt{\frac{1}{3}\left[(0.0137-1)^2+(0.0182-1)^2+(0.0215-1)^2\right]}+\sqrt{\frac{1}{3}\left[(0.0162-1)^2+(0.0262-1)^2+(0.0362-1)^2\right]}+ \\ \sqrt{\frac{1}{3}\left[(0.0000-1)^2+(0.0039-1)^2+(0.0116-1)^2\right]}+\sqrt{\frac{1}{3}\left[(0.1645-1)^2+(0.2176-1)^2+(0.2547-1)^2\right]} \end{array} \right\}$$
$$=7.2688$$

$$d_1^- = \left\{ \begin{array}{l} \sqrt{\frac{1}{3}\left[(0.2684-0)^2+(0.3557-0)^2+(0.4181-0)^2\right]}+\sqrt{\frac{1}{3}\left[(0.0240-0)^2+(0.0389-0)^2+(0.0537-0)^2\right]}+ \\ \sqrt{\frac{1}{3}\left[(0.0433-0)^2+(0.0626-0)^2+(0.0818-0)^2\right]}+\sqrt{\frac{1}{3}\left[(0.0202-0)^2+(0.0259-0)^2+(0.0288-0)^2\right]}+ \\ \sqrt{\frac{1}{3}\left[(0.0137-0)^2+(0.0182-0)^2+(0.0215-0)^2\right]}+\sqrt{\frac{1}{3}\left[(0.0162-0)^2+(0.0262-0)^2+(0.0362-0)^2\right]}+ \\ \sqrt{\frac{1}{3}\left[(0.0000-0)^2+(0.0039-0)^2+(0.0116-0)^2\right]}+\sqrt{\frac{1}{3}\left[(0.1645-0)^2+(0.2176-0)^2+(0.2547-0)^2\right]} \end{array} \right\}$$

$$=0.7513$$

Table 6.12: Distance from Each Alternative to FPIRP and FNIRP

Alternative	d_q^+	d_q^-
2ST	7.2688	0.7513
4ST	7.3615	0.6649
RST	7.4526	0.5768
MSD	7.5185	0.5103
SSD	7.6511	0.3873
HDGT	7.2698	0.7500
ADGT	7.3149	0.7072
HDGTH	7.4271	0.6001
HDGTS	7.4549	0.5759
AGTSC	7.4940	0.5379

The results shown in Table 6.12 are used to calculate CC_q. This is carried out in the next step.

6.5.6. Calculation of Closeness Coefficient (*Step 6*)

CC_q can be obtained by using Eq. (6.26). A propulsion system with a CC_q value closest to 1 has the shortest distance from the fuzzy positive ideal reference point and the largest distance from the fuzzy negative ideal reference point. In other words, a propulsion system with a larger CC_q value is more desirable. By using 2ST as an example, the calculation of CC_q can be shown as follows:

$$CC_1 = \frac{0.7513}{0.7513+7.2688} = 0.0937$$

A similar procedure is implemented for all the other alternatives in order to calculate CC_q. Finally, all CC_q values and the rankings of the propulsion systems are shown in Table 6.13.

Table 6.13: CC_q Values and Rankings of All Propulsion Systems

Alternative	CC_q	**Ranking**
2ST	0.0937	**01**
4ST	0.0828	**04**
RST	0.0718	**06**
MSD	0.0636	**09**
SSD	0.0482	**10**
HDGT	0.0932	**02**
ADGT	0.0882	**03**
HDGTH	0.0747	**05**
HDGTS	0.0711	**07**
AGTSC	0.0670	**08**

6.6. Discussion and Validation of the Model

From the obtained results it is clear that 2ST is the most economical propulsion system and SSD is the least economical propulsion system. For instance, VIB and REL criteria of 2ST have performance ratings (6.1500, 8.1500, 9.5800) and (6.2000, 8.2000, 9.6000) respectively (Table 6.9). The performance ratings of VIB and REL criteria of SSD are (0.1000, 1.2000, 3.2000) and (0.8800, 2.6500, 4.6500). It can be seen that the performance ratings of SSD are much lower than the corresponding performance ratings of 2ST. In this research it is considered that higher values of performance ratings are more desirable. When compared with other propulsion systems considered in this chapter, 2ST has the greatest number of criteria with high weightings which are assessed to high performance ratings values. This can be seen in Table 6.9. As such the most economical propulsion system should be 2ST.

The performance ratings of the annual EXP criteria of SSD are slightly higher than those of 2ST. However, when compared with other propulsion systems considered in this chapter, SSD has the greatest number of criteria with high weightings which are assessed to low performance ratings values. Therefore, the least economical propulsion system should be SSD. This is in harmony with the results obtained previously as 2ST has the top ranking and SSD has achieved the lowest ranking.

It should be noted that HDGT has higher performance ratings for VIB criterion than that of 2ST. However, the performance ratings of HDGT for other criteria with high weightings are slightly lower than the corresponding performance ratings of 2ST. Therefore, the ranking of HDGT has to be almost similar to or lower than the ranking of 2ST. It has also to be noticed that ADGT plant has higher performance ratings for VIB criterion than that of both 2ST and HDGT. The ADGT has the highest performance ratings from all the propulsion systems in this study for VIB criterion. However, performance ratings related to several criteria of ADGT are extremely lower than the corresponding performance ratings of both 2ST and HDGT. Therefore, the ranking of ADGT should be lower than the rankings of both 2ST and HDGT. This is also in harmony with the results achieved in Table 6.13. Therefore, it can be said that the obtained results seem reasonable.

In order to further validate the developed model, a sensitivity analysis is carried out. It will be conducted under six conditions, which have been shown in Table 6.14. The conditions are based on percentage increase or decrease in the associated weights of all the criteria in the hierarchy.

Table 6.14: Conditions for Changing the Weight Values as Percentages

Condition	Percentage
1	+5%
2	+10%
3	+20%
4	-5%
5	-10%
6	-20%

Figure 6.6 shows the variations of CC_q values with different conditions. The actual CC_q values and the rankings for the ten alternatives under consideration can be found in Appendix 6.3.

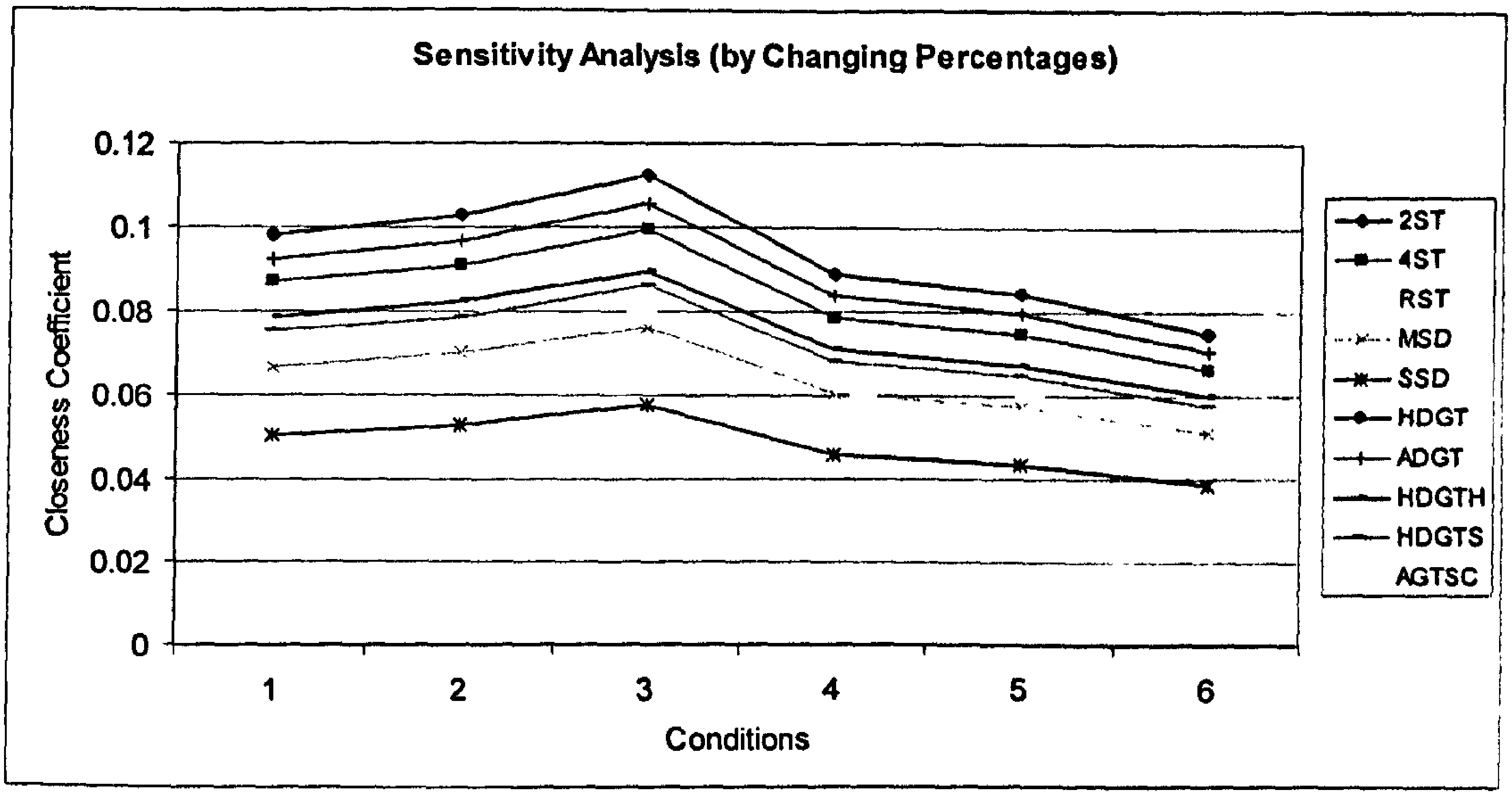


Figure 6.6: Sensitivity Analysis (by Changing Percentages)

It can be seen from Figure 6.6 that the CC_q values consistently increase with the increase in weight values as percentages (Conditions 1 to 3). If the model is correct such variations of the CC_q values should be in a similar pattern. By referring to Appendix 6.3 it can be seen that the rankings of the ten propulsion systems remain unchanged when the weights of the criteria are increased as percentages from Conditions 1 to 2.

However, when the weights of the criteria are increased as percentages from Conditions 2 to 3, the ranking positions of 2ST and HDGT have interchanged. The VIB criterion was originally given a very high weighting when compared with other criteria. When the weightings of all the criteria are increased by 20% the actual increase in weighting value for the VIB criterion is much greater than the increase in weighting values of the other criteria. It can be seen from Table 6.13 that the CC_q values of 2ST and HDGT are almost similar. Since the performance ratings for VIB criterion of HDGT is higher than that of 2ST (Table 6.9), it is highly possible to raise the ranking of HDGT above that of 2ST when the weighting of VIB criterion is increased as percentages.

When the weights of the criteria are decreased as percentages (Conditions 4 to 6) the rankings remain unchanged (Appendix 6.3). Although 2ST has a lower performance rating for VIB criterion than that of HDGT, Table 6.13 shows that the top ranking belongs to 2ST, followed by the ranking of HDGT. As such a 20% decrease in weighting value for the VIB criterion should not affect this ranking order, although the difference between CC_q values of 2ST and HDGT can vary. This is in agreement with the results obtained under Conditions 4 to 6. Therefore, the developed model seems reasonable.

Sensitivity analysis is also conducted by exchanging the weights of criteria as shown in Table 6.15. The variations of the CC_q values of the ten propulsion plants when the weights of criteria are exchanged are shown in Figure 6.7. The variations of rankings of the ten propulsion systems under the 28 conditions shown in Table 6.15 can be obtained from Appendix 6.4.

Table 6.15: Conditions for Exchanging the Weights

Conditions	VIB	ACC	FOC	MRC	LOC	IC	CC	REL
0	0.4343	0.0745	0.0961	0.0288	0.0226	0.0502	0.0388	0.2547
1	0.0745	0.4343	0.0961	0.0288	0.0226	0.0502	0.0388	0.2547
2	0.0961	0.0745	0.4343	0.0288	0.0226	0.0502	0.0388	0.2547
3	0.0288	0.0745	0.0961	0.4343	0.0226	0.0502	0.0388	0.2547
4	0.0226	0.0745	0.0961	0.0288	0.4343	0.0502	0.0388	0.2547
5	0.0502	0.0745	0.0961	0.0288	0.0226	0.4343	0.0388	0.2547
6	0.0388	0.0745	0.0961	0.0288	0.0226	0.0502	0.4343	0.2547
7	0.2547	0.0745	0.0961	0.0288	0.0226	0.0502	0.0388	0.4343
8	0.4343	0.0961	0.0745	0.0288	0.0226	0.0502	0.0388	0.2547
9	0.4343	0.0288	0.0961	0.0745	0.0226	0.0502	0.0388	0.2547
10	0.4343	0.0226	0.0961	0.0288	0.0745	0.0502	0.0388	0.2547
11	0.4343	0.0502	0.0961	0.0288	0.0226	0.0745	0.0388	0.2547
12	0.4343	0.0388	0.0961	0.0288	0.0226	0.0502	0.0745	0.2547
13	0.4343	0.2547	0.0961	0.0288	0.0226	0.0502	0.0388	0.0745
14	0.4343	0.0745	0.0288	0.0961	0.0226	0.0502	0.0388	0.2547
15	0.4343	0.0745	0.0226	0.0288	0.0961	0.0502	0.0388	0.2547
16	0.4343	0.0745	0.0502	0.0288	0.0226	0.0961	0.0388	0.2547
17	0.4343	0.0745	0.0388	0.0288	0.0226	0.0502	0.0961	0.2547
18	0.4343	0.0745	0.2547	0.0288	0.0226	0.0502	0.0388	0.0961
19	0.4343	0.0745	0.0961	0.0226	0.0288	0.0502	0.0388	0.2547
20	0.4343	0.0745	0.0961	0.0502	0.0226	0.0288	0.0388	0.2547
21	0.4343	0.0745	0.0961	0.0388	0.0226	0.0502	0.0288	0.2547
22	0.4343	0.0745	0.0961	0.2547	0.0226	0.0502	0.0388	0.0288
23	0.4343	0.0745	0.0961	0.0288	0.0502	0.0226	0.0388	0.2547
24	0.4343	0.0745	0.0961	0.0288	0.0388	0.0502	0.0226	0.2547
25	0.4343	0.0745	0.0961	0.0288	0.2547	0.0502	0.0388	0.0226

26	0.4343	0.0745	0.0961	0.0288	0.0226	0.0388	0.0502	0.2547
27	0.4343	0.0745	0.0961	0.0288	0.0226	0.2547	0.0388	0.0502
28	0.4343	0.0745	0.0961	0.0288	0.0226	0.0502	0.2547	0.0388

Conducting a sensitivity analysis by exchanging relative weights of criteria demonstrates the change in suitability of each propulsion system when the relative importance of the criteria changes. It has to be noted that in any case 2ST is always ranked in the top five places (Appendix 6.4).

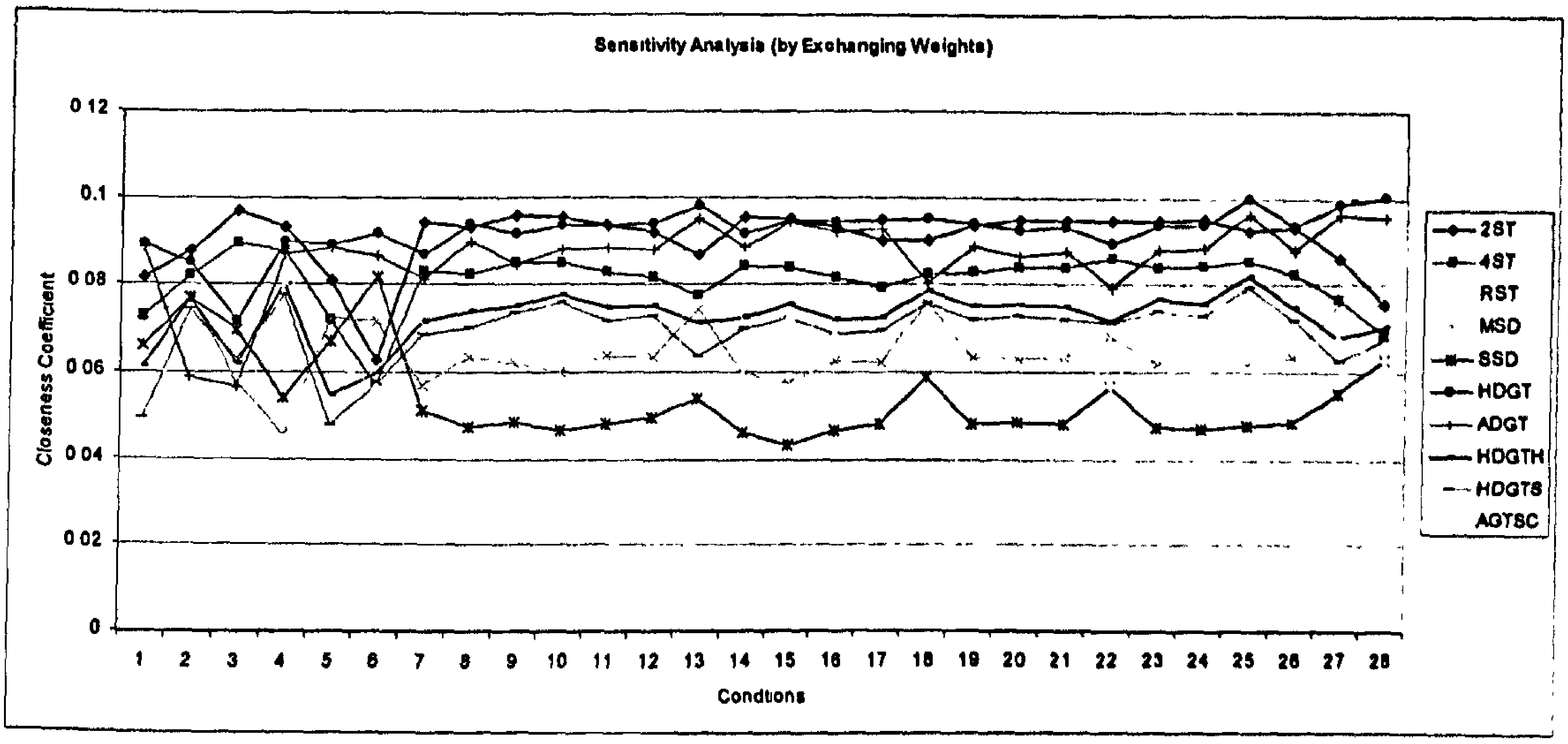


Figure 6.7: Sensitivity Analysis (by Exchanging Weights) Line Graph

The main aim of this chapter (Chapter 6) was to select the most economical propulsion system with the consideration of vibration characteristics. The selected most economical propulsion system was applied to a ship of 20000 kW propulsion power. This was achieved by conducting a cost benefit assessment and decision making within the Formal Safety Assessment (FSA) framework.

The developed model can be applied to any type of ship for the selection of a propulsion system based on the decision maker's requirement. This chapter concludes the application of FSA for SHV modelling.

6.7. Conclusion

SHV is mainly caused by the propulsion system of the ship. In this study a subjective cost benefit analysis approach was developed by utilising the fuzzy TOPSIS technique for the selection of the best propulsion system on an economic basis with the consideration of vibration characteristics. Such a combination of fuzzy sets and TOPSIS (fuzzy TOPSIS) can be employed as an alternative tool for cost benefit analysis in situations where both qualitative and quantitative data have to be synthesised.

This study provides a subjective cost benefit analysis approach especially for ship designers and ship owners. By using the developed generic model they can choose the best propulsion system based on the requirements of multiple criteria including vibration characteristics, annual expenses and reliability. The preference can be given by changing the allocated weight of the criterion. The sensitivity analysis conducted in this study was useful to find out the sensitiveness of the model for each input changes. Such an approach provided a platform to partially validate the model. It is concluded that the methodology proposed in this chapter possesses significant potential for the cost benefit analysis and decision making of the FSA methodology. Although the developed methodology is presented on the basis of the specific context in SHV modelling, it can also, with domain-specific knowledge, be tailored to facilitate cost benefit analysis and decision making in other application areas where a high level of uncertainty in data is involved.

Chapter 7 – Conclusions and Implications

SUMMARY

Highlighting the research contribution, final conclusions and recommendations of application of Formal Safety Assessment (FSA) for Ship Hull Vibration (SHV) modelling are drawn by summarising the research outcomes of the thesis. Implications for further research are described based on the key findings and limitations of this PhD research.

7.1. Research Contribution

SHV problems onboard can lead to serious accidents. Therefore, SHV related safety has to be improved; this can be carried out by using scientific risk assessment methodologies. The findings from the literature review have exposed that there are no conceptual risk assessment methodologies available for SHV problems and the risk assessment of SHV is closely associated with a high level of uncertainty. Thus, Chapters 3, 4, 5, and 6 have demonstrated the risk assessment of SHV based on safety principles of FSA under a high level of uncertainty. The developed novel methodologies are generic in nature and can be applied in any situation. In summary, these novel methodologies can be concluded as follows:

- Combining the fuzzy rule base and ER to develop a novel approach to estimate the risk of SHV based on identified hazards (Chapter 3).
- Combining the continuous fuzzy sets, fuzzy rule base and ER to generate a novel approach for decision making based on risk estimation results of SHV (Chapter 4).
- Combining the discrete fuzzy sets and AHP to create a novel approach for risk control options selection and decision making, based on identified high risk estimation areas leading to SHV (Chapter 5).
- Combining AHP, continuous fuzzy sets and TOPSIS to construct a novel approach for cost benefit assessment and decision making in order to select the most desirable alternative taking into account the SHV aspect (Chapter 6).

These novel generic methodologies are well suited for the application to problems with a high level of uncertainty. Additionally, it is particularly noteworthy that the combination of risk assessment methods can generate powerful supporting tools in SHV risk assessment, especially under high uncertainties. The significant contributions of this research should be beneficial to industry as well as academia. In certain cases, it may be time consuming to conduct risk assessment of SHV utilising some of the novel methodologies developed in this research. However, these novel methodologies pose enormous potential as important aids and effective alternatives for increasing the safety of the shipboard environment. Therefore, their implementation should have a highly beneficial effect in real life.

7.2. Final Conclusions and Recommendations

As described in the previous section, the risk assessment of SHV was conducted under uncertainties by developing novel methodologies. Each novel methodology illustrates an alternative approach for conducting risk assessment under uncertainties with a combination of risk assessment techniques. A bottom-up risk assessment approach was implemented throughout the thesis for the development of the generic models. The formulation of the novel methodologies developed in this research and their recommended applications can be summarised as follows:

- In Chapter 3 risk estimation was conducted based on the identified hazards. It involved both quantitative and qualitative criteria assessment. An ER approach was implemented to conduct risk estimation as it is a highly recognised uncertainty treatment method. However, criteria should be represented in common utility space (same universe) in order for them to be synthesised. Quantitative criteria were transformed to qualitative criteria by utilising a rule based quantitative data transformation technique. A mapping process was developed to transform qualitative lower level criteria into upper level criteria. All such transformations are based on a fuzzy rule base approach. Finally, ER was used for synthesis. This approach produces a subjective way to handle SHV problems under a high level of uncertainty. The proposed methodology can be used for risk estimation purposes in ship vibration studies. The developed approach can also be used to provide a benchmark for ship classification purposes. Therefore, this novel method is highly recommended to personnel who deal with ship vibration risk estimation problems.

- In Chapter 4 decision making was conducted based on the information produced from risk estimation of SHV. Novel uncertainty treatment methods were developed for transformation of interval quantitative and qualitative criteria using continuous fuzzy sets. A fuzzy rule base was implemented to carry out the mapping process. ER was used for synthesis and obtaining risk estimations of different ships. This was carried out after the normalisation of the associated criteria. The novel methodology proposed by using continuous fuzzy sets, a fuzzy rule base and ER can be recommended for ship selection under uncertainties.

- In Chapter 5 risk control option selection and decision making was conducted based on the identified high risk areas leading to the occurrence of SHV. A novel approach for the treatment of uncertainty was developed by combining discrete fuzzy sets and AHP. The novel method of selecting the risk control option by considering high risk areas provides a subjective way of modelling possible failure events onboard. This novel method is highly recommended to ship owners and engineers to identify high risk areas and also to carry out risk control options selection.

- In Chapter 6 cost benefit assessment and decision making was conducted by considering a reasonable amount of propulsion systems. AHP was used for the allocation of weights of the decision making criteria. Continuous fuzzy sets and TOPSIS were utilised for cost benefit assessment. The fuzzy TOPSIS technique is still a comparatively new approach. In this study such a novel technique was further strengthened by minimising the identified weaknesses. The selection of a propulsion system by using such a technique is recommended to ship designers and ship owners who aim at controlling SHV.

The treatment of uncertainty is a major issue in risk assessment. This study provides different methods for the treatment of uncertainty with the aid of expert judgements. The deficiencies in risk assessment due to high levels of uncertainty should be compensated for the general estimation capacity of persons who are capable of grasping the essence of the subject matter, even if it is vague or unclear. As such, the experience and knowledge of the experts consulted are vital because the viability of uncertainty treatment methods developed in this research is dependent upon their professional judgements.

The case studies of practical situations in this research have produced reasonable outcomes. This adds weight to the potential of the novel analytical models developed in this PhD study to improve the safety of the shipboard environment. This PhD study not only opens a new path for improving safety onboard by addressing SHV problems but also provides novel uncertainty treatment methods which can be used in any other industry for risk assessment purposes. As a final conclusion, the novel methodologies developed in this research can be integrated to provide a platform on which risk assessment of SHV can be facilitated by following the safety principles of FSA where traditional techniques cannot be utilised with confidence.

7.3. Limitation of Research

In order to fully validate the research outcomes (results), a benchmark, based on previous research, is often used and then a comparison between the two is conducted. However, the developed methodologies in Chapters 3, 4, 5, and 6 are brand-new. As such there are no benchmarks available to carry out a full validation. Lack of the data has also made a full validation of the proposed methodologies challenging. The developed methodologies may be applied in any circumstances, but they can be best used in situations where high levels of uncertainty exist, because the methodologies effectively quantify expert judgements which are often expressed qualitatively.

The opinions of experts are vital when the developed methodologies are applied in real case studies such as those described in this research. If the experts consulted do not have sufficient knowledge in the area under investigation, the outcomes of the methodologies may be poor. In addition, there are further limitations related to the methodologies constructed in this research. They are described as follows:

In Chapter 3 the experts have given fixed sets of linguistic terms (Tables 3.2-3.6) to represent qualitative criteria. Also in Chapter 4, for quantitative criteria modelling, the experts have allocated fixed sets of linguistic terms with a consistent number of linguistic terms (six) (Table 4.3). This may not be the case in every situation. Appropriate fuzzy rules may have to be developed in situations where the experts have given the freedom of many and different types of linguistic terms. Consequently, when the mapping process is conducted, many different algorithms may have to be developed.

In Section 4.4.4 of Chapter 4 the novel approach developed for qualitative interval data transformation is applicable under situations where the experts give a small range of belief degrees associated with a linguistic term. For instance, in situations where the difference between the upper and lower belief degrees for a linguistic term is less than 5%, then the developed algorithm is well suited. However, if the experts give a wide range of interval values associated with a linguistic term (i.e. a large difference between the upper and lower belief degrees), the developed algorithm may not be suitable.

In Chapter 5 the normalised numerical values of the seven linguistic terms used for criteria comparisons (Table 5.6) are within the scale from 0.03 to 1.00. Based on this scale, the pairwise comparison can be conducted to compare less important criteria. When more important criteria have to be considered the scale implemented here may not be appropriate. This problem may be overcome by changing the importance scale (categories) shown in Table 5.5. The importance scale in Table 5.5 has been developed through many research activities and case studies. Obtaining a new scale may be challenging as well as time consuming.

In Chapter 6 the fuzzy TOPSIS decision matrix (Table 6.9) was developed by using expert judgements. Throughout this PhD thesis four experts have been consulted and each expert's experience and knowledge in the field was considered the same. As such, the importance of each expert was equal throughout the thesis. Based on the algorithm developed in Eq. (6.14), it is only possible to use experts with similar experience and knowledge. This may be highlighted as a disadvantage when the fuzzy TOPSIS technique is applied where multiple experts with different levels of knowledge and backgrounds are consulted.

Finally, the literature review conducted in Chapter 2 and risk assessment of SHV conducted in Chapters 3, 4, 5, and 6 were integrated using the flexible structure of FSA shown in Figure 2.6. The novel methodologies developed in this research can be utilised, not only for SHV studies, but also in any other situations, since they are generic in nature. However, there are some limitations with regard to the developed methodologies. Further research is required to address these limitations.

7.4. Implications for Further Research

On the basis of the key findings and limitations of this PhD research, further research will be needed in a number of areas. The major challenge of conducting this research was the high level of uncertainty which arises from the lack of data for use in risk assessment. The confidence and effectiveness of application of the FSA methodology is highly dependent on the reliability of systems' failure and accident data. It was found that many organisations dealing with ship vibration problems have a poor organisational structure. This research shows the importance of recording relevant vibration accident data for conducting risk assessment to obtain reasonable results. It is anticipated that the application of FSA may trigger the organisations concerned about ship vibrations to collect the relevant data by improving their organisational structure. The organisations may improve their organisational structure by implementing the following steps:

- Keep a separate log book for each ship to record vibration problems onboard.
- Encourage engineers who work onboard to record failures of components due to vibration problems and report them to the relevant authority.
- Keep health records for workers under health surveillance.
- Keep a record of the risk assessment and control actions.
- Review and update the risk assessment regularly.

The analysis of historical failure data conducted shows that general cargo ships have the highest propulsion system vibration defects, followed by oil tankers. However, ship hull defects induced by SHV were unacceptably high for oil tankers compared with all other ship types. It was found that the vibration related maintenance activities on such cargo ships are almost non existent. Further research is required to determine the reasons for the high level of vibration problems onboard cargo ships. Development of a novel vibration related maintenance model will also be beneficial under such circumstances.

Appropriate training and educational programmes could be developed for the crew identifying ways in which ship vibration problems could be prevented and how such problems should be dealt with should they occur. Such training programmes could become the starting point for the development of a safety culture within the ship vibration industry. The outcome of the risk assessment of ship vibrations may be used to identify areas in which development of such training and education programmes is required. This could lead to the reduction of human error onboard which is one of the leading contributory factors for marine accidents (IMO MSC/Circ. 565, 2001). The findings and results produced in this research can also be helpful in conducting human error analysis.

There are some limitations of the generic uncertainty treatment methods developed in this research. Further research would be needed to improve these novel methods. Since these methods are generic they can be applied and improved in other industries such as nuclear, oil and gas, and aviation. Furthermore, the development of software tools incorporating the developed models in this research may be potentially useful.

The marine industry is heading towards a goal-setting risk-based regime under the safety principles of FSA, which gives decision makers more flexibility for developing and utilising novel risk assessment methods; one of which is a subjective modelling approach. The novel analytical models developed in this research can be further improved and validated with more case studies relating to SHV. This PhD research provides a platform on which further research on risk assessment of SHV, based on the safety principles of FSA, could be undertaken to improve the safety of the shipboard environment.

References

Abrahamsen, K.A. (2005), "Noise Control for Noise Sensitive Vessels", *Proceedings of the 1st International Ship Noise and Vibration Conference*, 20-21 June, London, United Kingdom, pp. 1-15.

ABS (2001a), "Guide for Passenger Comfort on Ships", *American Bureau of Shipping*, December, pp. 1-30.

ABS (2001b), "Passengers, Crews and Fast Ferries", *American Bureau of Shipping*, March, pp. 1-12.

ABS (2002), "Guide for Crew Habitability on Offshore Installations", *American Bureau of Shipping*, May, pp. 1-112.

ABS (2006a), "Guidance Notes on Ship Vibration", *American Bureau of Shipping*, April, pp. 1-85.

ABS (2006b), "Guidance Notes on Propulsion Shafting Alignment", *American Bureau of Shipping*, April, pp. 1-120.

AFSA (2000), "Air Force System Safety Handbook", *Air Force Safety Agency*, July, pp. 1-152.

Anderson, D.R., Sweeney, D.J. & Williams, T.A. (2003), "An Introduction to Management Science: Quantitative Approaches to Decision Making", Melissa Accuna, 10th Edition, pp. 706-718, ISBN: 0-324-14563-2.

Ang, A.H.S. & Tang, W.H. (1984), "Probability Concepts in Engineering Planning and Design", John Wiley Sons.

Anon (1989), "Counteracting Vibration", *Marine Engineers Review*, January, pp. 24-26.

Anon (1999), "Noise and Vibration", *Marine Engineers Review*, October, pp. 13-17.

Arbel, A. & Vargas, L.G. (1993), "Preference Simulation and Preference Programming: Robustness Issues in Priority Deviation", *European Journal of Operational Research*, Vol. 69, No. 2, pp. 200-209.

Arslan, T. & Khisty, C.J. (2005), "A Rational Reasoning Method from Fuzzy Perceptions in Route Choice", *Fuzzy Sets and Systems*, Vol. 150, No. 3, pp. 419-435.

Asmussen, I. & Muller-Schmerl, A. (1995), "Consideration of Medium-Speed Four-Stroke Engines in Ship Vibration Analyses", *Proceedings of the 1st International Conference on Marine Technology*, September, Szczecin, Poland, pp. 367-374.

Ayag, Z. (2005), "A Fuzzy AHP based Simulation Approach to Concept Evaluation in a NPD Environment", *IIE Transactions*, Vol. 37, pp. 827-842.

Bhangale, P.P., Agrawal, V.P. & Saha, S.K. (2004), "Attribute based Specification, Comparison and Selection of a Robot", *Mechanism and Machine Theory*, Vol. 39, No. 12, pp. 1345-1366.

Bottani, E. & Antonio, R. (2006), "A Fuzzy TOPSIS Methodology to Support Outsourcing of Logistics Services", *Supply Chain Management*, Vol. 11, No. 4, pp. 294-308.

Bowles, J.B. & Pelaez, C.E. (1995), "Fuzzy Logic Prioritization of Failures in a System Failure Mode, Effects and Criticality Analysis", *Reliability Engineering and System Safety*, Vol. 50, No. 2, pp. 203-213.

Brescia, G., Lavini, G. & Avellino, G. (2001), "Designing a 30-Knot Ferry for Low Vibration Levels", *Naval Architect*, September, pp. 7-12.

Broadbent, D.E. (1975), "The Magic Number Seven After Fifteen Years", In. Kennedy, A and Wilkes, A. (Eds.), Studies in Long-Term Memory, New York: Wiley, pp. 3-18.

Brown, A. & Haugene, B. (1998), "Assessing the Impact of Management and Organizational Factors on the Risk Tanker Grounding", *Proceedings of the*

International Offshore and Polar Engineering Conference, 24-29 May, Canada, Vol. 4, pp. 469-476.

Brownlie, K. (1998), "Controllable Pitch Propellers", The Institute of Marine Engineers, ISBN: 0 90253601 X.

Chan, F.T.S., Chan, M.H. & Tang, N.K.H. (2000), "Evaluation Methodologies for Technology Selection", *Journal of Materials Processing Technology*, Vol. 107, No. 1, pp. 330-337.

Chang, P.C. & Liao, T.W. (2006), "Combining SOM and Fuzzy Rule Base for Flow Time Prediction in Semiconductor Manufacturing Factory", *Applied Soft Computing Journal*, Vol. 6, No. 2, pp. 198-206.

Chen, C.T. (2000), "Extensions of the TOPSIS for Group Decision Making under Fuzzy Environment", *Fuzzy Sets and Systems*, Vol. 114, pp. 1-9.

Chen, K., Russell, B. & Jacobson, C. (2001), "MCE-RISK: Integrating Multicriteria Evaluation and GIS for Risk Decision-Making in Natural Hazards", *Environmental Modelling and Software*, Vol. 16, No. 4, pp. 387-397.

Chen, S.J. & Hwang, C.L. (1992), "Fuzzy Multiple Attribute Decision Making: Methods and Applications", Springer-Verlag Berlin, ISBN: 3540549986.

Cheng, C.H. (1997), "Evaluating Naval Tactical Missile Systems by Fuzzy AHP based on the Grade Value of Membership Function", *European Journal of Operational Research*, Vol. 96, No. 2, pp. 343-350.

Cheng, C.H., Yang, K.L. & Hwang, C.L. (1999), "Evaluating Attack Helicopters by AHP based on Linguistic Variable Weight", *European Journal of Operational Research*, Vol. 16, No. 2, pp. 423-435.

Colombo, A. & Chilo, B. (1984), "Experimental Verifications of a Theoretical Procedure for Propeller-Induced Hull Pressure Calculations", *Marine Technology*, Vol. 21, No. 2, pp. 119-133.

Drake, P.R. (1998), "Using the Analytic Hierarchy Process in Engineering Education", *International Journal of Engineering Education*, Vol. 14, No. 3, pp. 191-196.

Eleye-Datubo, A.G. (2006), "Integrated Risk-Based Assessment Modelling of Safety-Critical Marine and Offshore Applications", *PhD Thesis*, School of Engineering, Liverpool John Moores University, United Kingdom.

Fitzsimmons, P.A. (1977), "Propeller Excited Vibration: A Cavitation Criterion for the Assessment of Scaled Model Wakes", *Naval Architect*, No. 6, pp. 203-205.

Fu, A.W., Wong, M.H., Sze, S.C., Wong, W.C., Wong, W.L. & Yu, W.K. (1998), "Finding Fuzzy Sets for the Mining Fuzzy Association Rules for Numerical Attributes", *Proceedings of International Symposium on Intelligent Data Engineering and Learning (IDEAL)*, 14-16 October, Hong Kong, pp. 263-268.

Gabriel, R. & Atlar, M. (1998), "Calculation of the Performance of a Ship Propeller with Cyclic Blade Pitch Control", *International Shipbuilding Progress*, Vol. 45, No. 443, pp. 201-223.

Garrick, B.J., Hall, J.E., Kilger, M., McDonald, J.C., O'Toole, T., Probst, P.S., Parker, E.R., Rosenthal, R., Trivelpiece, A.W., Arsdale, L.A.V. & Zebroski, E.L. (2004), "Confronting the Risks of Terrorism: Making the Right Decisions", *Reliability Engineering and System Safety*, Vol. 86, No. 2, pp. 129-176.

Giovanni, B., Gianpiero, L. & Gennaro, A. (2001), "High Speed and Low Vibration Design for a Twin Screw Passenger Ferry", *RINA Conference Proceedings*, 4-6 September, Southampton, United Kingdom, pp. 57-63.

GL (2001), "Ship Vibration", *Germanischer Lloyd*, pp. 1-51.

Hadler, J.B., English, J.W. & Gupta, S.K. (1985), "Program to Minimize Propeller-Induced Vibration on Converted Maersk 'E' Class Ships", *Transactions - Society of Naval Architects and Marine Engineers*, Vol. 92, pp. 185-221.

Harker, P.T. & Vargas, L.G. (1987), "The Theory of Ratio Scale Estimation: Saaty's Analytic Hierarchy Process", *Management Science*, Vol. 33, No. 11, pp. 1383-1403.

Henshall, S.H. (1996), "Medium and High Speed Diesel Engines for Marine Use", 4th Edition, The Institute of Marine Engineers London.

Herrmann, J.L.V., Wood, P.J., Gaertner, J.P. & Wall, I.B. (1989), "The Practical Application of PRA: An Evaluation of Utility Experience and USNRC Perspectives", *Reliability Engineering and System Safety*, Vol. 24, pp. 167-198.

Holtrop, J. & Valkhof, H. (2003), "Propellers and Propulsion for High-Powered Container Ships", *Naval Architect*, September, pp. 136-144.

Horn, M. (2005), "Developing Safety-Security Critical Systems: A Prototype LEGO Mindstorm Detection System", *PhD Thesis*, Department of Computer and Information Science, Norwegian University of Science and Technology (NTNU), Norway.

Hwang, C.L. & Yoon, K. (1981), "Multi Attribute Decision Making Methods and Applications", Springer-Verlag, New York, ISBN: 0-387-10558-1.

http://www.maintenanceresources.com/ReferenceLibrary/Alignment/Importance.htm
Accessed Date: 27/ 02/ 2006 Time: 15:50 hrs.

http://www.mercurymarine.com/chapter_4_-_propeller_technology
Accessed Date: 22/ 02/ 2006 Time: 10:42 hrs.

ILO (1977a), "C148 Working Environment (Air Pollution, Noise and Vibration) Convention", International Labour Organization, June.

ILO (1977b), "R156 Working Environment (Air Pollution, Noise and Vibration) Recommendation", International Labour Organization, June.

IMO (1982), "Noise Levels on Board Ships", International Maritime Organization, London, UK, A.468(XII), ISBN: 9280111345.

IMO (1997a), "Trial Application to High Speed Passenger Catamaran Vessels", International Maritime Organization, London, UK, DE41/ INF 7, December.

IMO (1997b), "Formal Safety Assessment Trial Application to High Speed Passenger Vessels", International Maritime Organization, London, UK, MSC68/14/2, May.

IMO (1998a), "Aspects of FSA Methodology: Experience Gained from the Trial Application undertaken by the United Kingdom", International Maritime Organization, London, UK, MSC69/ INF 14, February.

IMO (1998b), "Joint Nordic Project on Safety Assessment of HSC Operations", International Maritime Organization, London, UK, MSC70/ INF 15, October.

IMO (1998c), "Joint Nordic Project on Safety Assessment of HSC Operations", International Maritime Organization, London, UK, MSC70/ INF 15, January.

IMO (1998d), "FSA Study on Disabled Oil Tankers", International Maritime Organization, London, UK, MSC70/20/2, July.

IMO (1998e), "FSA Novel Emergency Propulsion and Steering Devices for Oil Tanker Analysed with the FSA Method", International Maritime Organization, London, UK, MSC69/14/1, February.

IMO (1998f), "Bulk Carrier Safety", International Maritime Organization, London, UK, MSC70/4/1, September.

IMO (1998g), "Trial Application of FSA to the Dangerous Goods on Passenger/ Ro-Ro Vessels", International Maritime Organization, London, UK, MSC69/ INF24.

IMO (2000), "Safety of Bulk Carriers – Basis of the International Collaborative Formal Safety Assessment Study", International Maritime Organization, London, UK, MSC72/ INF18, March.

IMO (2001), "Guidance on Fatigue Mitigation and Management", International Maritime Organization, London, UK, MSC/ Circ. 1014, 2001, pp. 1-103.

IMO (2002a), "International Collaborative FSA Study on Bulk Carriers – Step 2", International Maritime Organization, London, UK, MSC75/ INF22, March.

IMO (2002b), "International Collaborative FSA Study on Bulk Carriers – Step 3", International Maritime Organization, London, UK, MSC76/ INF8, September.

IMO MSC/ Circ.565 (2001), "Fatigue as a Contributory Factor in Maritime Accidents", International Maritime Organization, London, UK.

IMO MSC/ Circ.829 (1997), "Interim Guidelines for Formal Safety Assessment (FSA) for Use in the IMO Rule-Making Process", International Maritime Organization, London, UK.

IMO MSC/ Circ.1023 (2002), "Guidelines for Formal Safety Assessment (FSA) for Use in the IMO Rule-Making Process", International Maritime Organization, London, UK.

Islam, R., Biswal, M.P. & Alam, S.S. (1997), "Preference Programming and Inconsistent Interval Judgements", *European Journal of Operational Research*, Vol. 97, No. 1, pp. 53-62.

ISO 4867 (1984), "Code for Measurement and Reporting of Shipboard Vibration Data", *The British Standard Institution*, pp. 1-18.

ISO 6954 (1984), "Overall Evaluation of Vibration in Merchant Ships", *The British Standard Institution*, pp. 1-4.

ISO 6954 (2000), "Guidelines for the Measurement, Reporting and Evaluation of Vibration with Regard to Habitability on Passenger and Merchant Ships", *The British Standard Institution*, pp. 1-8.

ISO 8041 (2005), "Human Response to Vibration – Measuring Instrumentation", *The British Standard Institution*, pp. 1-91.

Jacobsen, H.S. (2002), "Representation and Calculation of Economic Uncertainties: Intervals, Fuzzy Numbers and Probabilities", *International Journal of Production Economics*, Vol. 78, No. 1, pp. 91-98.

Jenson, F.V. (2001), "Bayesian Network and Decision Graphs", Springer-Verlag, ISBN: 0387952594.

JISC (2005), "Noise and Vibration On Board", Joint Industrial Safety Council, ISBN: 91 7522 123 3.

Jordaan, I. (2005), "Decisions Under Uncertainty", Cambridge University Press, ISBN: 0 521 78277 5.

Kahraman, C., Cevik, S., Ates, N.Y. & Gulbay, M. (2007), "Fuzzy Multi-Criteria Evaluation of Industrial Robotic Systems", *Computers and Industrial Engineering*, Vol. 52, No. 4, pp. 414-433.

Kandel, A. (1986), "Fuzzy Mathematical Techniques with Applications", Addison-Wesley Publishing Company Inc., ISBN: 0-201-11752-5.

Kaya, M. & Alhajj, R. (2005), "Generic Algorithm Based Framework for Mining Fuzzy Association Rules" *Fuzzy Sets and Systems*, Vol. 152, No. 3, pp. 587-601.

Keuning, P.J. (1992), "Hull-Propulsor Interaction Related to Ship Vibrations", *Proceedings of MARIN Workshops on: Advanced Vessels, Station Keeping, Propulsor-Hull Interaction, and Nautical Simulators,* May, Wageningen, Netherlands, pp. 431-436.

Kinns, R. & Bloor, C.D. (2004), "Hull Vibration Excitation due to Monopole and Dipole Propeller Sources, *Journal of Sound and Vibration,* Vol. 270, No. 5, pp. 951-980.

Kinns, R., Peake, N. & Spivack, O.R. (2003), "Hull Vibration Excitation by Propeller Sources: A Link between Hydrodynamics and Marine Acoustics", *Naval Hydrodynamics,* 24th Symposium, London, United Kingdom, pp. 1-12.

Kinns, R. & Pim, C.D. (2005), "Hull Disturbing Forces due to Propeller Sources", *Noise and Vibration Worldwide*, Vol. 36, No. 6, pp. 12-20.

Klir, G.J. & Yuan, B. (1995), "Fuzzy Sets and Fuzzy Logic: Theory and Applications", Prentice-Hall, ISBN: 0-13-101171-5.

Kruse, R., Gebharat, J. & Klawonn, F. (1994), "Foundations of Fuzzy Systems", John Wiley & Sons, ISBN: 0 471 94243 X.

Kumamoto, H. & Henley, E.J. (1992), "Probabilistic Risk Assessment and Management for Engineers and Scientists", IEE Press, 2nd Edition, ISBN: 0-7803-1004-7.

Kumar, N.V. & Ganesh, L.S. (1996), "An Empirical Analysis of the use of the Analytic Hierarchy Process for Estimating Membership Values in a Fuzzy Set", *Fuzzy Sets and Systems*, Vol. 82, No. 1, pp. 1-16.

Kuo, R.J., Chi, S.C. & Kao, S.S. (2002), "A Decision Support System for Selecting Convenience Store Location through Integration of Fuzzy AHP and Artificial Neural Network", *Computers in Industry*, Vol. 47, No. 2, pp. 199-214.

Labvosky, J., Svandova, Z., Markos, J. & Jelemensky, M. (2007), "Model-Based HAZOP Study of a Real MTBE Plant", *Journal of Loss Prevention*, Vol. 20, No. 3, pp. 230-237.

Lambert, J.H., Peterson, K.D. & Joshi, N.N. (2006), "Synthesis of Quantitative and Qualitative Evidence for Accident Analysis in Risk-Based Highway Planning", *Accident Analysis and Prevention*, Vol. 38, No. 5, pp. 925-935.

Lee, M., Pham, H. & Zhang, X. (1999), "A Methodology for Priority Setting with Application to Software Development Process", *European Journal of Operational Research*, Vol. 118, No. 2, pp. 375-389.

Lee, W.B., Lau, H., Liu, Z. & Tam, S. (2001), "A Fuzzy Analytic Hierarchy Process Approach in Modular Product Design", *Expert Systems*, Vol. 18, No. 1, pp. 32-42.

Lim, T.C., Thanopoulou, H.A., Beynon, M.J. & Beresford, A.K.C. (2004), "An Application of AHP on Transhipment Port Selection: A Global Perspective", *Maritime Economics and Logistics*, Vol. 6, pp. 70-91.

Liu, J., Yang, J.B., Wang, J. & Sii, H.S. (2005), "Engineering System Safety Analysis and Synthesis Using the Fuzzy Rule-Based Evidential Reasoning Approach", *Quality and Reliability Engineering International*, Vol. 21, No. 4, pp. 387-411.

Lois, P. (2004), "Cyprus and Mediterranean Cruise Market: A Financial and Economic Appraisal", *PhD Thesis*, School of Engineering, Liverpool John Moores University, United Kingdom.

Loughran, C., Pillay, A., Wang, J., Wall, A.D. & Ruxton, T. (2003), "A Preliminary Study of Fishing Vessel Safety", *Journal of Risk Research*, Vol. 5, No. 1, pp. 3-21.

LR (1978), "Shaft Vibration and Alignment", *Lloyds Register*, January, pp. 1-18.

LR (2006), "Ship Vibration and Noise Guidance Notes", *Lloyds Register*, July, pp. 1-52.

Luoh, L & Wang, W.J. (2001), "A Simple Method for Computing the Entropy of the Product of General Fuzzy Intervals", *Mathematics and Computers in Simulation*, Vol. 58, No. 1, pp. 37-49.

Madu, C.N., Kuei, C.H. & Madu, A.N. (1991), "Setting Priorities for the IT Industry in Taiwan – A Delphi Study", *Long Range Planning*, Vol. 24, No. 5, pp. 105-118.

Magazinovic, G. (2002), "Shafting Vibration Primer", *CADEA*, pp. 1-14.

MAIB (1990-2008), "Marine Accident Reports", Marine Accident Investigation Branch of the Department of the Environment Transport and the Regions, London.

Mano, M. (1985), "Ship Design Considerations for Minimal Vibration", *Proceedings - Ship Technology and Research (STAR) Symposium*, No. 9, 21-24 May, Norfolk, USA, pp. 143-156.

Marine Engineers Review (MER). (2007), "Bunker Prices", *IMarEST Publications*, June, pp. 33.

Mauri, G. (2000), "Integrating Safety Analysis Techniques, Supporting Identification of Common Cause Failures", *PhD Thesis*, Department of Computer Science, University of York United Kingdom.

McGeorge, H.D. (1995), "Marine Auxiliary Machinery", Butterworth Heinemann, 7th Edition, ISBN: 0 7506 4398 6.

MDS (1992-2007), "Lloyds Register Marine Data Systems EMEA", Lloyds Register of Shipping, London, United Kingdom.

Meel, A. & Seider, W.D. (2006), "Plant-Specific Dynamic Failure Assessment Using Bayesian Theory", *Chemical Engineering Science*, Vol. 61, pp. 7036-7056.

MIL-STD-882 (1969), "Military Standard System Safety Program Requirements", Department of Defence United States of America, MIL-STD-882.

MIL-STD-882c (1993), "Military Standard System Safety Program Requirements", Department of Defence United States of America, MIL-STD-882c, January, pp. 1-119.

MIL-STD-882d (2000), "Military Standard System Safety Program Requirements", Department of Defence United States of America, MIL-STD-882d, February, pp. 1-31.

MIL-STD-1629a (1980), "Procedures for Performing A Failure Mode, Effects and Criticality Analysis", Department of Defence United States of America, MIL-STD-1629a, November.

Miller, G.A. (1956), "The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information" *The Psychological Review*, pp. 81-97.

MSA (1993), "Formal Safety Assessment MSC 66/14" Marine Safety Agency United Kingdom.

Nieuwhof, G.W.E. (1975), "An Introduction to Fault Tree Analysis with Emphasis on Failure Rate Evaluation", *Microelectronics and Reliability*, Vol. 14, pp. 105-119.

Nilsson, A.C. (1980), "Propeller Induced Hull Plate Vibrations", *Journal of Sound and Vibration*, Vol. 69, No. 4, pp. 539-557.

Norton, M.P. & Karczub, D.G. (2003), "Fundamentals of Noise and Vibration Analysis for Engineers", Cambridge University Press, 2nd Edition, ISBN: 0 521 49913 5.

Olson, D.L. (2004), "Comparison of Weights in TOPSIS Models", *Mathematical and Computer Modelling*, Vol. 40, No. 7, pp. 721-727.

Pan, H.P., Okello, N., McMichael, D. & Roughan, M. (1998), "Fuzzy Casual Probabilistic Networks and Multisensor Fusion", *Proceedings of SPIE - The International Society for Optical Engineering*, 21-23 October, Bellingham, USA, Vol. 3545, pp. 550-561.

Parken, C. & Wu, M.L. (1999), "Decision-Making and Performance Measurement Models with Applications to Robot Selection", *Computers and Industrial Engineering*, Vol. 36, No. 3, pp. 503-523.

Pedrycz, W. & Gomide, F. (1998), "An Introduction to Fuzzy Sets: Analysis and Design", The MIT Press, ISBN: 0262161710.

Phylip-Jones, G. (1998), "Marine Engineering", *Liverpool John Moores University*, pp. 1-99.

Pillay, A. (2001), "Formal Safety Assessment of Fishing Vessels", *PhD Thesis*, School of Engineering, Liverpool John Moores University, United Kingdom.

Pillay, A. & Wang, J. (2001), "Risk Assessment of Fishing Vessels using Fuzzy Set Approach", *International Journal of Reliability, Quality and Safety Engineering*, Vol. 9, No. 2, pp. 163-181.

Pillay, A. & Wang, J. (2003), "Modified Failure Mode and Effects Analysis Using Approximate Reasoning", *Reliability Engineering and System Safety*, Vol. 79, No. 1, pp. 69-85.

Pillay, A. & Wang, J. (2003), "Technology and Safety of Marine Systems", Elsevier Ocean Engineering Book Series, ISBN: 0 08 044148 3.

Reddy, A.K. (1983), "Vibration Problems of Propulsion Systems in Large Naval Ships", *Journal of the Institution of Engineers (India),* Vol. 64, November, pp. 24-27.

Satty, T.L. (1980), "The Analytic Hierarchy Process", McGraw Hill International New York, ISBN: 0070543712.

Saaty, T.L., Vargas, L.G. (1987), "Uncertainty and Rank Order in the Analytic Hierarchy Process", *European Journal of Operational Research,* Vol. 32, No. 1, pp. 107-117.

Schmucker, K.J. (1984), "Fuzzy Sets, Natural Language Computations and Risk Analysis, Computer Science Press, ISBN: 0-914894-83-8.

Schofield, S. (1998), "Offshore QRA and ALARP Principle", *Reliability Engineering and System Safety,* Vol. 61, No. 1, pp. 31-37.

Shang, J.S., Tjader, Y. & Ding, Y. (2004), "A Unified Framework for Multi-Criteria Evaluation of Transportation Projects", *IEEE Transactions on Engineering Management,* Vol. 51, No. 3, pp. 300-313.

Sii, H.S. (2001), "Marine and Offshore Safety Assessment", *PhD Thesis,* School of Engineering, Liverpool John Moores University, United Kingdom.

Sii, H.S., Ruxton, T. & Wang, J. (2001), "A Fuzzy Logic Based Approach to Qualitative Safety Modelling for Marine Systems", *Reliability Engineering and System Safety,* Vol. 73, No. 1, pp. 19-34.

Sii, H.S. & Wang, J. (2003), "A Design-Decision Support Framework for Evaluation of Design Options/Proposals using a Composite Structure Methodology based on the Approximate Reasoning Approach and the Evidential Reasoning Method", *Proceedings of the Institution of Mechanical Engineers, Part E (Journal of Process Mechanical Engineering),* Vol. 17, No. 1, pp. 59-76.

Smith, D.J. (2005), "Reliability Maintainability and Risk", Butterworth Heinemann, 7th Edition, ISBN: 0 7506 6694 3.

Soares, C.G. & Teixeira, A.P. (2001), "Risk Assessment in Maritime Transportation", *Reliability Engineering and System Safety*, Vol. 74, pp. 299-309.

Sobczak, A. & Berry, D.M. (2007), "Distributed Priority Ranking of Strategic Preliminary Requirements for Management Information Systems in Economic Organisations", *Information and Software Technology*, Vol. 49, No. 9, pp. 960-984.

Sönmez, M., Yang, J.B. & Holt, G.D. (2001), "Addressing the Contractor Selection Problem Using an Evidential Reasoning Approach", *Engineering, Construction and Architectural Management*, Vol. 8, No. 3, pp. 198-210.

Stewart, R.A., Mohamed, S. & Daet, R. (2002), "Strategic Implementation of IT/IS Projects in Construction: A Case Study", *Automation in Construction*, Vol. 11, No. 6, pp. 681-694.

Tang, W.H., Spurgeon, K., Wu, Q.H. & Richardson, Z.J. (2004), "An Evidential Reasoning Approach to Transformer Condition Assessments", *IEEE Transactions on Power Delivery*, Vol. 19, No. 4, pp. 1696-1703.

Teng, S.G. & Jaramillo, H. (2005), "A Model for Evaluation and Selection of Suppliers in Global Textile and Apparel Supply Chains", *International Journal of Physical Distribution & Logistics Management*, Vol. 35, No. 7, pp. 503-523.

Todd, F.H. (1961), "Ship Hull Vibration", Edward Arnold Publishers Ltd, 1st Edition.

Trbojevic, V.M. (2002), "Risk Based Methodology for Safety Improvements in Ports", *Journal of Hazardous Materials*, Vol. 71, pp. 93-109.

Ugboma, C., Ugboma, O. & Ogwude, I.C. (2006), "An Analytic Hierarchy Process (AHP) Approach to Port Selection Decisions – Empirical Evidence from Nigerian Ports", *Maritime Economics and Logistics*, Vol. 8, pp. 251-266.

Ung, S.T. (2007), "The Development of Safety and Security Assessment Techniques and their Application to Port Operations", *PhD Thesis*, School of Engineering, Liverpool John Moores University, United Kingdom.

Ung, S.T., Williams, V., Chen, H.S., Bonsall, S. & Wang, J. (2006), "Human Error Assessment and Management in Port Operations using Fuzzy AHP", *Marine Technology Society Journal*, Vol. 40, No. 1, pp. 73-86.

Villemeur, A. (1992), "Reliability, Availability, Maintainability and Safety Assessment", John Wiley and Sons, Vol. 1, ISBN: 0 471 93048 2.

Wang, J. (1995), "Economic Comparison of Various Marine Propulsion Systems", *Liverpool John Moores University*, pp. 1-27.

Wang, J. (2000), "Subjective Modelling Tool Applied to Formal Ship Safety Assessment", *Ocean Engineering*, Vol. 27, No. 10, pp. 1019-1035.

Wang, J. (2006), "Maritime Risk Assessment and its Current Status", *Quality and Reliability Engineering International*, Vol. 22, pp. 3-19.

Wang, J. & Foinikis, P. (2001), "Formal Safety Assessment of Containerships", *Marine Policy*, Vol. 25, No. 2, pp. 143-157.

Wang, J. & Ruxton, T. (1995), "Design for Safety of Marine Engineering Systems with Multiple Failure State Variables", *Reliability Engineering and System Safety*, Vol. 50, No. 3, pp. 271-284.

Wang, J. & Ruxton, T. (1998), "A Design for Safety Methodology of Large Engineering Systems", *Journal of Engineering Design*, Vol. 9, No. 2, pp. 159-170.

Wang, J., Sii, H.S., Yang, J.B., Pillay, A., Yu, D., Liu, J, Maistralis, E. & Saajedi, A. (2004), "Use of Advances in Technology for Maritime Risk Assessment", *Risk Analysis*, Vol. 24, No. 4, pp. 1041-1063.

Wang, J. & Trbojevic, V. (2007), "Design for Safety of Marine and Offshore Systems", The Institute of Marine Engineering Science and Technology, ISBN: 1-902536-58-4.

Wang, J., Yang, J.B. & Sen, P. (1995), "Safety Analysis and Synthesis using Fuzzy Sets and Evidential Reasoning", *Reliability Engineering and System Safety*, Vol. 47, No. 2, pp. 103-118.

Wang, J., Yang, J.B. & Sen, P. (1996), "Multi-Person and Multi-Attribute Decision Evaluations Using Evidential Reasoning Based on Subjective Safety and Cost Analysis", *Reliability Engineering and System Safety*, Vol. 52, pp. 113-128.

Wang, T.C. & Chang, T.H. (2007), "Application of TOPSIS in Evaluating Initial Training Aircraft under a Fuzzy Environment", *Expert Systems with Applications*, Vol. 33, pp. 870-880.

Wang, Y. (2004), "Development of a Computer-Aided Fault Tree Synthesis Methodology for Quantitative Risk Analysis in the Chemical Process Industry", *PhD Thesis*, Texas A&M University, USA.

Wang, Y.M. & Elhag, T.M.S. (2006), "Fuzzy TOPSIS Method based on Alpha Level Sets with an Application to Bridge Risk Assessment", *Expert Systems with Applications*, Vol. 31, No. 2, pp. 309-319.

Wang, Y.M. Yang, J.B. Xu, D.L. & Chin, K.S. (2006), "The Evidential Reasoning Approach for Multiple Attribute Decision Analysis Using Interval Belief Degrees", *European Journal of Operational Research*, Vol. 175, No.1, pp. 35-66.

Wells, G. (1996), "Hazards Identification and Risk Assessment", Institution of Chemical Engineers, Rugby.

Wharton, A.J. (1991), "Diesel Engines", Elsevier Butterworth-Heinemann, 3rd Edition, ISBN: 0 7506 0217 1.

Woodyard, D. (2004), "Pounder's Marine Diesel Engines and Gas Turbines", Elsevier Butterworth-Heinemann, ISBN: 0 7506 58460, pp. 15-47.

Xie, X., Wang, S., Roberts, C. & Wang, J. (2006), "Locating Bus Stations Using Fuzzy Rule-Based ERA", *Proceeding of the 5th International Conference on Traffic & Transportation Studies*, 2-4 August, Xi'an, China, pp. 1-10.

Xu, D.L. & Yang, J.B. (2005), "Intelligent Decision System based on the Evidential Reasoning Approach and its Applications", *Journal of Telecommunications and Information Technology*, No. 3, pp. 73-80.

Xu, D.L., Yang, J.B. & Wang, Y.M. (2006), "The Evidential Reasoning Approach for Multi-Attribute Decision Analysis under Interval Uncertainty", *European Journal of Operational Research*, Vol. 174, No.3, pp. 1914-1943.

Yacamini, R., Chang, S.C. & Smith, K.S. (1996), "Noise Generation in Marine Motors", *Transactions IMarEST*, Vol. 107, No. 4, pp. 241-256.

Yang, J.B. (2001), "Rule and Utility Based Evidential Reasoning Approach for Multiattribute Decision Analysis under Uncertainties", *European Journal of Operational Research*, Vol. 131, No.1, pp. 31-61.

Yang, J.B. & Singh, M.G. (1994), "An Evidential Reasoning Approach for Multiple Attribute Decision Making with Uncertainty", *IEEE Transactions on System, Man and Cybernetic*, Vol. 24, No. 1, pp. 1-18.

Yang, J.B. & Xu, D.L. (2002), "Nonlinear Information Aggregation via Evidential Reasoning in Multiattribute Decision Analysis under Uncertainty", *IEE Transactions on System, Man and Cybernetic—Part A: Systems and Humans*, Vol. 32, No. 3, pp. 376-393.

Yang, J.B. & Xu, D.L. (2002), "On the Evidential Reasoning Algorithm for Multiple Attribute Decision Analysis under Uncertainty", *IEEE Transactions on System, Man and Cybernetic—Part A: Systems and Humans*, Vol. 32, No.3, pp. 289-304.

Yang, T., Lee, R.S. & Hsieh, C. (2003), "Solving a Process Engineer's Manpower-Planning Problem using Analytic Hierarchy Process", *Production Planning and Control*, Vol. 14, No. 3, pp. 266-272.

Yang, Z. (2006), "Risk Assessment and Decision Making of Container Supply Chains", *PhD Thesis*, School of Engineering, Liverpool John Moores University, United Kingdom.

Yang, Z., Bonsall, S., Wall, A. & Wang, J. (2005), "Reliable Container Supply Chains – A New Risk Assessment Framework for Improving Safety Performance", *Journal of World Maritime University*, Vol. 4, No. 1, pp. 105-120.

Yang, Z., Wang, J., Bonsall, S., Yang, J. & Fang, Q. (2005), "Subjective Risk Assessment of Container Supply Chains", *International Journal of Automation and Computing*, Vol. 2, No. 1, pp. 20-28.

Yen, J. & Langari, R. (1999), "Fuzzy Logic", Prentice Hall Inc., ISBN: 0-13-525817-0.

Zadeh, L.A. (1965), "Fuzzy Sets", *Information and Control*, Vol. 8, pp. 338-353.

Zadeh, L.A. (1987), "Fuzzy Sets and Applications: Selected Papers", John Wiley & Sons, ISBN: 0-471-85710-6.

Zheng, H., Liu, G.R., Tao, J.S. & Lam, K.Y. (2001), "FEM/BEM Analysis of Diesel Piston-Slap Induced Ship Hull Vibration and Underwater Noise", *Applied Acoustics*, Vol. 64, No. 4, pp. 341-358.

Zimmermann, H.J. (2000), "An Application-Oriented View of Modelling Uncertainty", *European Journal of Operational Research*, Vol. 122, No. 2, pp. 190-198.

Appendices

Appendix 1

Appendix 1.1: Conference Publications Arising from this Research

Godaliyadde, D., Phylip-Jones, G., Batako, A.D. & Wang, J. (2006) "Risk Analysis of Ship Hull Vibration using Evidential Reasoning", *Proceeding of the 2nd GERI Annual Research Symposium 2006*, Peter Jost Enterprise Centre, 15th June 2006, Liverpool John Moores University, UK, 8 pages.

Godaliyadde, D., Godaliyadde, L.B., Phylip-Jones, G., Batako, A.D. & Wang, J. (2007) "A Subjective Decision Making Approach for Ship Hull Vibration", *Proceeding of the 3rd GERI Annual Research Symposium 2007*, Peter Jost Enterprise Centre, 27th June 2007, Liverpool John Moores University, UK, 7 pages.

Godaliyadde, D., Godaliyadde, P.M.M., Phylip-Jones, G., Batako, A.D. & Wang, J. (2008) "A Risk Management Approach for Ship Hull Vibration", *Proceeding of the 4th GERI Annual Research Symposium 2008*, Peter Jost Enterprise Centre, 25h June 2008, Liverpool John Moores University, UK, 8 pages.

Godaliyadde, D., Godaliyadde, D.D.K., Phylip-Jones, G., Batako, A.D. & Wang, J. "A Cost Benefit Analysis Approach for Ship Hull Vibration", Under Review at: *GERI*, 7 Pages.

Appendix 1.2: Journal Publications Arising from this Research

Godaliyadde, D., Phylip-Jones, G., Batako, A.D. & Wang, J. "A Subjective Risk Estimation Approach for Modeling Ship Hull Vibration", Under Review at: *Journal of Ship Research*, 36 pages.

Godaliyadde, D., Godaliyadde, L.B., Phylip-Jones, G., Batako, A.D. & Wang, J. "A Subjective Multiple Criteria Decision Making Approach for Modeling Ship Hull Vibration", Under Review at: *Marine Structures*, 33 pages.

Godaliyadde, D., Godaliyadde, M.M., Phylip-Jones, G., Batako, A.D. & Wang, J. "A Subjective Risk Management Approach for Modeling of Failures Onboard Ships", Under Review at: *Journal of Marine Science and Technology*, 38 pages.

Godaliyadde, D., Godaliyadde, D.D.K., Phylip-Jones, G., Batako, A.D. & Wang, J. "A Subjective Cost Benefit Analysis Approach for Selecting Ship Propulsion Systems", Under Review at: *Marine Technology Society Journal*, 34 Pages.

Godaliyadde, D., Phylip-Jones, G., Batako, A.D. & Wang, J. "An Analysis of Ship Hull Vibration Failure Data", Under Review at: *Accident Analysis and Prevention*, 12 pages.

Note: Several more papers are being prepared for submission to academic journals.

Appendix 2

Appendix 2.1: Propulsion System Vibration Defects Data (MDS, 1992-2007)

Ship Type	*Number of Defects*
Bulk Carrier	78
Chemical Tanker	17
Container Ship	55
Dredger-Hopper	11
Ferry	68
Tug	78
General Cargo Ship	190
Cable Repair Ship	13
Offshore Supply Vessel	30
Oil Tanker	103
Passenger Ship	45
Refrigerated Cargo Vessel	12
RoRo Cargo Ship	32
Fishing Vessel	36
Other	55
Total	**823**

Appendix 2.2: Ship Hull Vibration Defects Data (MDS, 1992-2007)

Ship Type	Number of Defects
Bulk Carrier	30
Chemical Tanker	21
Container Ship	8
Dredger-Hopper	7
Ferry	26
Tug	15
General Cargo Ship	20
LNG Tanker	7
Offshore Supply Vessel	15
Oil Tanker	169
Passenger Ship	5
Refrigerated Cargo Vessel	8
RoRo Cargo Ship	30
Vehicle Carrier	10
Other	20
Total	**391**

Appendix 3

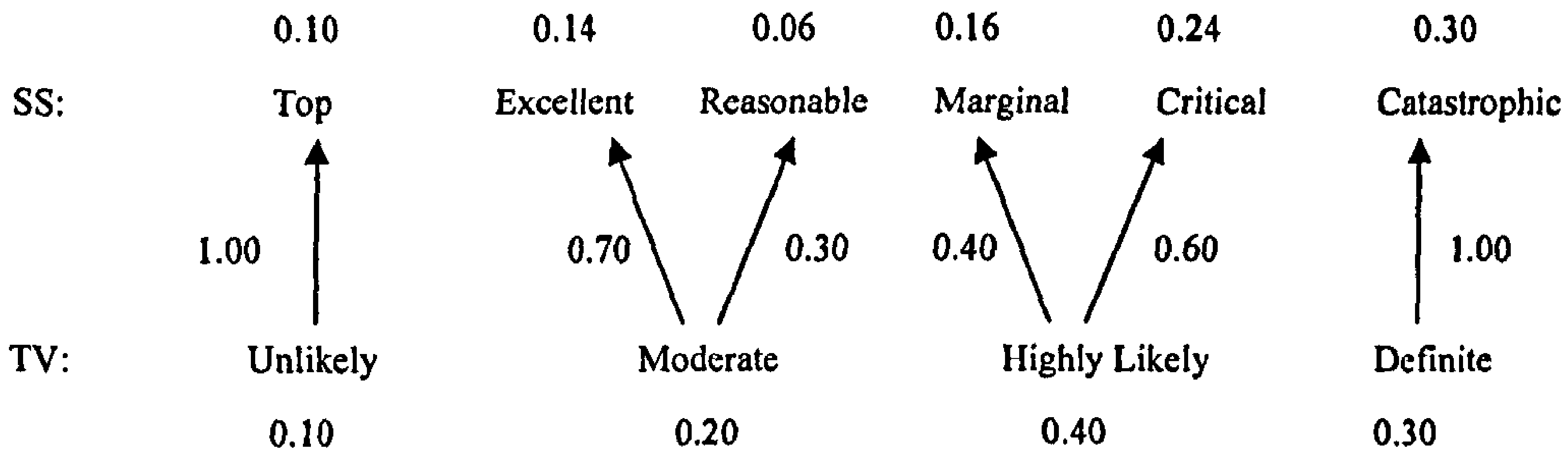
Appendix 3.1: Ship Specification

Name of the Ship: Rogers Dilini
Type of the Ship: Bulk Carrier
Year of Built: 1967
Length OA: 80 m
Breadth: 16 m
Draft: 8.5 m
Gross Tonnage: 1755 GRT
Engine Type: Slow Speed Diesel
Power Output: 3400 kW MCR
Engine RPM: 115
Number of Cylinders: 5
Maximum Speed: 11 knots
Propeller type: FPP
Propeller Diameter: 2.75 m

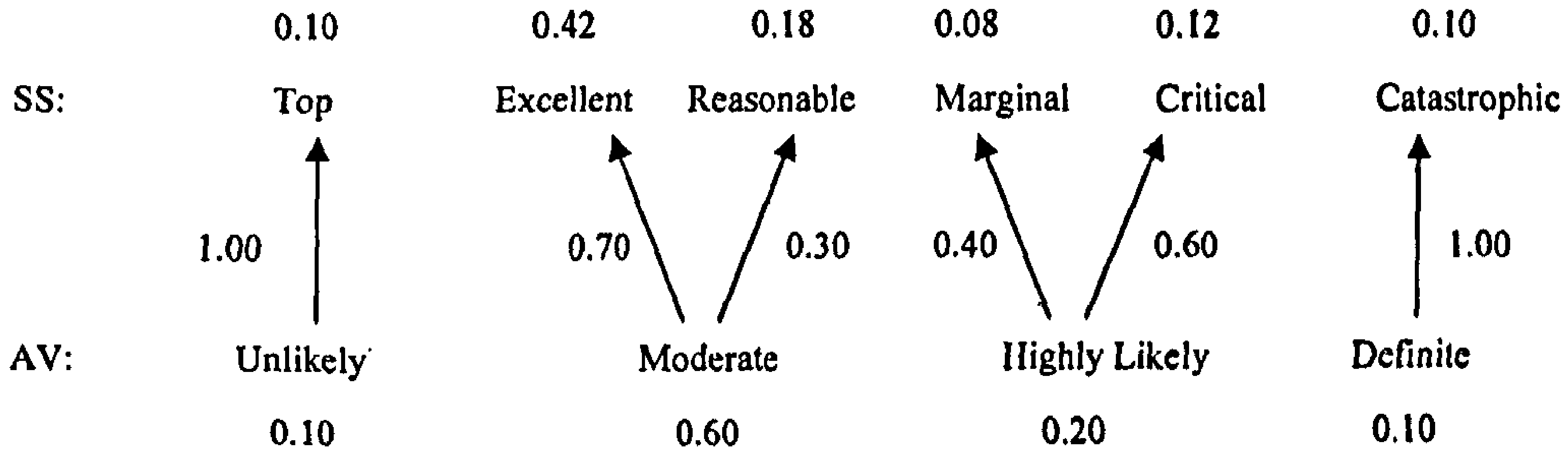
Propeller Blade Area: 5.7 m^2
Number of Blades: 3
Propeller RPM: 115
Propeller and Rudder Clearance: 0.990 m
Propeller and Hull Clearance: 0.480 m
Classification Society: -

Appendix 3.2: Mapping

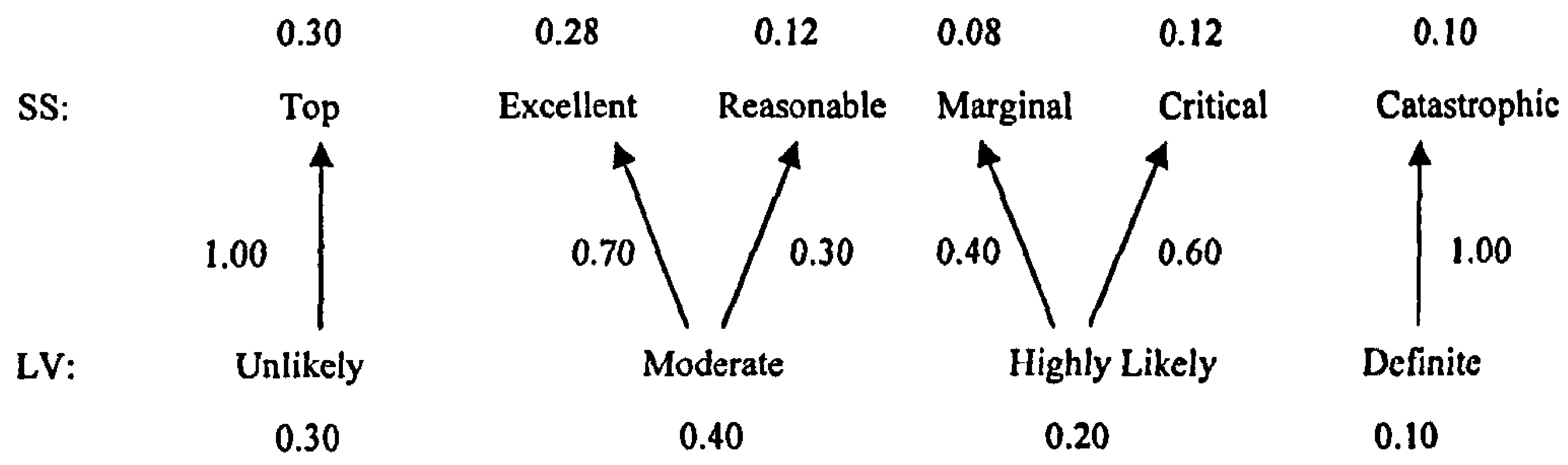
Mapping from Torsional Vibration (TV) to Shaft System (SS)



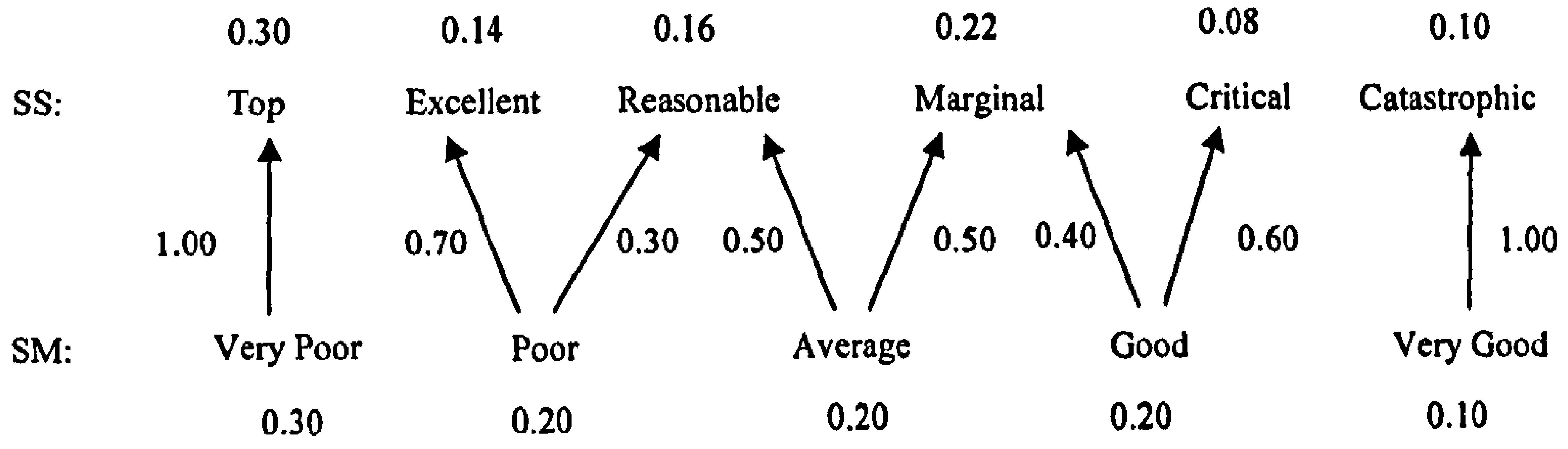
Mapping from Axial Vibration (AV) to Shaft System (SS)



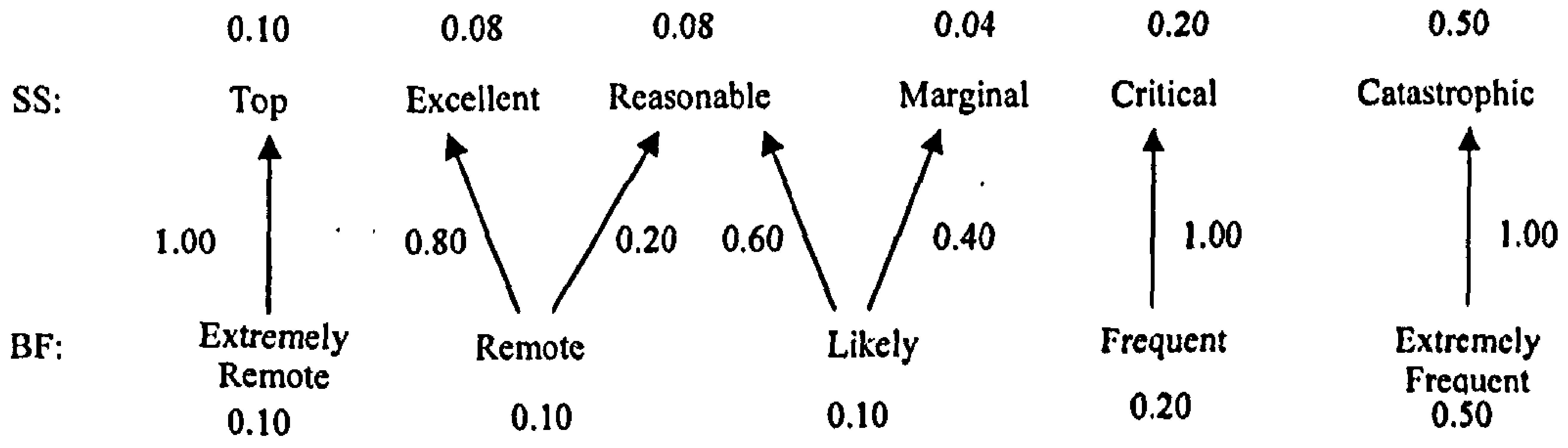
Mapping from Lateral Vibration (LV) to Shaft System (SS)



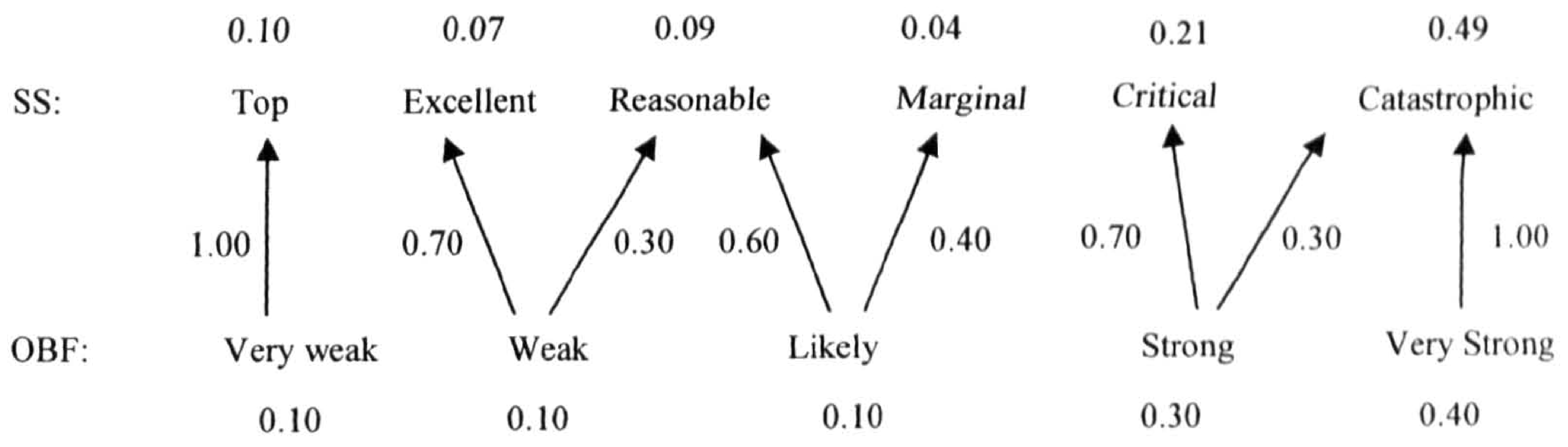
Mapping from Shaft Misalignment (SM) to Shaft System (SS)



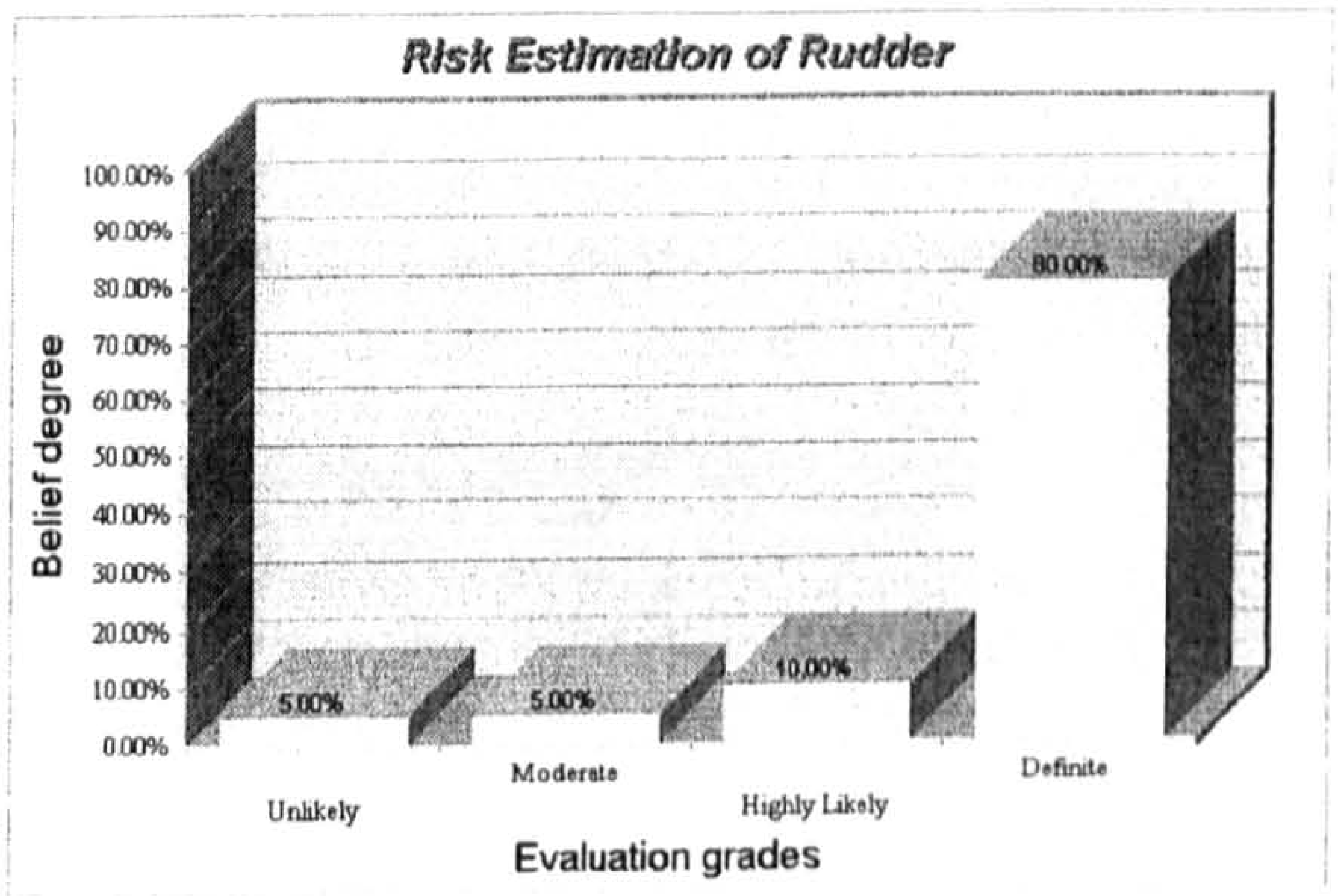
Mapping from Bearing Failure (BF) to Shaft System (SS)

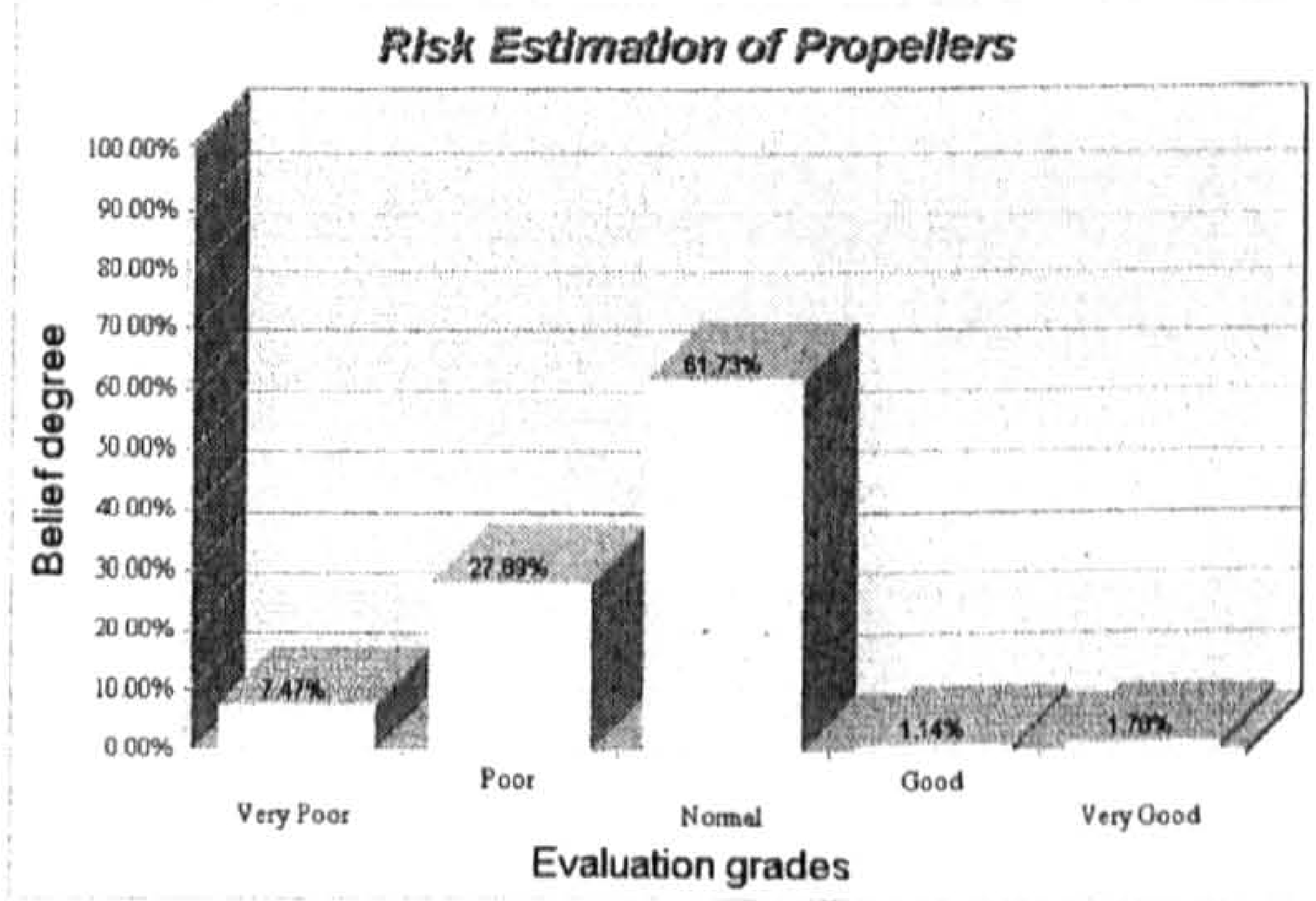


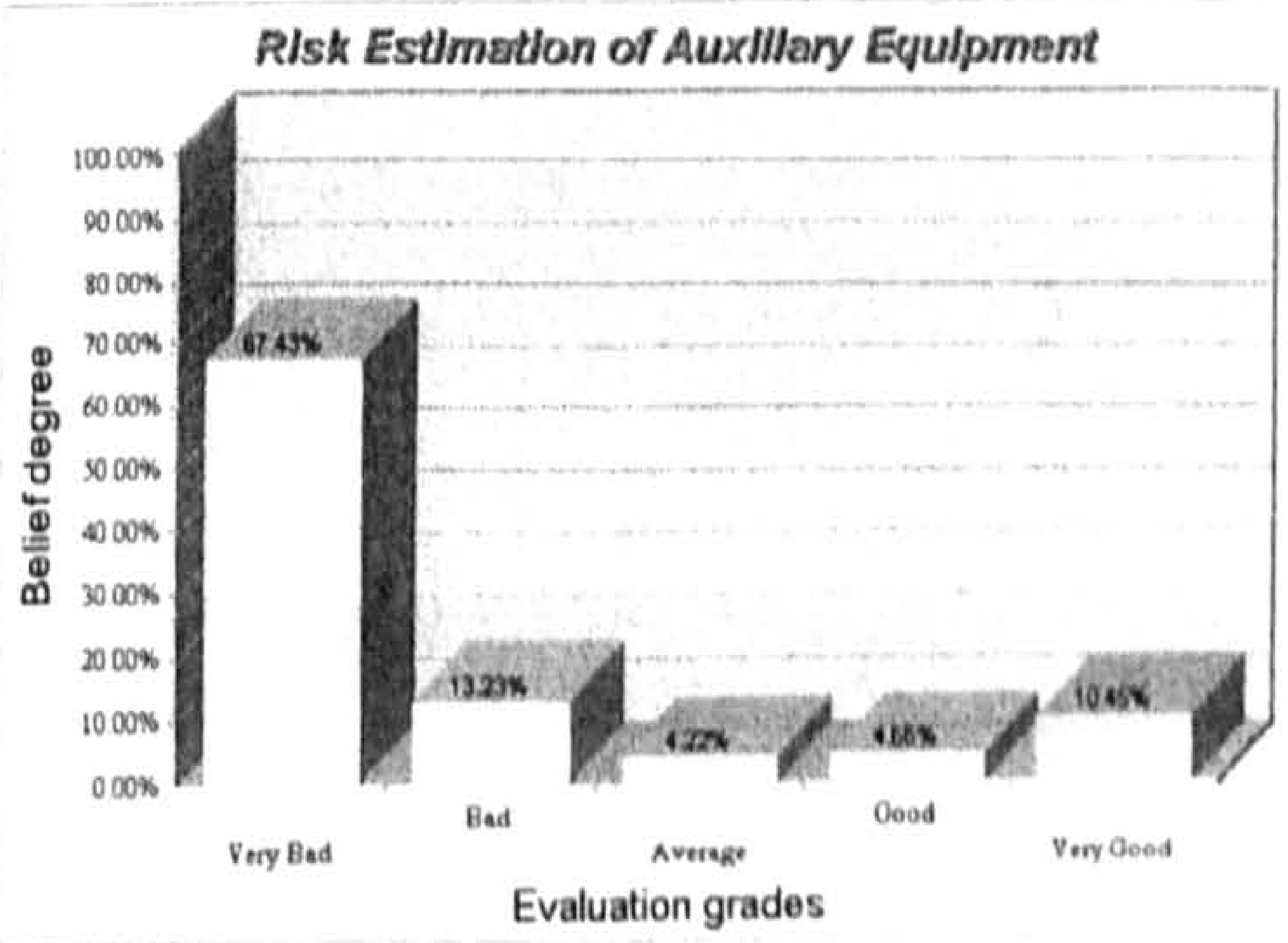
Mapping from Out of Balance Forces (OBF) to Shaft System (SS)

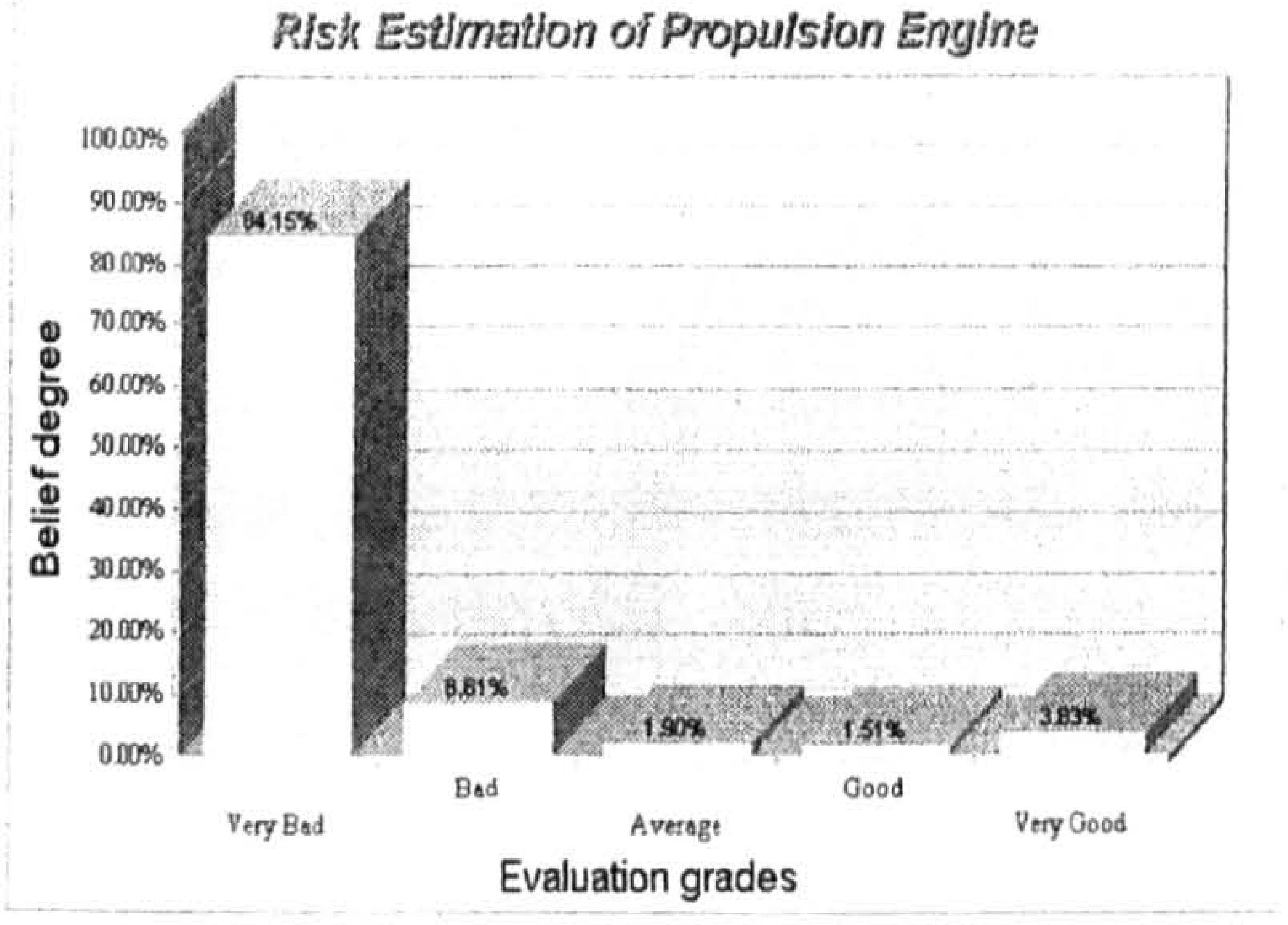


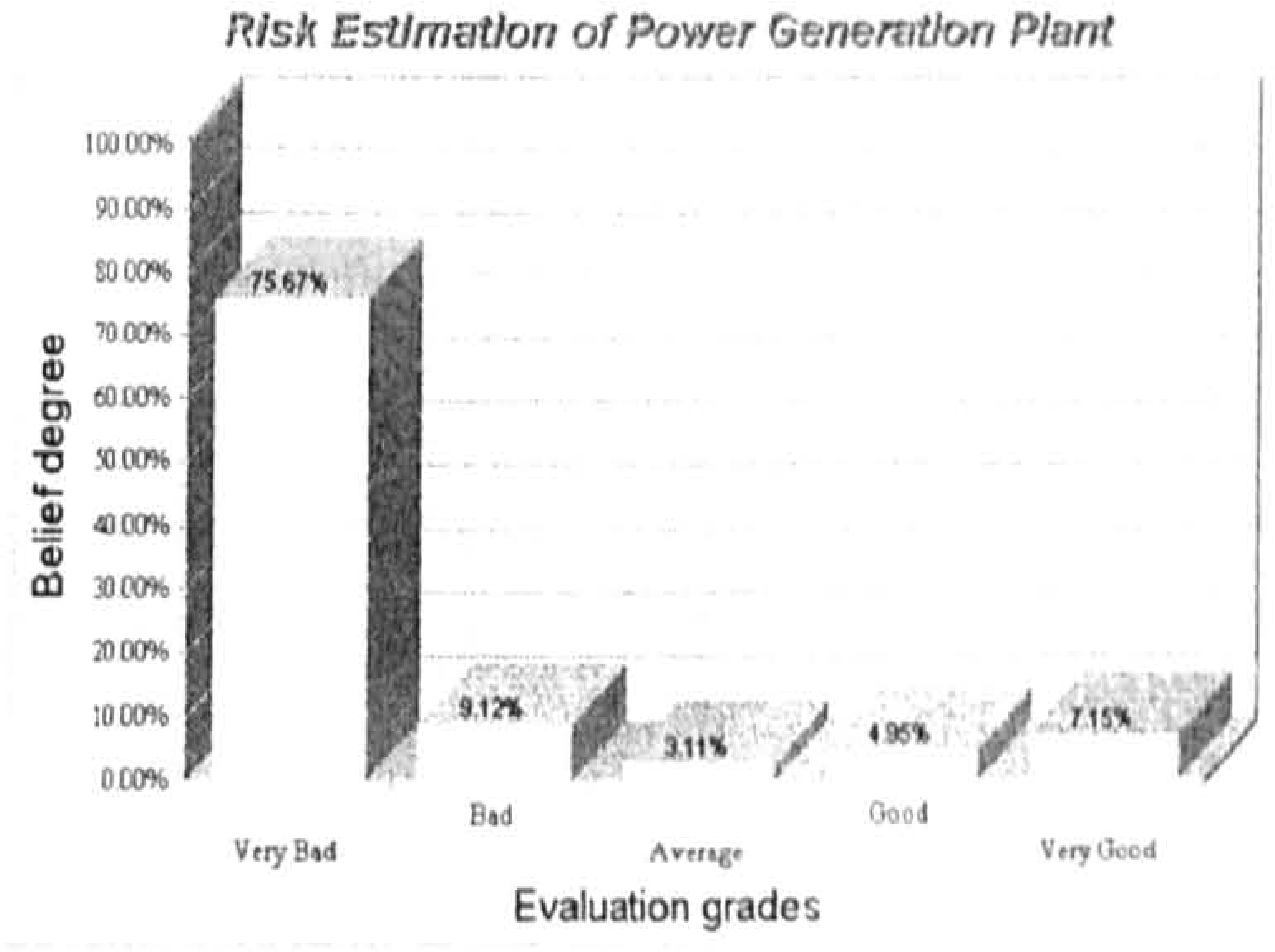
Appendix 3.3: Risk Estimation











Appendix 4

Appendix 4.1: Input Data

Qualitative Inputs for Ship 1

Design Criteria	Excellent	Very Good	Good	Normal	Bad	Very Bad
Propeller Design						
Propeller Pitch	(0)	(0)	(0)	(0)	(0.60)	(0.40)
Blade Thickness	(0)	(0)	(0)	(0.15, 0.20)	(0.20, 0.23)	(0.65)
Propeller Load	(0)	(0)	(0)	(0.30, 0.33)	(0.55)	(0.10, 0.14)
Propeller Skew	(0)	(0)	(0)	(0)	(0.75)	(0.25)
Shaft System Design						
Shaft Stiffness	(0)	(0)	(0)	(0)	(0.80)	(0.20)
Shaft Alignment	(0)	(0)	(0)	(0)	(0.50)	(0.50)
Bearings	(0)	(0)	(0)	(0.30)	(0.70)	(0)
Engine Design						
Power to Weight Ratio	(0)	(0)	(0)	(0.35)	(0.65)	(0)
Damping Systems	(0)	(0)	(0)	(0)	(0.80)	(0.20)
Engine Firing	(0)	(0)	(0.32, 0.36)	(0.45)	(0.20)	(0)
Engine Alignment	(0)	(0)	(0)	(0)	(0.72)	(0.28)
Ship Body Design						
Aft Body Design	(0)	(0)	(0)	(0)	(0.60)	(0.40)
Fore Body Design	(0)	(0)	(0)	(0.50)	(0.50)	(0)
Hull Smoothness	(0)	(0)	(0)	(0.10, 0.12)	(0.70)	(0.20)
Rudder Design	(0)	(0)	(0)	(0)	(0.55)	(0.45)

Qualitative Inputs for Ship 2

Design Criteria	Excellent	Very Good	Good	Normal	Bad	Very Bad
Propeller Design						
Propeller Pitch	(0)	(0)	(0)	(0.50)	(0.50)	(0)
Blade Thickness	(0.50)	(0.50)	(0)	(0)	(0)	(0)
Propeller Load	(0.85)	(0.15)	(0)	(0)	(0)	(0)
Propeller Skew	(0)	(0)	(0)	(0.60)	(0.40)	(0)
Shaft System Design						
Shaft Stiffness	(0)	(0)	(0)	(0.50)	(0.50)	(0)
Shaft Alignment	(0)	(0)	(0)	(0.35)	(0.65)	(0)
Bearings	(0)	(0)	(0)	(0.75)	(0.25)	(0)
Engine Design						
Power to Weight Ratio	(0)	(0)	(0)	(0.50)	(0.50)	(0)
Damping Systems	(0)	(0)	(0)	(0.20)	(0.80)	(0)
Engine Firing	(0)	(0)	(0.70)	(0.30)	(0)	(0)
Engine Alignment	(0)	(0)	(0)	(0)	(0.75)	(0.25)
Ship Body Design						
Aft Body Design	(0)	(0)	(0)	(0)	(0.20)	(0.80)
Fore Body Design	(0)	(0)	(0)	(0.20)	(0.80)	(0)
Hull Smoothness	(0)	(0)	(0)	(0.70, 0.72)	(0.28)	(0)
Rudder Design	(0)	(0)	(0.60)	(0.40)	(0)	(0)

Qualitative Inputs for Ship 3

Design Criteria	Excellent	Very Good	Good	Normal	Bad	Very Bad
Propeller Design						
Propeller Pitch	(0)	(0)	(0)	(0)	(0.30)	(0.70)
Blade Thickness	(0)	(0)	(0.64)	(0.36)	(0)	(0)
Propeller Load	(0)	(0.20)	(0.80)	(0)	(0)	(0)
Propeller Skew	(0)	(0)	(0)	(0)	(0.05)	(0.95)
Shaft System Design						
Shaft Stiffness	(0)	(0)	(0)	(0.20, 0.22)	(0.25, 0.29)	(0.52)
Shaft Alignment	(0)	(0)	(0)	(0)	(0.10)	(0.90)
Bearings	(0)	(0)	(0)	(0)	(0.30)	(0.70)
Engine Design						
Power to Weight Ratio	(0)	(0)	(0)	(0)	(0.85)	(0.15)
Damping Systems	(0)	(0)	(0)	(0)	(0)	(1.00)
Engine Firing	(0)	(0)	(0)	(0)	(0.32, 0.37)	(0.64, 0.66)
Engine Alignment	(0)	(0)	(0)	(0)	(0.80)	(0.20)

Ship Body Design						
Aft Body Design	(0)	(0)	(0.50)	(0.50)	(0)	(0)
Fore Body Design	(0)	(0)	(0)	(0.60)	(0.40)	(0)
Hull Smoothness	(0)	(0)	(0)	(0)	(0.45)	(0.55)
Rudder Design	(0)	(0)	(0)	(0)	(0.50)	(0.50)

Appendix 4.2: Normalised Data

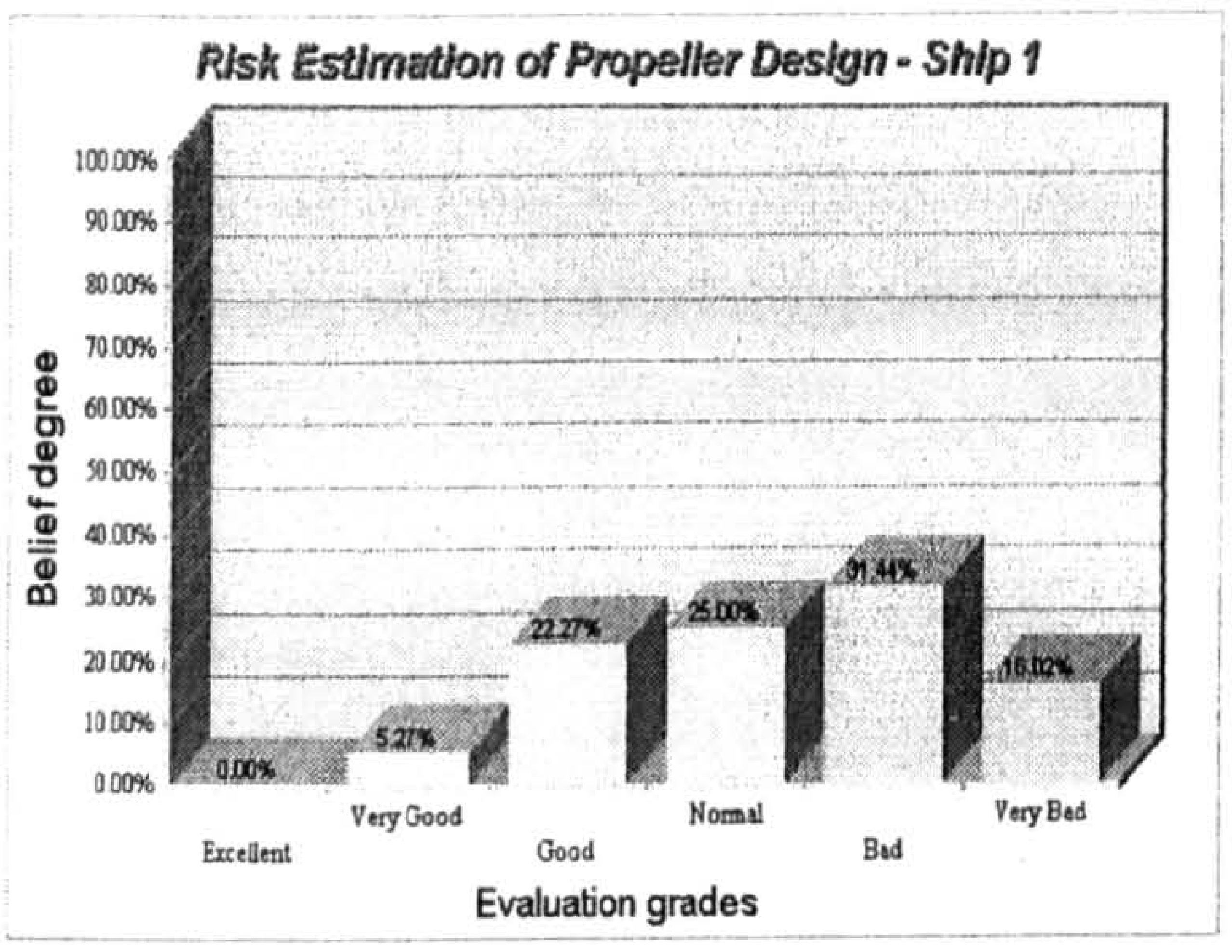
Results for Ship 1

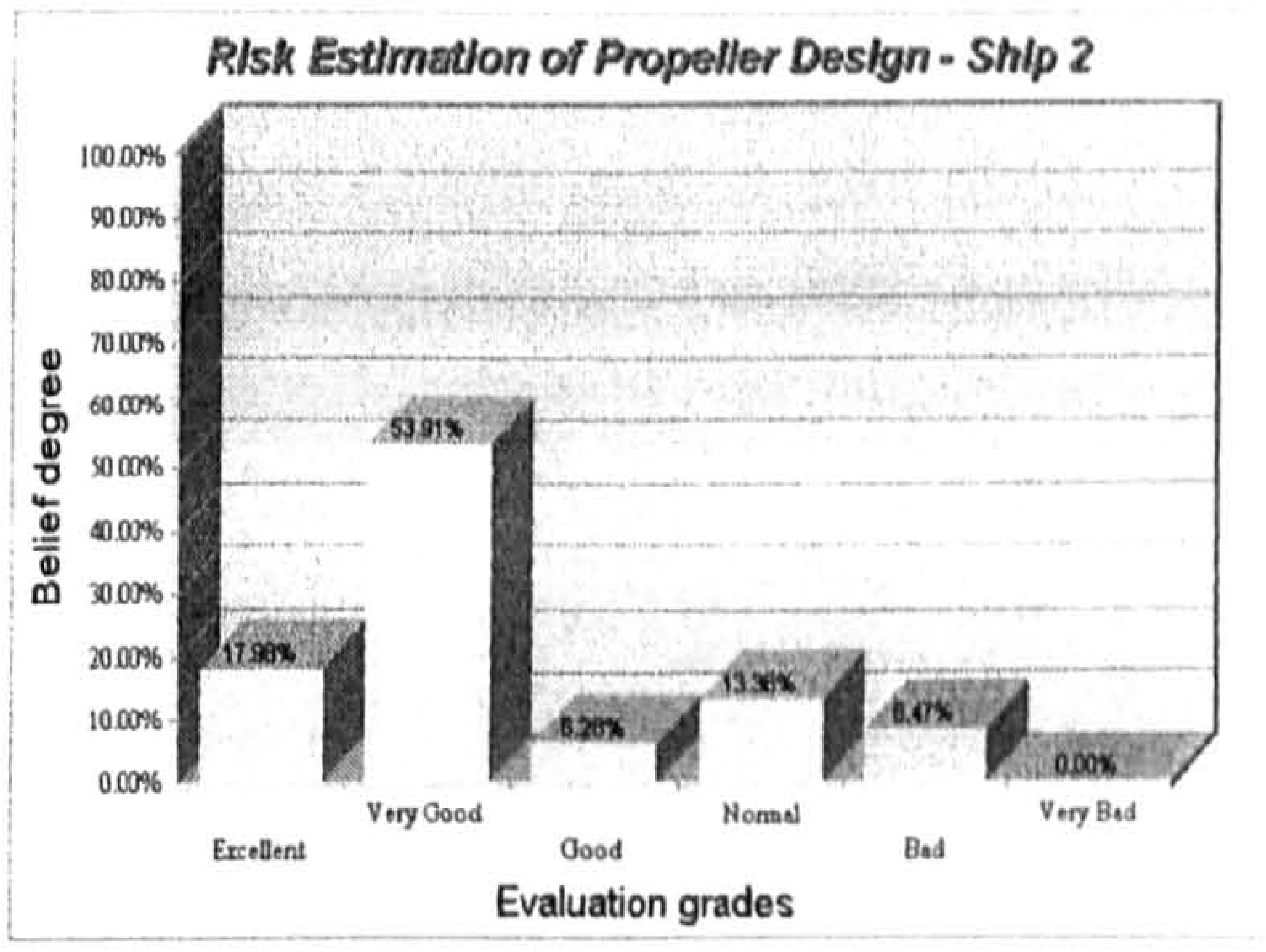
Design Criteria	Excellent	Very Good	Good	Normal	Bad	Very Bad
Propeller Design						
Propeller RPM	0.0000	0.0000	0.0250	0.4750	0.5000	0.0000
Propeller Diameter	0.0000	0.0000	0.6000	0.4000	0.0000	0.0000
Blade Area	0.0000	0.0000	0.2500	0.7500	0.0000	0.0000
Number of Blades	0.0000	0.6000	0.4000	0.0000	0.0000	0.0000
Propeller Pitch	0.0000	0.0000	0.0000	0.0000	0.6000	0.4000
Blade Thickness	0.0000	0.0000	0.0000	0.1682	0.2068	0.6250
Propeller Load	0.0000	0.0000	0.0000	0.3198	0.5584	0.1218
Propeller Skew	0.0000	0.0000	0.0000	0.0000	0.7500	0.2500
Shaft System Design						
Shaft System Length	0.0000	0.0000	0.3000	0.3000	0.4000	0.0000
Shaft Stiffness	0.0000	0.0000	0.0000	0.0000	0.8000	0.2000
Shaft Alignment	0.0000	0.0000	0.0000	0.0000	0.5000	0.5000
Bearings	0.0000	0.0000	0.0000	0.3000	0.7000	0.0000
Engine Design						
Engine RPM	0.0000	0.0000	0.0000	0.0425	0.1701	0.7874
Number of Engines	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
Number of Cylinders	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
Power to Weight Ratio	0.0000	0.0000	0.0000	0.3500	0.6500	0.0000
Damping Systems	0.0000	0.0000	0.0000	0.0000	0.8000	0.2000
Engine Firing	0.0000	0.0000	0.3434	0.4545	0.2021	0.0000
Engine Alignment	0.0000	0.0000	0.0000	0.0000	0.7200	0.2800
Ship Body Design						
Aft Body Design	0.0000	0.0000	0.0000	0.0000	0.6000	0.4000
Fore Body Design	0.0000	0.0000	0.0000	0.5000	0.5000	0.0000
Hull Smoothness	0.0000	0.0000	0.0000	0.1089	0.6930	0.1981
Rudder Design	0.0000	0.0000	0.0000	0.0000	0.5500	0.4500

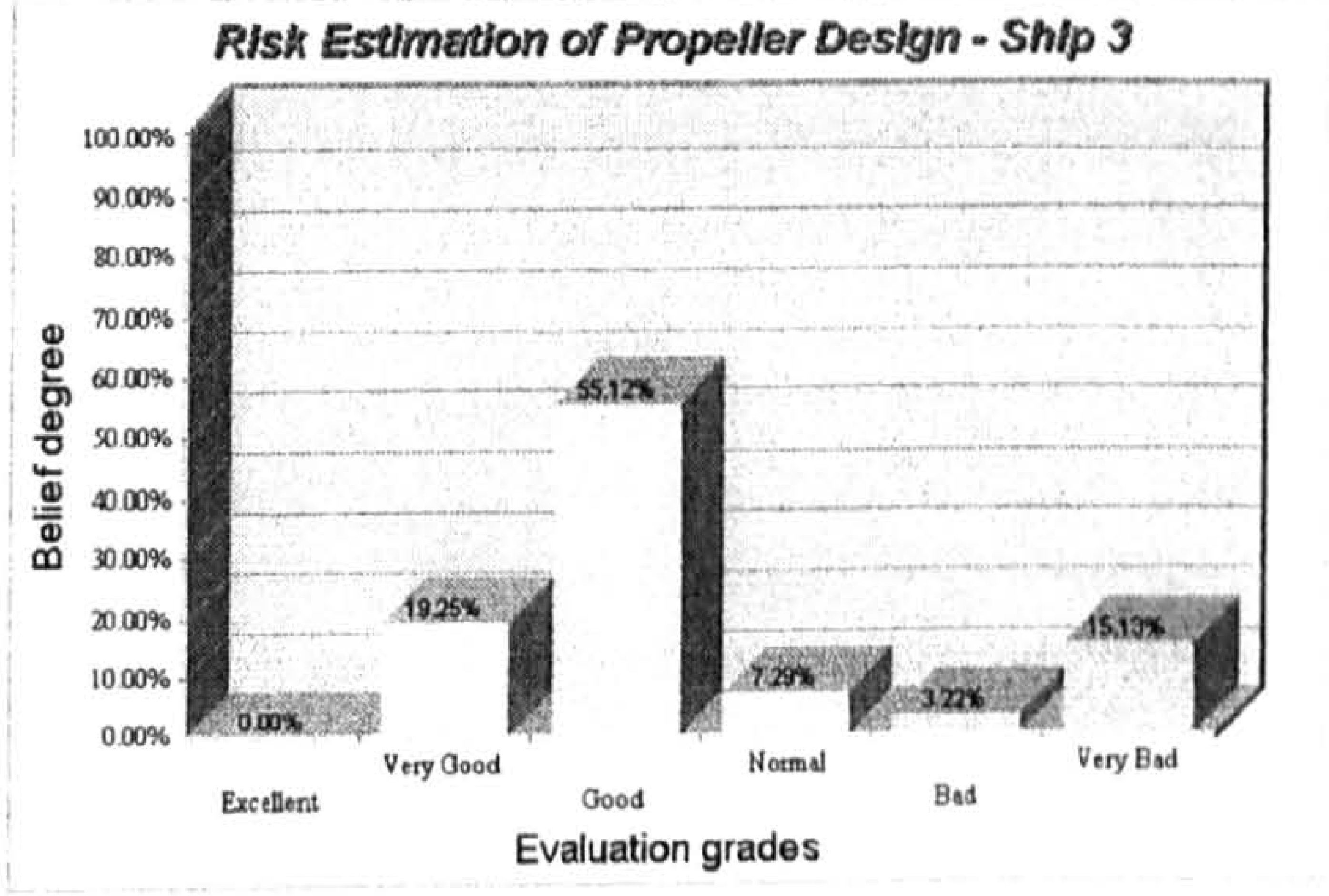
Results for Ship 3

Design Criteria	Excellent	Very Good	Good	Normal	Bad	Very Bad
Propeller Design						
Propeller RPM	0.0000	0.4000	0.3000	0.3000	0.0000	0.0000
Propeller Diameter	0.0000	0.5000	0.5000	0.0000	0.0000	0.0000
Blade Area	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
Number of Blades	0.0000	0.6000	0.4000	0.0000	0.0000	0.0000
Propeller Pitch	0.0000	0.0000	0.0000	0.0000	0.3000	0.7000
Blade Thickness	0.0000	0.0000	0.6400	0.3600	0.0000	0.0000
Propeller Load	0.0000	0.2000	0.8000	0.0000	0.0000	0.0000
Propeller Skew	0.0000	0.0000	0.0000	0.0000	0.0500	0.9500
Shaft System Design						
Shaft System Length	0.0000	0.0000	0.6000	0.4000	0.0000	0.0000
Shaft Stiffness	0.0000	0.0000	0.0000	0.2100	0.2700	0.5200
Shaft Alignment	0.0000	0.0000	0.0000	0.0000	0.1000	0.9000
Bearings	0.0000	0.0000	0.0000	0.0000	0.3000	0.7000
Engine Design						
Engine RPM	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
Number of Engines	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
Number of Cylinders	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
Power to Weight Ratio	0.0000	0.0000	0.0000	0.0000	0.8500	0.1500
Damping Systems	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
Engine Firing	0.0000	0.0000	0.0000	0.0000	0.3467	0.6533
Engine Alignment	0.0000	0.0000	0.0000	0.0000	0.8000	0.2000
Ship Body Design						
Aft Body Design	0.0000	0.0000	0.5000	0.5000	0.0000	0.0000
Fore Body Design	0.0000	0.0000	0.0000	0.6000	0.4000	0.0000
Hull Smoothness	0.0000	0.0000	0.0000	0.0000	0.4500	0.5500
Rudder Design	0.0000	0.0000	0.0000	0.0000	0.5000	0.5000

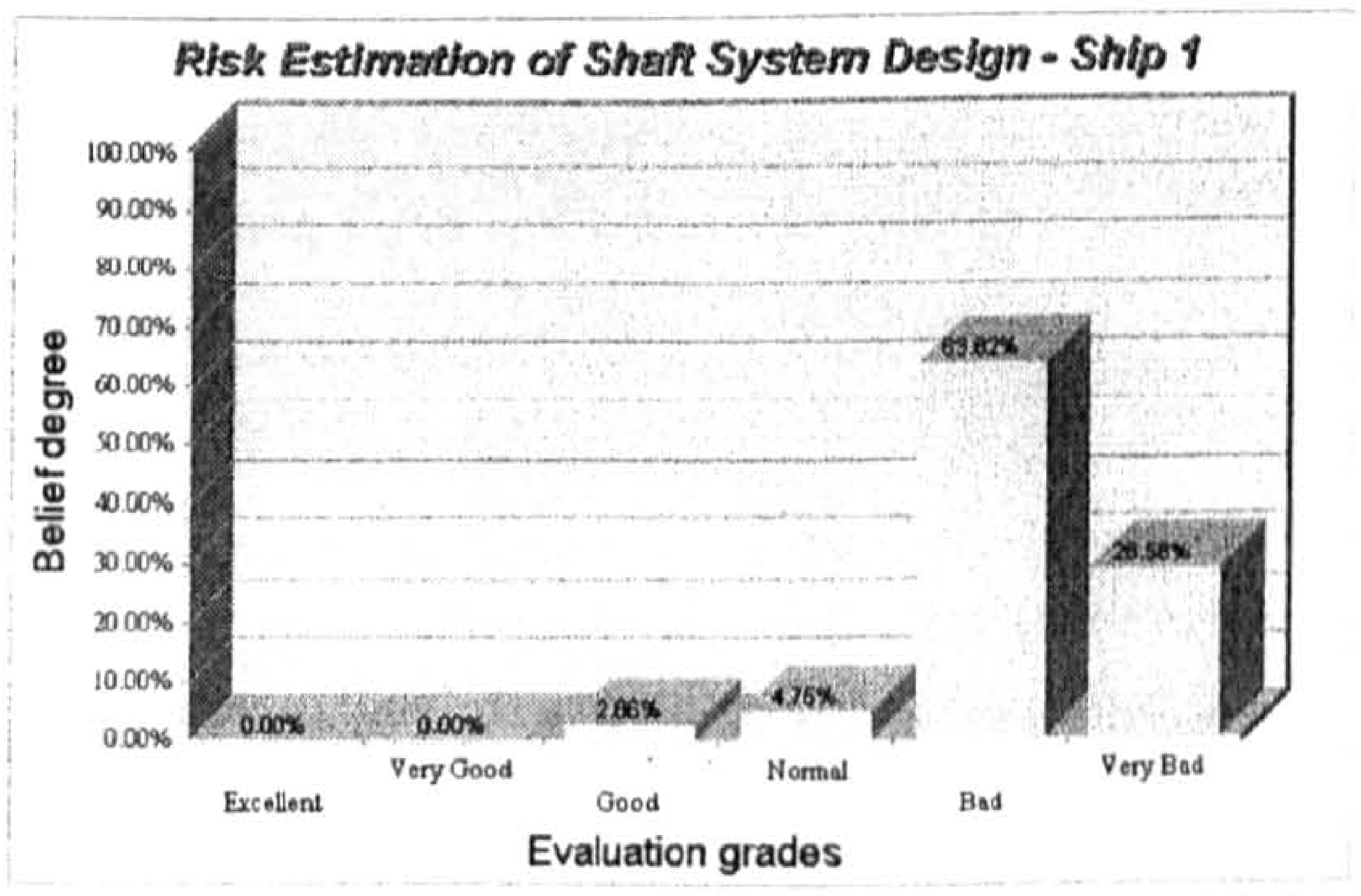
Appendix 4.3: Risk Estimation of Propeller Design

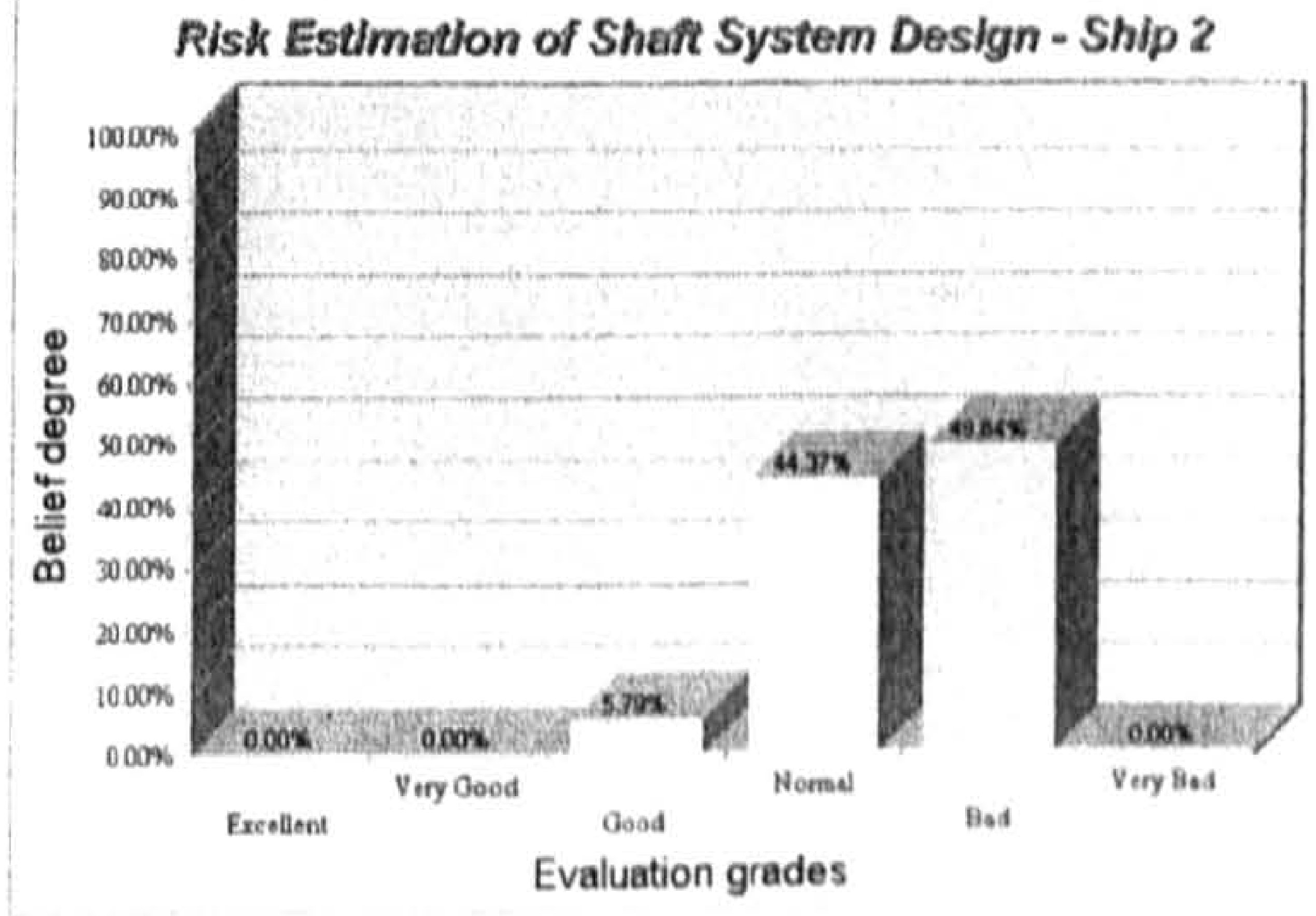

Risk Estimation of Propeller Design - Ship 1

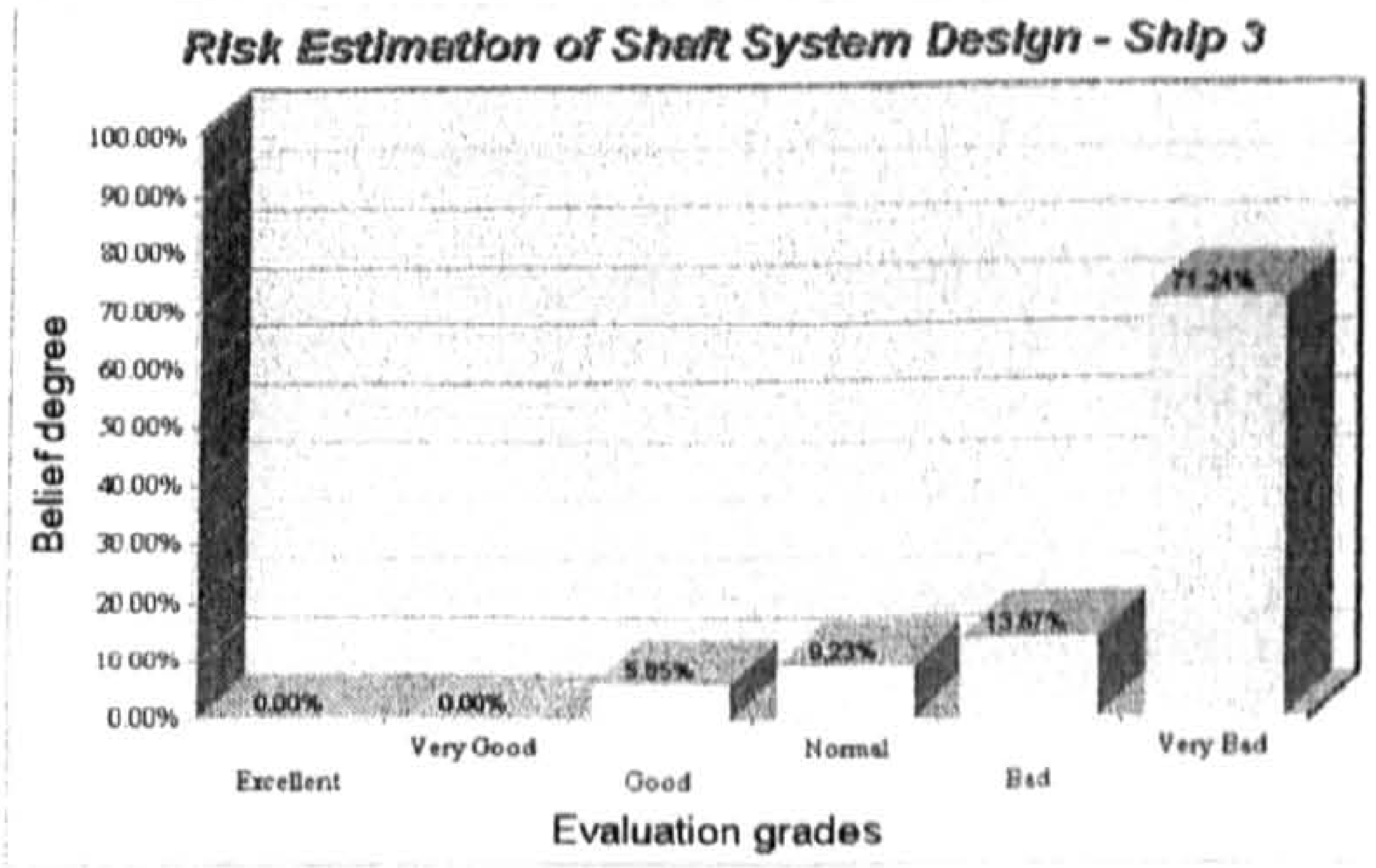

Risk Estimation of Propeller Design - Ship 2


Risk Estimation of Propeller Design - Ship 3

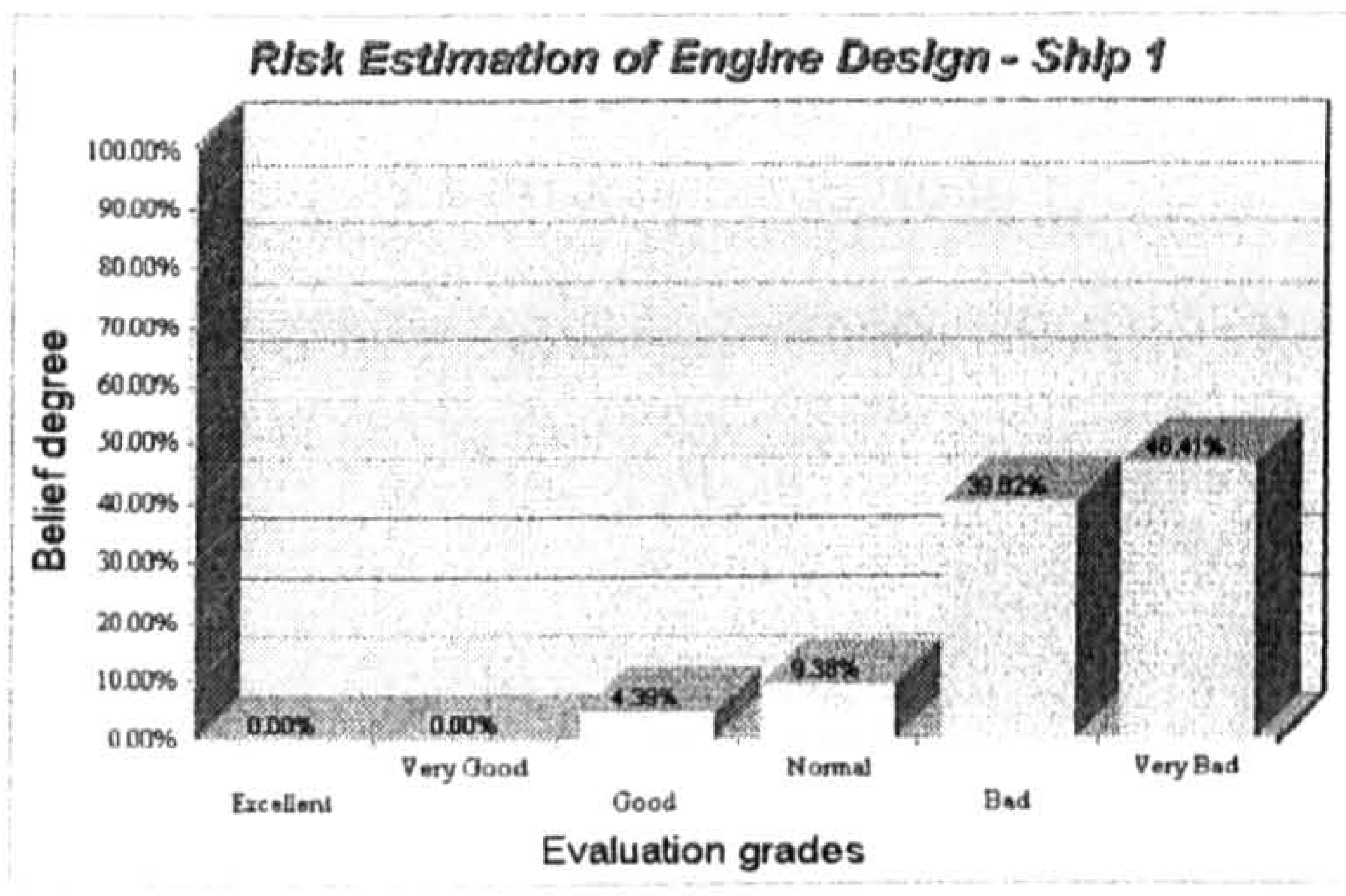
Appendix 4.4: Risk Estimation of Shaft System Design

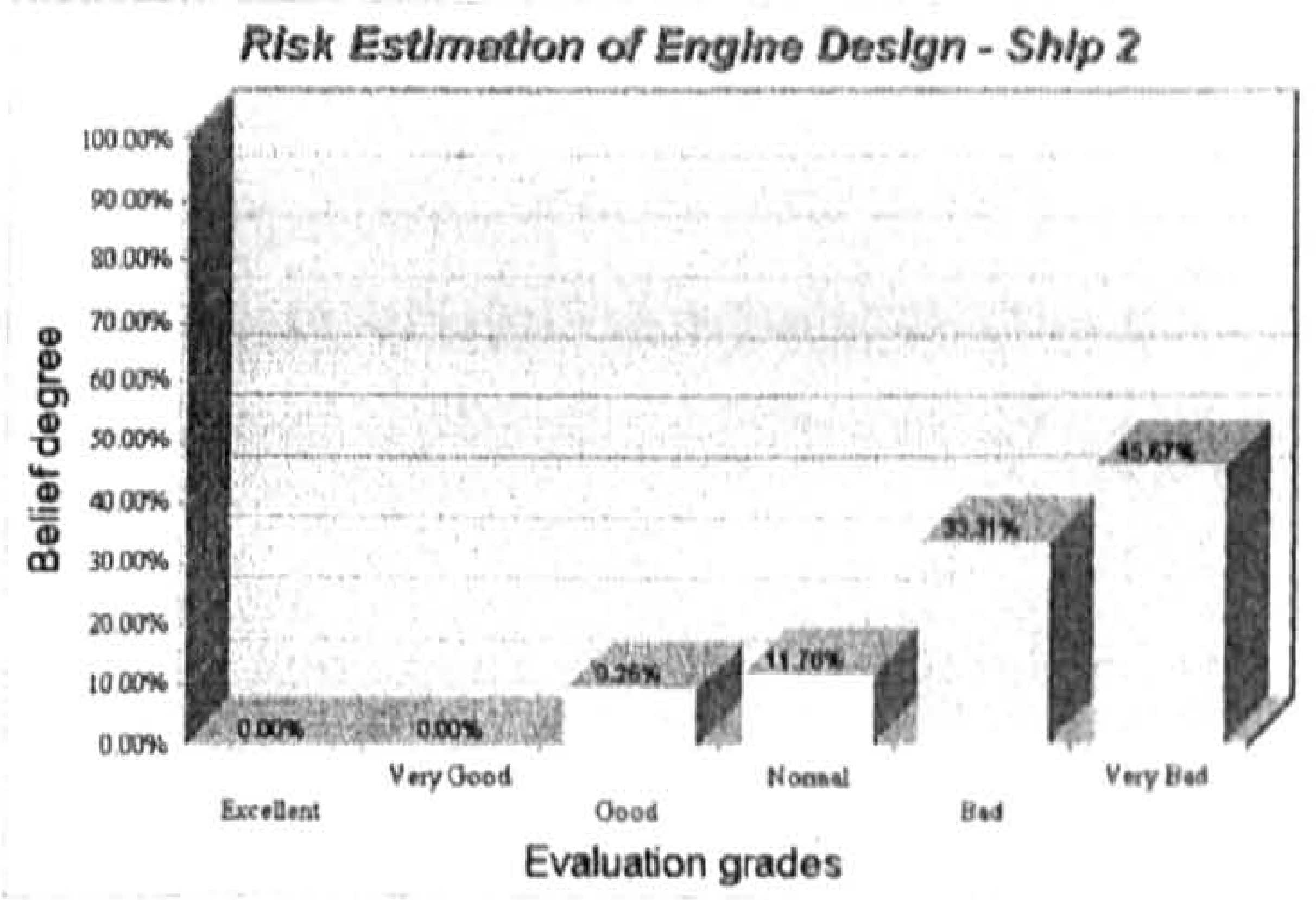

Risk Estimation of Shaft System Design - Ship 1

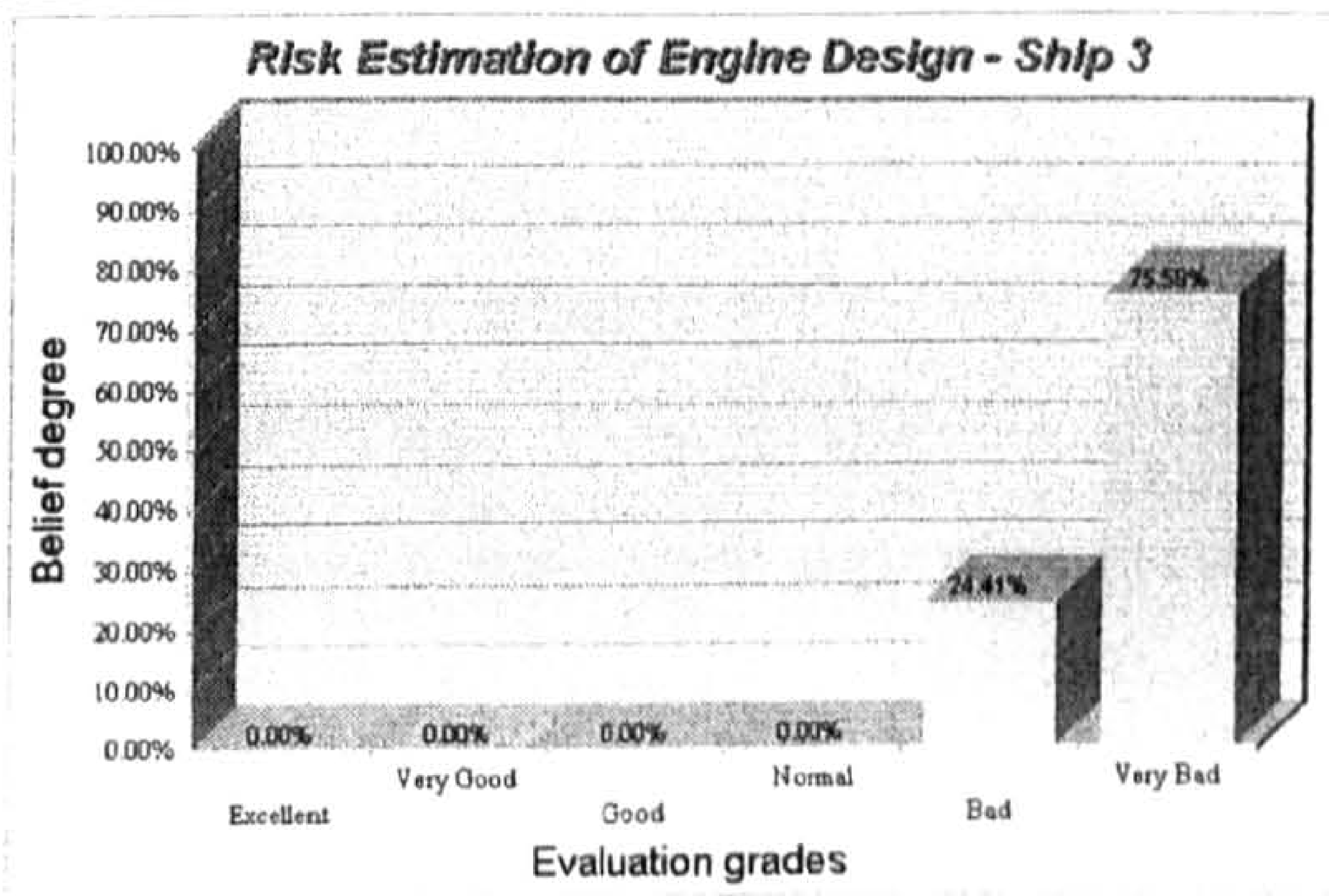

Risk Estimation of Shaft System Design - Ship 2


Risk Estimation of Shaft System Design - Ship 3

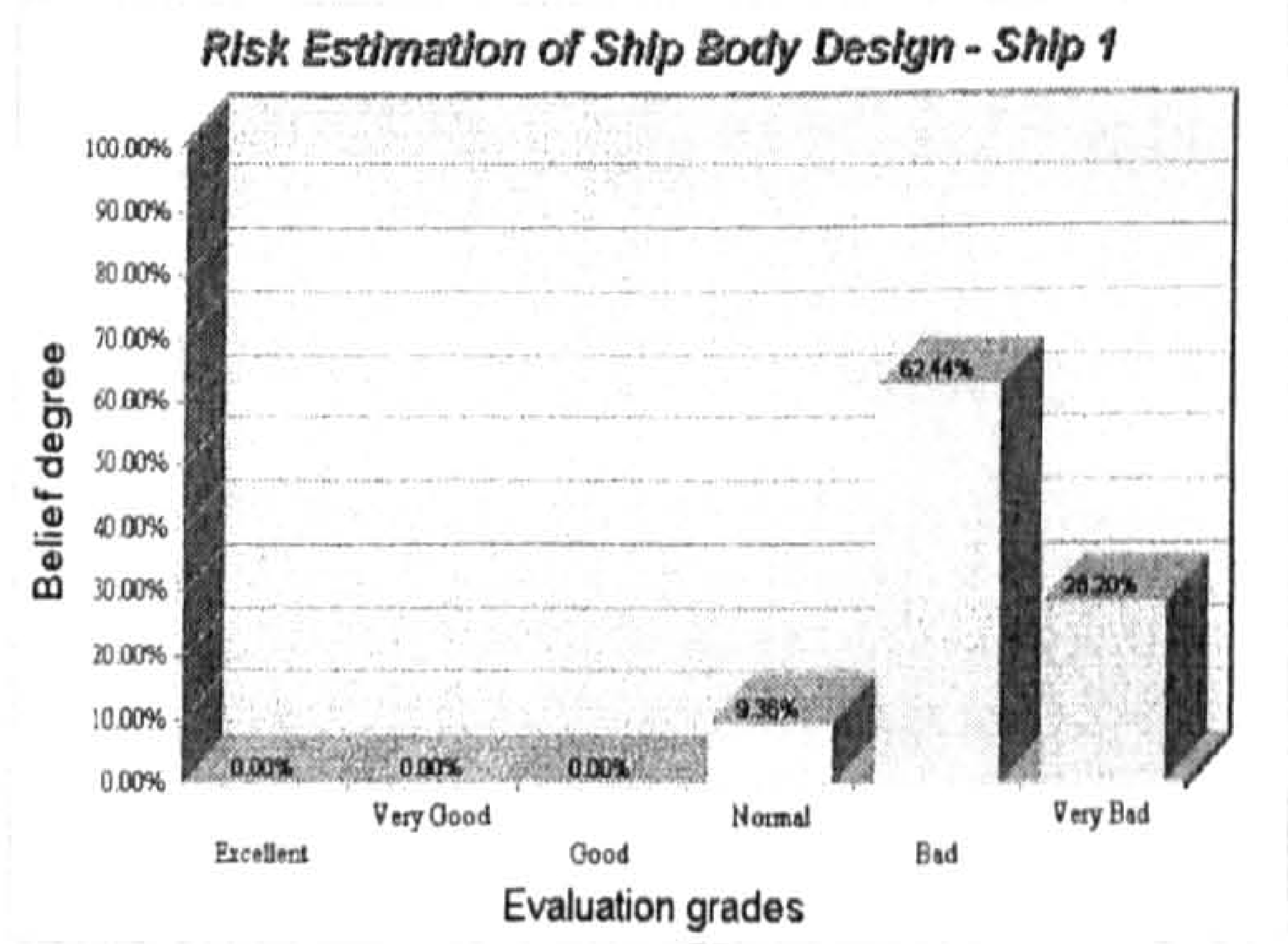
Appendix 4.5: Risk Estimation of Engine Design

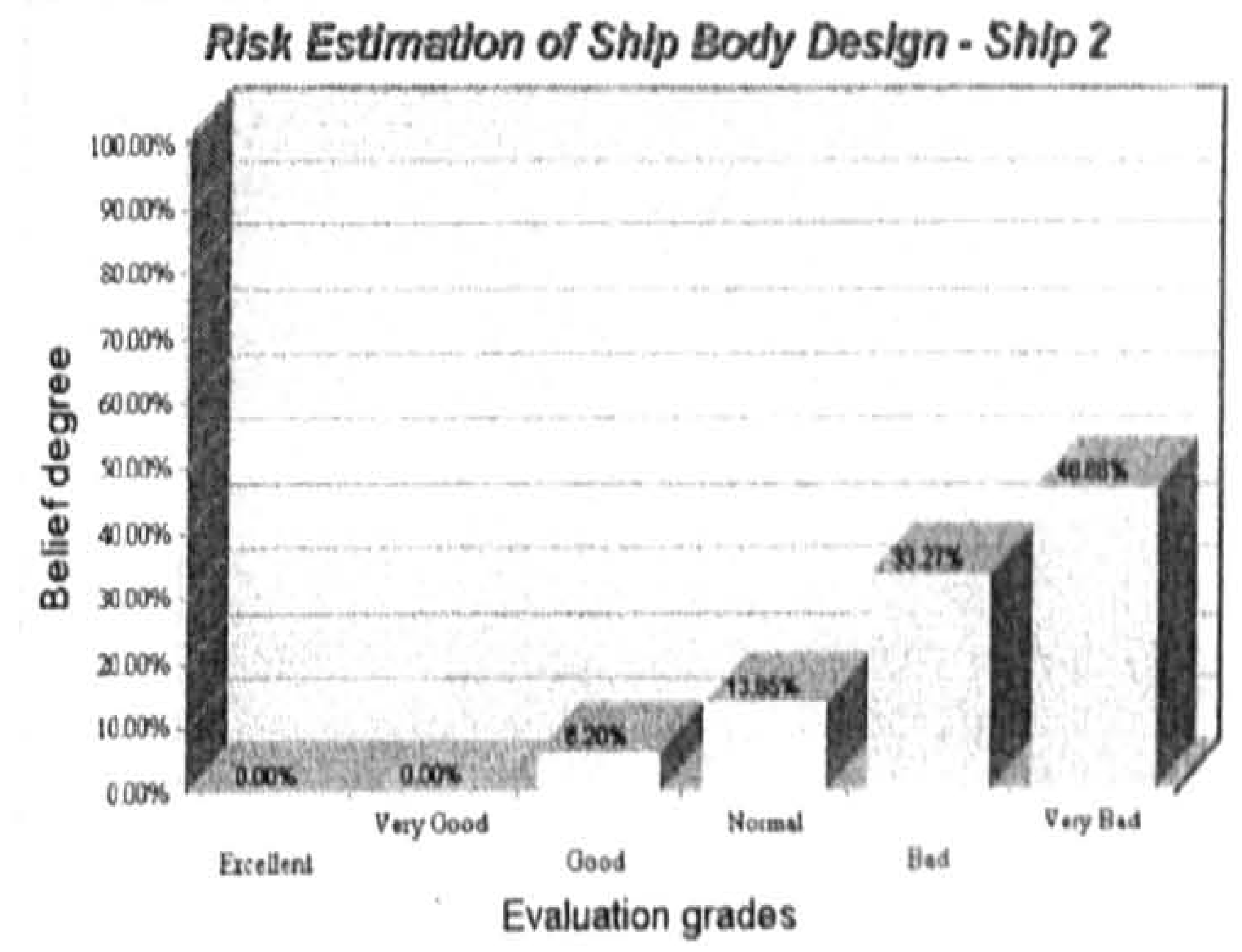


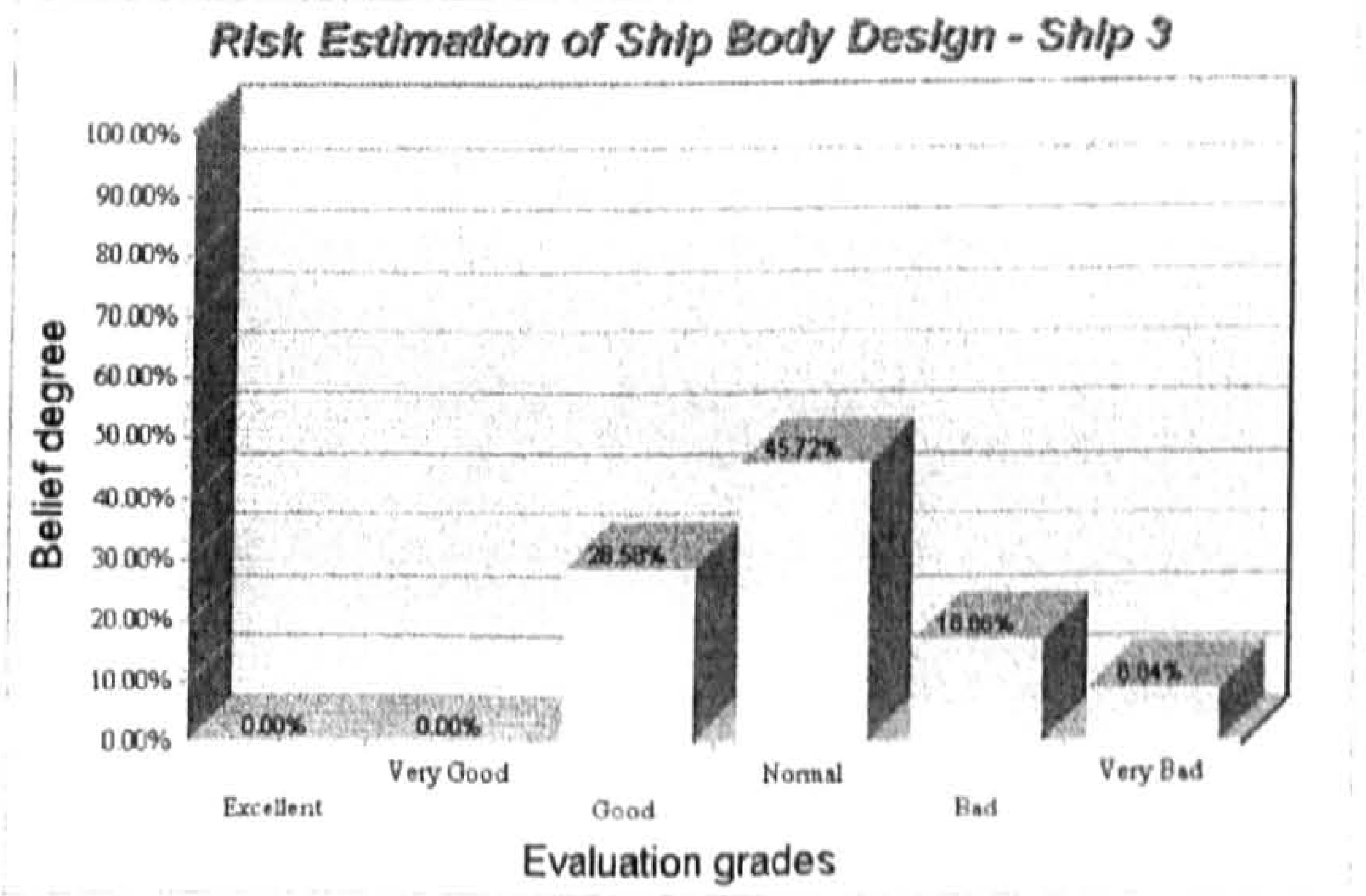




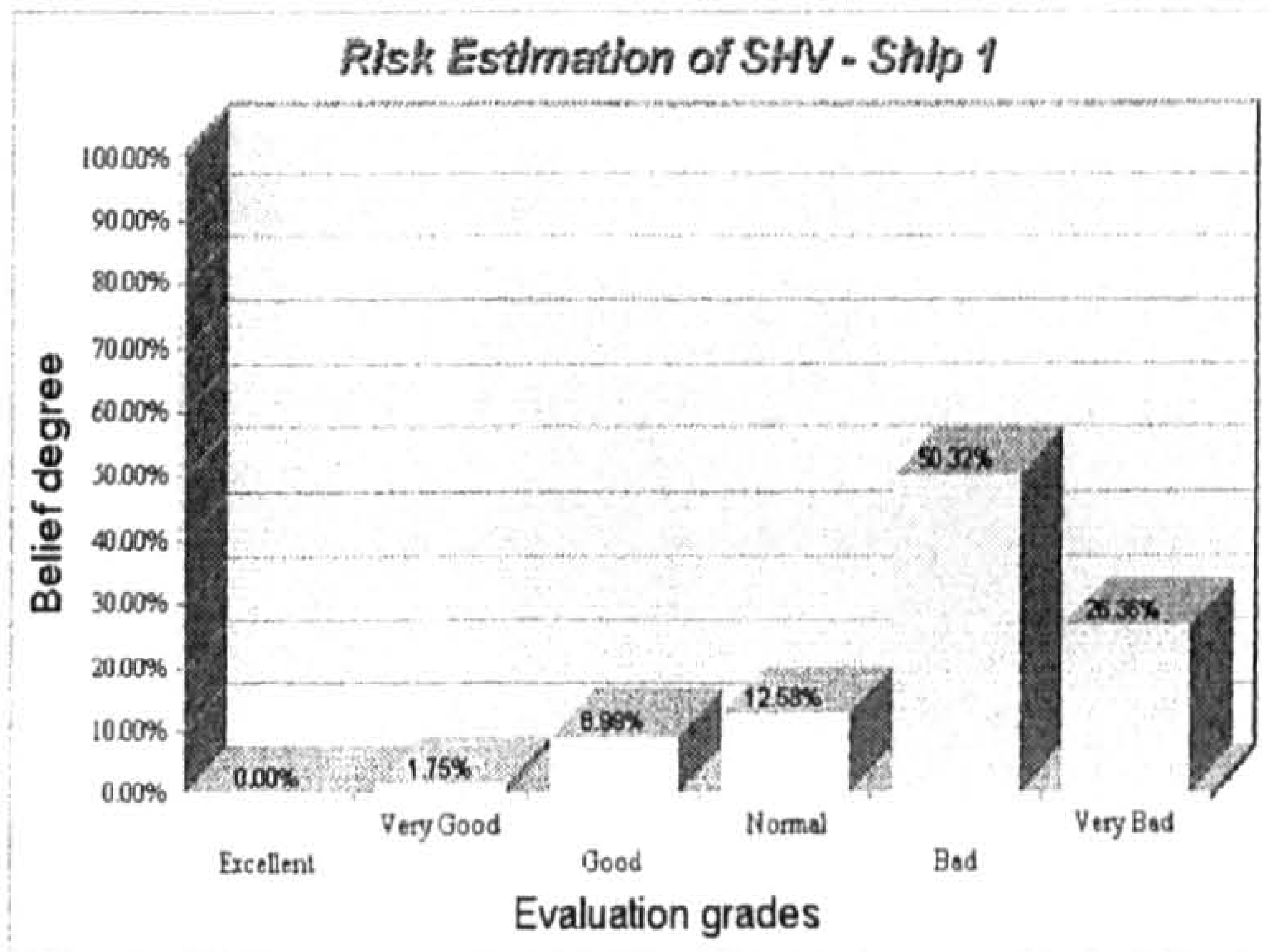
Appendix 4.6: Risk Estimation of Ship Body Design

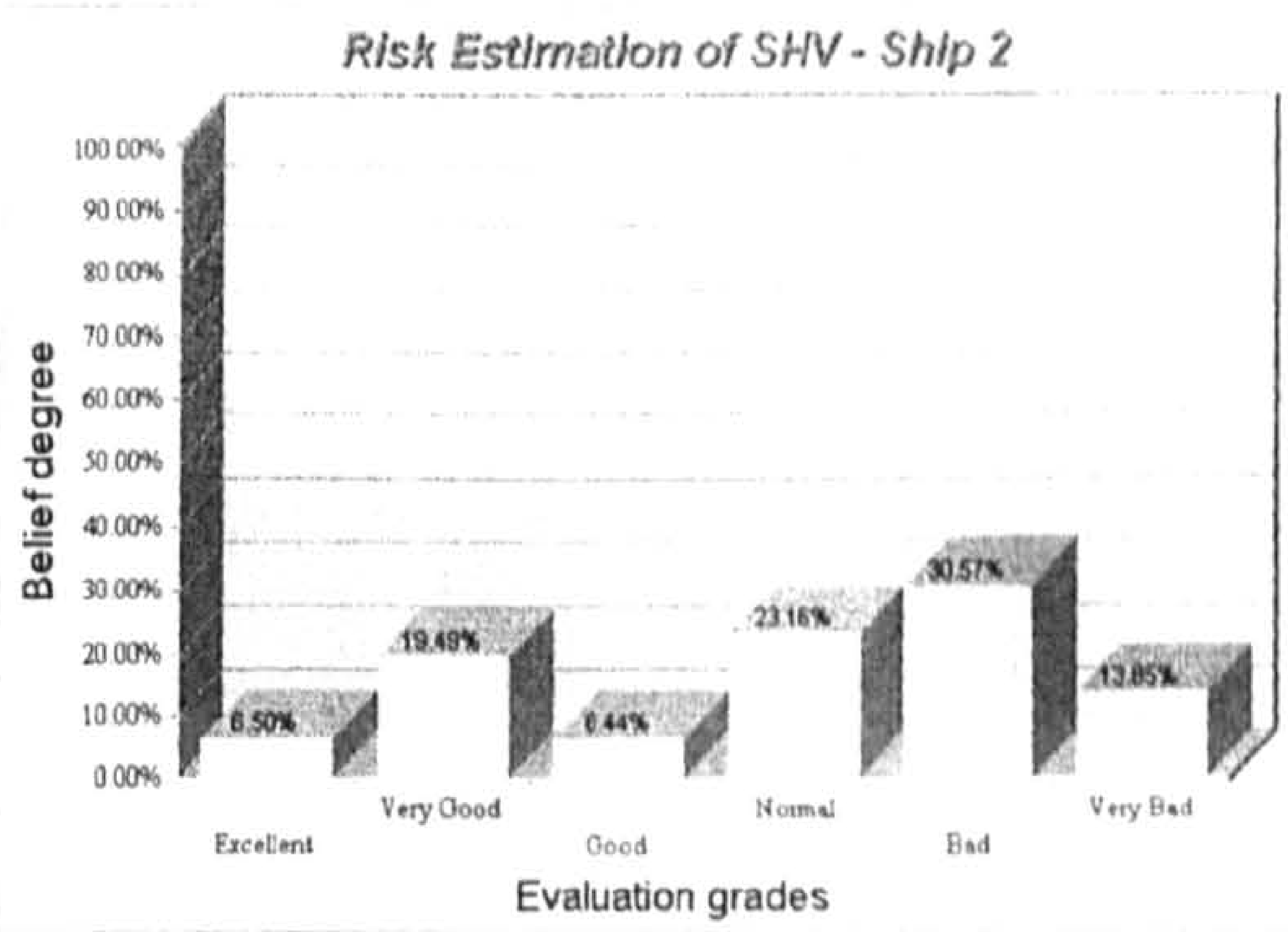


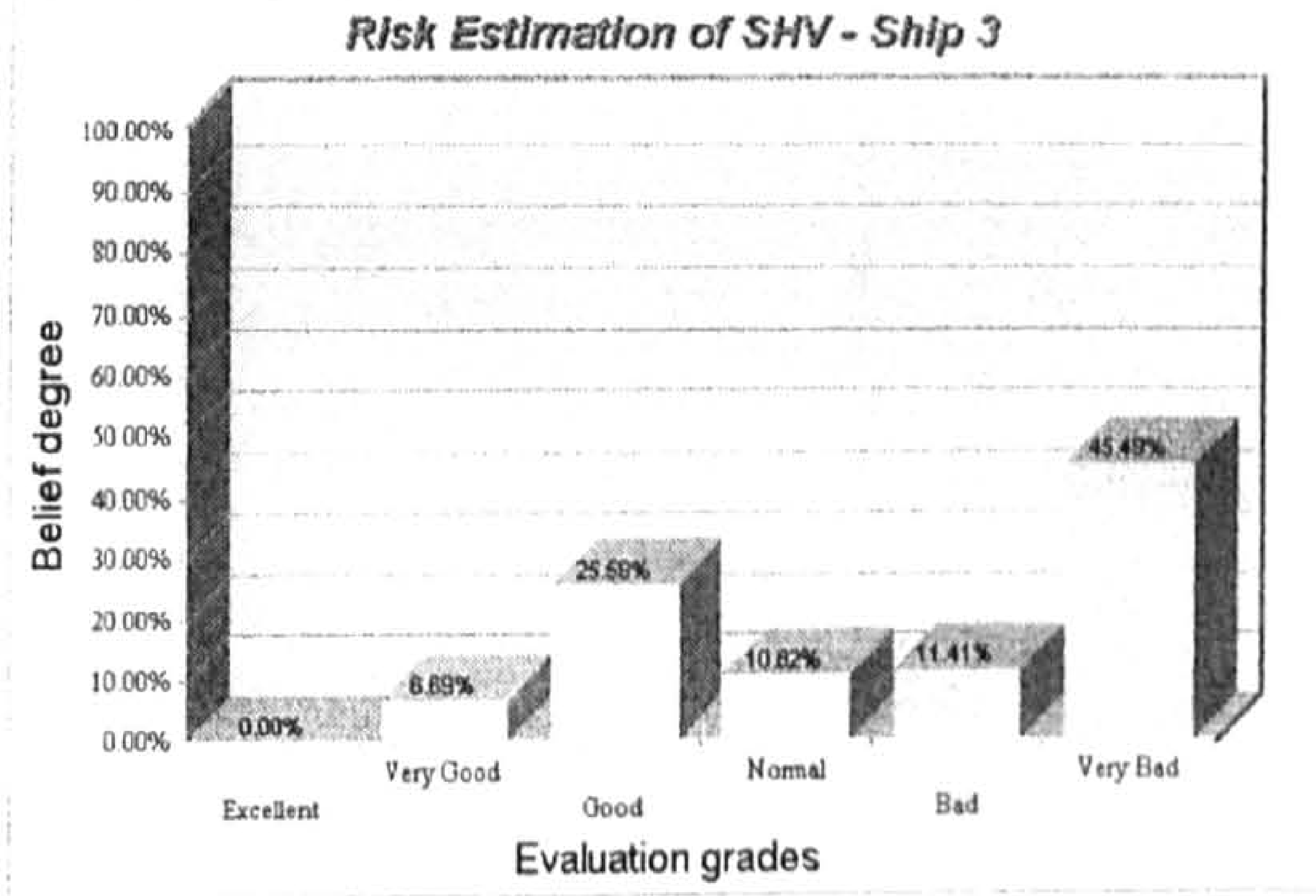




Appendix 4.7: Risk Estimation of SHV







Appendix 5

Appendix 5.1: The Crisp Importance Values in Level 3 in terms of Failure Capability

The Crisp Importance Values of Pairwise Comparisons between the Thrust Block Failure and Propeller Failure, Shafting Failure, Engine Component Failure and Hull Failure

	Propeller Failure	Shafting Failure	Thrust Block Failure	Engine Component Failure	Hull Failure
Thrust Block Failure	0.676	0.559	1.0	0.305	0.182

The Crisp Importance Values of Pairwise Comparisons between the Propeller Failure and Shafting Failure, Engine Component Failure and Hull Failure

	Propeller Failure	Shafting Failure	Engine Component Failure	Hull Failure
Propeller Failure	1.0	0.572	0.449	0.237

The Crisp Importance Values of Pairwise Comparisons between the Shafting Failure and Engine Component Failure and Hull Failure

	Shafting Failure	Engine Component Failure	Hull Failure
Shafting Failure	1.0	0.611	0.455

The Crisp Importance Values of Pairwise Comparisons *between the Engine* Component Failure and Hull Failure

	Engine Component Failure	Hull Failure
Engine Component Failure	1.0	0.527

Appendix 5.2: The Crisp Importance Values in Level 3 in terms of Failure Recovery Incapability

The Crisp Importance Values of Pairwise Comparisons between the Thrust Block Failure and Propeller Failure, Shafting Failure, Engine Component Failure and Hull Failure

	Propeller Failure	Shafting Failure	Thrust Block Failure	Engine Component Failure	Hull Failure
Thrust Block Failure	0.116	0.684	1.000	0.442	0.348

The Crisp Importance Values of Pairwise Comparisons between the Shafting Failure and Propeller Failure, Engine Component Failure and Hull Failure

	Propeller Failure	Shafting Failure	Engine Component Failure	Hull Failure
Shafting Failure	0.154	1.000	0.468	0.546

The Crisp Importance Values of Pairwise Comparisons between the Engine Component Failure and Propeller Failure and Hull Failure

	Propeller Failure	Engine Component Failure	Hull Failure
Engine Component Failure	0.356	1.000	0.735

The Crisp Importance Values of Pairwise Comparisons between the Hull Failure and Propeller Failure

	Propeller Failure	Hull Failure
Hull Failure	0.752	1.000

Appendix 5.3: The Crisp Importance Values in Level 3 in terms of Failure Consequence Probability

The Crisp Importance Values of Pairwise Comparisons between the Thrust Block Failure and Propeller Failure, Shafting Failure, Engine Component Failure and Hull Failure

	Propeller Failure	Shafting Failure	Thrust Block Failure	Engine Component Failure	Hull Failure
Thrust Block Failure	0.087	0.455	1.000	0.331	0.624

The Crisp Importance Values of Pairwise Comparisons between the Hull Failure and Propeller Failure, Shafting Failure and Engine Component Failure

	Propeller Failure	Shafting Failure	Engine Component Failure	Hull Failure
Hull Failure	0.173	0.546	0.429	1.000

The Crisp Importance Values of Pairwise Comparisons between the Shafting Failure and Propeller Failure and Engine Component Failure

	Propeller Failure	Shafting Failure	Engine Component Failure
Shafting Failure	0.370	1.000	0.533

The Crisp Importance Values of Pairwise Comparisons between the Engine Component Failure and Propeller Failure

	Propeller Failure	Engine Component Failure
Engine Component Failure	0.559	1.000

Appendix 5.4: The Crisp Importance Values in Level 4 in terms of Failure Likelihood

Propeller Failure

The Crisp Importance Values of Pairwise Comparisons between the Back Bubble Cavitation and Sheet Cavitation, Tip/ Hub Vortex Cavitation, Propeller-Hull Vortex Cavitation and Physical Damages

	Back Bubble Cavitation	Sheet Cavitation	Tip/ Hub Vortex Cavitation	Propeller-Hull Vortex Cavitation	Physical Damages
Back Bubble Cavitation	1.000	0.735	0.201	0.356	0.579

The Crisp Importance Values of Pairwise Comparisons between the Sheet Cavitation and Tip/ Hub Vortex Cavitation, Propeller-Hull Vortex Cavitation and Physical Damages

	Sheet Cavitation	Tip/ Hub Vortex Cavitation	Propeller-Hull Vortex Cavitation	Physical Damages
Sheet Cavitation	1.000	0.305	0.442	0.795

The Crisp Importance Values of Pairwise Comparisons between the Physical Damages and Tip/ Hub Vortex Cavitation and Propeller-Hull Vortex Cavitation

	Tip/ Hub Vortex Cavitation	Propeller-Hull Vortex Cavitation	Physical Damages
Physical Damages	0.416	0.533	1.000

The Crisp Importance Values of Pairwise Comparisons between the Propeller-Hull Vortex Cavitation and Tip/ Hub Vortex Cavitation

	Tip/ Hub Vortex Cavitation	Propeller-Hull Vortex Cavitation
Propeller-Hull Vortex Cavitation	0.527	1.000

Shafting Failure

The Crisp Importance Values of Pairwise Comparisons between the Bearing Failure and Misalignment, Torque Variations, Crankshaft Deflection and Shaft Whirling

	Misalignment	Bearing Failure	Torque Variations	Crankshaft Deflection	Shaft Whirling
Bearing Failure	0.087	1.000	0.254	0.403	0.598

The Crisp Importance Values of Pairwise Comparisons between the Shaft Whirling and Misalignment, Torque Variations and Crankshaft Deflection

	Misalignment	Torque Variations	Crankshaft Deflection	Shaft Whirling
Shaft Whirling	0.144	0.305	0.481	1.000

The Crisp Importance Values of Pairwise Comparisons between the Crankshaft Deflection and Misalignment and Torque Variations

	Misalignment	Torque Variations	Crankshaft Deflection
Crankshaft Deflection	0.263	0.442	1.000

The Crisp Importance Values of Pairwise Comparisons between the Torque Variations and Misalignment

	Misalignment	Torque Variations
Torque Variations	0.585	1.000

Thrust Block Failure

The Crisp Importance Values of Pairwise Comparisons between the Deformation from the Thrust Load and Thrust Block Misalignment, Thrust Block Rocking and Excessive Thrust Block Wear

	Deformation from the Thrust Load	Thrust Block Misalignment	Thrust Block .Rocking	Excessive Thrust Block Wear
Deformation from the Thrust Load	1.000	0.305	0.598	0.769

The Crisp Importance Values of Pairwise Comparisons between the Excessive Thrust Block Wear and Thrust Block Misalignment and Thrust Block Rocking

	Thrust Block Misalignment	Thrust Block Rocking	Excessive Thrust Block Wear

Excessive Thrust Block Wear	0.507	0.631	1.000

The Crisp Importance Values of Pairwise Comparisons between the Thrust Block Rocking and Thrust Block Misalignment

	Thrust Block Misalignment	Thrust Block Rocking
Thrust Block Rocking	0.659	1.000

Engine Component Failure

The Crisp Importance Values of Pairwise Comparisons between the Component Wear and Out of Balance Forces, Incorrect Power Balance, Variable Gas Pressures and Engine Misalignment

	Component Wear	Out of Balance Forces	Incorrect Power Balance	Variable Gas Pressures	Engine Misalignment
Component Wear	1.000	0.192	0.585	0.442	0.271

The Crisp Importance Values of Pairwise Comparisons between the Incorrect Power Balance and Out of Balance Forces, Variable Gas Pressures and Engine Misalignment

	Out of Balance Forces	Incorrect Power Balance	Variable Gas Pressures	Engine Misalignment
Incorrect Power Balance	0.254	1.000	0.735	0.416

The Crisp Importance Values of Pairwise Comparisons between the Variable Gas Pressures and Out of Balance Forces and Engine Misalignment

	Out of Balance Forces	Variable Gas Pressures	Engine Misalignment
Variable Gas Pressures	0.434	1.000	0.667

The Crisp Importance Values of Pairwise Comparisons between the Engine Misalignment and Out of Balance Forces

	Out of Balance Forces	Engine Misalignment
Engine Misalignment	0.659	1.000

Hull Failure

The Crisp Importance Values of Pairwise Comparisons between Grounding and Sagging & Hogging of the Hull due to Sea Conditions, Ship Loading & Discharging, Corrosion and Grounding

	Sagging & Hogging	Ship Loading & Discharging	Corrosion	Grounding
Grounding	0.078	0.585	0.271	1.000

The Crisp Importance Values of Pairwise Comparisons between Ship Loading & Discharging and Sagging & Hogging of the Hull due to Sea Conditions and Corrosion

	Sagging & Hogging	Ship Loading & Discharging	Corrosion
Ship Loading & Discharging	0.192	1.000	0.442

The Crisp Importance Values of Pairwise Comparisons between Ship Loading & Discharging and Sagging & Hogging of the Hull due to Sea Conditions and Corrosion

	Sagging & Hogging	Corrosion
Corrosion	0.373	1.000

Appendix 5.5: The Crisp Importance Values in Level 4 in terms of Failure Capability

Propeller Failure

The Crisp Importance Values of Pairwise Comparisons between the Cloud Cavitation and Back Bubble Cavitation, Sheet Cavitation, Tip/ Hub Vortex Cavitation, Propeller-Hull Vortex Cavitation and Physical Damages

	Back Bubble Cavitation	Sheet Cavitation	Cloud Cavitation	Tip/ Hub Vortex Cavitation	Propeller-Hull Vortex Cavitation	Physical Damages
Cloud Cavitation	0.769	0.585	1.000	0.442	0.494	0.068

The Crisp Importance Values of Pairwise Comparisons between the Back Bubble Cavitation and Sheet Cavitation, Tip/ Hub Vortex Cavitation, Propeller-Hull Vortex Cavitation and Physical Damages

	Back Bubble Cavitation	Sheet Cavitation	Tip/ Hub Vortex Cavitation	Propeller-Hull Vortex Cavitation	Physical Damages
Back Bubble Cavitation	1.000	0.710	0.488	0.546	0.144

The Crisp Importance Values of Pairwise Comparisons between the Sheet Cavitation and Tip/ Hub Vortex Cavitation, Propeller-Hull Vortex Cavitation and Physical Damages

	Sheet Cavitation	Tip/ Hub Vortex Cavitation	Propeller-Hull Vortex Cavitation	Physical Damages
Sheet Cavitation	1.000	0.540	0.659	0.237

The Crisp Importance Values of Pairwise Comparisons between the Propeller-Hull Vortex Cavitation and Tip/ Hub Vortex Cavitation and Physical Damages

	Tip/ Hub Vortex Cavitation	Propeller-Hull Vortex Cavitation	Physical Damages
Propeller-Hull Vortex Cavitation	0.735	1.000	0.566

The Crisp Importance Values of Pairwise Comparisons between the Propeller-Hull Vortex Cavitation and Tip/ Hub Vortex Cavitation and Physical Damages

	Tip/ Hub Vortex Cavitation	Physical Damages
Tip/ Hub Vortex Cavitation	1.000	0.667

Shafting Failure

The Crisp Importance Values of Pairwise Comparisons between the Bearing Failure and Misalignment, Torque Variations, Crankshaft Deflection and Shaft Whirling

	Misalignment	Bearing Failure	Torque Variations	Crankshaft Deflection	Shaft Whirling
Bearing Failure	0.271	1.000	0.182	0.579	0.125

The Crisp Importance Values of Pairwise Comparisons between the Crankshaft Deflection and Misalignment, Torque Variations and Shaft Whirling

	Misalignment	Torque Variations	Crankshaft Deflection	Shaft Whirling
Crankshaft Deflection	0.572	0.339	1.000	0.254

The Crisp Importance Values of Pairwise Comparisons between the Misalignment and Torque Variations and Shaft Whirling

	Misalignment	Torque Variations	Shaft Whirling
Misalignment	1.000	0.501	0.475

The Crisp Importance Values of Pairwise Comparisons between the Misalignment and Torque Variations and Shaft Whirling

	Torque Variations	Shaft Whirling
Torque Variations	1.000	0.624

Thrust Block Failure

The Crisp Importance Values of Pairwise Comparisons between the Deformation from the Thrust Load and Thrust Block Misalignment, Thrust Block Rocking and Excessive Thrust Block Wear

	Deformation from the Thrust Load	Thrust Block Misalignment	Thrust Block Rocking	Excessive Thrust Block Wear
Deformation from the Thrust Load	1.000	0.237	0.116	0.693

The Crisp Importance Values of Pairwise Comparisons between the Excessive Thrust Block Wear and Thrust Block Misalignment and Thrust Block Rocking

	Thrust Block Misalignment	Thrust Block Rocking	Excessive Thrust Block Wear
Excessive Thrust Block Wear	0.410	0.254	1.000

The Crisp Importance Values of Pairwise Comparisons between the Thrust Block Misalignment and Thrust Block Rocking

	Thrust Block Misalignment	Thrust Block Rocking
Thrust Block Misalignment	1.000	0.481

Engine Component Failure

The Crisp Importance Values of Pairwise Comparisons between the Component Wear and Out of Balance Forces, Incorrect Power Balance, Variable Gas Pressures and Engine Misalignment

	Component Wear	Out of Balance Forces	Incorrect Power Balance	Variable Gas Pressures	Engine Misalignment
Component Wear	1.000	0.305	0.087	0.585	0.373

The Crisp Importance Values of Pairwise Comparisons between the Variable Gas Pressures and Out of Balance Forces, Incorrect Power Balance and Engine Misalignment

	Out of Balance Forces	Incorrect Power Balance	Variable Gas Pressures	Engine Misalignment
Variable Gas Pressures	0.429	0.192	1.000	0.494

The Crisp Importance Values of Pairwise Comparisons between the Engine Misalignment and Out of Balance Forces and Incorrect Power Balance

	Out of Balance Forces	Incorrect Power Balance	Engine Misalignment
Engine Misalignment	0.598	0.356	1.000

The Crisp Importance Values of Pairwise Comparisons between the Out of Balance Forces and Incorrect Power Balance

	Out of Balance Forces	Incorrect Power Balance
Out of Balance Forces	1.000	0.618

Hull Failure

The Crisp Importance Values of Pairwise Comparisons between Corrosion and Sagging & Hogging of the Hull due to Sea Conditions, Ship Loading & Discharging, Corrosion and Grounding

	Sagging & Hogging	Ship Loading & Discharging	Corrosion	Grounding
Corrosion	0.305	0.192	1.000	0.598

The Crisp Importance Values of Pairwise Comparisons between Grounding and Sagging & Hogging of the Hull due to Sea Conditions and Ship Loading & Discharging

	Sagging & Hogging	Ship Loading & Discharging	Grounding
Grounding	*0.572*	0.339	1.000

The Crisp Importance Values of Pairwise Comparisons between Grounding and Sagging & Hogging of the Hull due to Sea Conditions and Ship Loading & Discharging

	Sagging & Hogging	Ship Loading & Discharging
Sagging & Hogging	1.000	0.618

Appendix 5.6: The Crisp Importance Values in Level 4 in terms of Failure Recovery Incapability

Propeller Failure

The Crisp Importance Values of Pairwise Comparisons between the Cloud Cavitation and Back Bubble Cavitation, Sheet Cavitation, Tip/ Hub Vortex Cavitation, Propeller-Hull Vortex Cavitation and Physical Damages

	Back Bubble Cavitation	Sheet Cavitation	Cloud Cavitation	Tip/ Hub Vortex Cavitation	Propeller-Hull Vortex Cavitation	Physical Damages

Cloud Cavitation	0.744	0.598	1.000	0.475	0.339	0.182

The Crisp Importance Values of Pairwise Comparisons between the Back Bubble Cavitation and Sheet Cavitation, Tip/ Hub Vortex Cavitation, Propeller-Hull Vortex Cavitation and Physical Damages

	Back Bubble Cavitation	Sheet Cavitation	Tip/ Hub Vortex Cavitation	Propeller-Hull Vortex Cavitation	Physical Damages
Back Bubble Cavitation	1.000	0.769	0.546	0.356	0.237

The Crisp Importance Values of Pairwise Comparisons between the Sheet Cavitation and Tip/ Hub Vortex Cavitation, Propeller-Hull Vortex Cavitation and Physical Damages

	Sheet Cavitation	Tip/ Hub Vortex Cavitation	Propeller-Hull Vortex Cavitation	Physical Damages
Sheet Cavitation	1.000	0.701	0.533	0.455

The Crisp Importance Values of Pairwise Comparisons between the Tip/ Hub Vortex Cavitation and Propeller-Hull Vortex Cavitation and Physical Damages

	Tip/ Hub Vortex Cavitation	Propeller-Hull Vortex Cavitation	Physical Damages
Tip/ Hub Vortex Cavitation	1.000	0.693	0.540

The Crisp Importance Values of Pairwise Comparisons between the Propeller-Hull Vortex Cavitation and Physical Damages

	Propeller-Hull Vortex Cavitation	Physical Damages
Propeller-Hull Vortex Cavitation	1.000	0.572

Shafting Failure

The Crisp Importance Values of Pairwise Comparisons between the Crankshaft Deflection and Misalignment, Bearing Failure, Torque Variations and Shaft Whirling

	Misalignment	Bearing Failure	Torque Variations	Crankshaft Deflection	Shaft Whirling
Crankshaft Deflection	0.429	0.667	0.125	1.000	0.280

The Crisp Importance Values of Pairwise Comparisons between the Bearing Failure and Misalignment, Torque Variations and Shaft Whirling

	Misalignment	Bearing Failure	Torque Variations	Shaft Whirling
Bearing Failure	0.585	1.000	0.254	0.348

The Crisp Importance Values of Pairwise Comparisons between the Misalignment and Torque Variations and Shaft Whirling

	Misalignment	Torque Variations	Shaft Whirling
Misalignment	1.000	0.403	0.416

The Crisp Importance Values of Pairwise Comparisons between the Shaft Whirling and Torque Variations

	Torque Variations	Shaft Whirling
Shaft Whirling	0.546	1.000

Thrust Block Failure

The Crisp Importance Values of Pairwise Comparisons between the Excessive Thrust Block Wear and Deformation from the Thrust Load, Thrust Block Misalignment and Thrust Block Rocking

	Deformation from the Thrust Load	Thrust Block Misalignment	Thrust Block Rocking	Excessive Thrust Block Wear

Excessive Thrust Block Wear	0.631	0.288	0.135	1.000

The Crisp Importance Values of Pairwise Comparisons between the Deformation from the Thrust Load and Thrust Block Misalignment and Thrust Block Rocking

	Deformation from the Thrust Load	Thrust Block Misalignment	Thrust Block Rocking
Deformation from the Thrust Load	1.000	0.356	0.229

The Crisp Importance Values of Pairwise Comparisons between the Thrust Block Misalignment and Thrust Block Rocking

	Thrust Block Misalignment	Thrust Block Rocking
Thrust Block Misalignment	1.000	0.455

Engine Component Failure

The Crisp Importance Values of Pairwise Comparisons between the Component Wear and Out of Balance Forces, Incorrect Power Balance, Variable Gas Pressures and Engine Misalignment

	Component Wear	Out of Balance Forces	Incorrect Power Balance	Variable Gas Pressures	Engine Misalignment
Component Wear	1.000	0.288	0.624	0.429	0.125

The Crisp Importance Values of Pairwise Comparisons between the Incorrect Power Balance and Out of Balance Forces, Variable Gas Pressures and Engine Misalignment

	Out of Balance Forces	Incorrect Power Balance	Variable Gas Pressures	Engine Misalignment
Incorrect Power Balance	0.423	1.000	0.585	0.246

The Crisp Importance Values of Pairwise Comparisons between the Variable Gas Pressures and Out of Balance Forces and Engine Misalignment

	Out of Balance Forces	Variable Gas Pressures	Engine Misalignment
Variable Gas Pressures	0.546	1.000	0.403

The Crisp Importance Values of Pairwise Comparisons between the Variable Gas Pressures and Out of Balance Forces and Engine Misalignment

	Out of Balance Forces	Engine Misalignment
Out of Balance Forces	1.000	0.592

Hull Failure

The Crisp Importance Values of Pairwise Comparisons between Corrosion and Sagging & Hogging of the Hull due to Sea Conditions, Ship Loading & Discharging and Grounding

	Sagging & Hogging	Ship Loading & Discharging	Corrosion	Grounding
Corrosion	0.442	0.154	1.000	0.305

The Crisp Importance Values of Pairwise Comparisons between Sagging & Hogging of the Hull due to Sea Conditions and Ship Loading & Discharging and Grounding

	Sagging & Hogging	Ship Loading & Discharging	Grounding
Sagging & Hogging	1.000	0.322	0.434

The Crisp Importance Values of Pairwise Comparisons between Sagging & Hogging of the Hull due to Sea Conditions and Ship Loading & Discharging and Grounding

	Ship Loading & Discharging	Grounding
Grounding	0.579	1.000

Appendix 5.7: The Crisp Importance Values in Level 4 in terms of Failure Consequence Probability

Propeller Failure

The Crisp Importance Values of Pairwise Comparisons between the Cloud Cavitation and Back Bubble Cavitation, Sheet Cavitation, Tip/ Hub Vortex Cavitation, Propeller-Hull Vortex Cavitation and Physical Damages

	Back Bubble Cavitation	Sheet Cavitation	Cloud Cavitation	Tip/ Hub Vortex Cavitation	Propeller-Hull Vortex Cavitation	Physical Damages
Cloud Cavitation	0.786	0.676	1.000	0.163	0.314	0.553

The Crisp Importance Values of Pairwise Comparisons between the Back Bubble Cavitation and Sheet Cavitation, Tip/ Hub Vortex Cavitation, Propeller-Hull Vortex Cavitation and Physical Damages

	Back Bubble Cavitation	Sheet Cavitation	Tip/ Hub Vortex Cavitation	Propeller-Hull Vortex Cavitation	Physical Damages
Back Bubble Cavitation	1.000	0.744	0.211	0.365	0.585

The Crisp Importance Values of Pairwise Comparisons between the Sheet Cavitation and Tip/ Hub Vortex Cavitation, Propeller-Hull Vortex Cavitation and Physical Damages

	Sheet Cavitation	Tip/ Hub Vortex Cavitation	Propeller-Hull Vortex Cavitation	Physical Damages
Sheet Cavitation	1.000	0.322	0.436	0.803

The Crisp Importance Values of Pairwise Comparisons between the Physical Damages and Tip/ Hub Vortex Cavitation and Propeller-Hull Vortex Cavitation

	Tip/ Hub Vortex Cavitation	Propeller-Hull Vortex Cavitation	Physical Damages
Physical Damages	0.429	0.527	1.000

The Crisp Importance Values of Pairwise Comparisons between the Propeller-Hull Vortex Cavitation and Tip/ Hub Vortex Cavitation

	Tip/ Hub Vortex Cavitation	Propeller-Hull Vortex Cavitation
Propeller-Hull Vortex Cavitation	0.533	1.000

Shafting Failure

The Crisp Importance Values of Pairwise Comparisons between the Bearing Failure and Misalignment, Torque Variations, Crankshaft Deflection and Shaft Whirling

	Misalignment	Bearing Failure	Torque Variations	Crankshaft Deflection	Shaft Whirling
Bearing Failure	0.078	1.000	0.246	0.416	0.611

The Crisp Importance Values of Pairwise Comparisons between the Shaft Whirling and Misalignment, Torque Variations and Crankshaft Deflection

	Misalignment	Torque Variations	Crankshaft Deflection	Shaft Whirling
Shaft Whirling	0.163	0.297	0.488	1.000

The Crisp Importance Values of Pairwise Comparisons between the Crankshaft Deflection and Misalignment and Torque Variations

	Misalignment	Torque Variations	Crankshaft Deflection
Crankshaft	0.271	0.436	1.000

Deflection			

The Crisp Importance Values of Pairwise Comparisons between the Torque Variations and Misalignment

	Misalignment	Torque Variations
Torque Variations	0.572	1.000

Thrust Block Failure

The Crisp Importance Values of Pairwise Comparisons between the Deformation from the Thrust Load and Thrust Block Misalignment, Thrust Block Rocking and Excessive Thrust Block Wear

	Deformation from the Thrust Load	Thrust Block Misalignment	Thrust Block Rocking	Excessive Thrust Block Wear
Deformation from the Thrust Load	1.000	0.314	0.585	0.761

The Crisp Importance Values of Pairwise Comparisons between the Excessive Thrust Block Wear and Thrust Block Misalignment and Thrust Block Rocking

	Thrust Block Misalignment	Thrust Block Rocking	Excessive Thrust Block Wear
Excessive Thrust Block Wear	0.501	0.624	1.000

The Crisp Importance Values of Pairwise Comparisons between the Thrust Block Rocking and Thrust Block Misalignment

	Thrust Block Misalignment	Thrust Block Rocking
Thrust Block Rocking	0.667	1.000

Engine Component Failure

The Crisp Importance Values of Pairwise Comparisons between the Component Wear and Out of Balance Forces, Incorrect Power Balance, Variable Gas Pressures and Engine Misalignment

	Component Wear	Out of Balance Forces	Incorrect Power Balance	Variable Gas Pressures	Engine Misalignment
Component Wear	1.000	0.201	0.598	0.436	0.263

The Crisp Importance Values of Pairwise Comparisons between the Incorrect Power Balance and Out of Balance Forces, Variable Gas Pressures and Engine Misalignment

	Out of Balance Forces	Incorrect Power Balance	Variable Gas Pressures	Engine Misalignment
Incorrect Power Balance	0.280	1.000	0.752	0.429

The Crisp Importance Values of Pairwise Comparisons between the Variable Gas Pressures and Out of Balance Forces and Engine Misalignment

	Out of Balance Forces	Variable Gas Pressures	Engine Misalignment
Variable Gas Pressures	0.442	1.000	0.676

The Crisp Importance Values of Pairwise Comparisons between the Engine Misalignment and Out of Balance Forces

	Out of Balance Forces	Engine Misalignment
Engine Misalignment	0.667	1.000

Hull Failure

The Crisp Importance Values of Pairwise Comparisons between Grounding and Sagging & Hogging of the Hull due to Sea Conditions, Ship Loading & Discharging, Corrosion and Grounding

	Sagging & Hogging	Ship Loading & Discharging	Corrosion	Grounding
Grounding	0.087	0.598	0.263	1.000

The Crisp Importance Values of Pairwise Comparisons between Ship Loading & Discharging and Sagging & Hogging of the Hull due to Sea Conditions and Corrosion

	Sagging & Hogging	Ship Loading & Discharging	Corrosion
Ship Loading & Discharging	0.182	1.000	0.436

The Crisp Importance Values of Pairwise Comparisons between Ship Loading & Discharging and Sagging & Hogging of the Hull due to Sea Conditions and Corrosion

	Sagging & Hogging	Corrosion
Corrosion	0.365	1.000

Appendix 5.8: The Crisp Importance Values Describing the Level of Effectiveness of Each RCO in terms of Failure Likelihood

Shafting Failure

Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Cause 1	1.000	1.000	1.000	0.585	0.803

Engine Component Failure

Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Cause 2	1.000	1.000	1.000	0.667	0.288

Hull Failure

Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Cause 1	0.701	0.455	1.000	0.030	0.087

Appendix 5.9: The Crisp Importance Values Describing the Level of Effectiveness of Each RCO in terms of Failure Consequence Probability

Propeller Failure

Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Cause 4	0.786	0.812	1.000	0.068	0.030
Cause 5	0.752	0.812	1.000	0.068	0.030
Cause 6	0.611	0.803	0.795	0.030	1.000

Shafting Failure

Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Cause 1	1.000	1.000	1.000	0.585	0.803

Engine Component Failure

Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Cause 2	1.000	1.000	1.000	0.667	0.288

Hull Failure

Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Cause 1	0.701	0.455	1.000	0.030	0.087

Appendix 5.10: The Crisp Importance Values Describing the Level of Effectiveness of Each RCO in terms of Failure Capability

Propeller Failure

Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Cause 4	0.786	1.000	1.000	0.049	0.030
Cause 5	0.786	1.000	1.000	0.049	0.030
Cause 6	0.598	1.000	0.803	0.030	0.030

Shafting Failure

Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Cause 1	1.000	1.000	1.000	0.624	1.000

Engine Component Failure

Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Cause 2	1.000	1.000	1.000	0.667	0.288

Hull Failure

Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Cause 1	0.701	0.455	1.000	0.030	0.087

Appendix 5.11: The Crisp Importance Values Describing the Level of Effectiveness of Each RCO in terms of Failure Recovery Incapability

Propeller Failure

Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Cause 4	0.786	1.000	1.000	0.049	0.030
Cause 5	0.786	1.000	1.000	0.049	0.030
Cause 6	0.598	1.000	0.803	0.030	0.030

Shafting Failure

Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Cause 1	1.000	1.000	1.000.	0.624	1.000

Engine Component Failure

Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Cause 2	1.000	1.000	1.000	0.684	0.288

Hull Failure

Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Cause 1	0.701	0.455	0.812	0.030	0.087

Appendix 5.12: Normalised Results of the Effectiveness of Each RCO

Normalised Results of the Effectiveness of Each RCO in terms of Failure Consequence Probability

Failure Type	Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Propeller Failure	4	0.0268	0.0289	0.0036	0.0024	0.0011
	5	0.0169	0.0174	0.0214	0.0015	0.0006
	6	0.0065	0.0085	0.0084	0.0003	0.0106
Shafting Failure	1	0.0085	0.0085	0.0085	0.0050	0.0069
Engine Component Failure	2	0.0117	0.0117	0.0117	0.0078	0.0034
Hull Failure	1	0.0087	0.0056	0.0124	0.0004	0.0011

Normalised Results of the Effectiveness of Each RCO in terms of Failure Capability

Failure Type	Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Propeller Failure	4	0.0007	0.0009	0.0009	0.0001	0.0001
	5	0.0006	0.0007	0.0007	0.0001	0.0001
	6	0.0014	0.0024	0.0019	0.0001	0.0001
Shafting Failure	1	0.0008	0.0008	0.0008	0.0005	0.0008
Engine Component Failure	2	0.0019	0.0019	0.0019	0.0013	0.0006
Hull Failure	1	0.0049	0.0032	0.0070	0.0002	0.0006

Normalised Results of the Effectiveness of Each RCO in terms of Failure Recovery Incapability

Failure Type	Cause No.	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5
Propeller Failure	4	0.0018	0.0022	0.0022	0.0001	0.0001
	5	0.0024	0.0030	0.0030	0.0001	0.0001
	6	0.0032	0.0054	0.0043	0.0002	0.0002
Shafting Failure	1	0.0002	0.0002	0.0002	0.0001	0.0002
Engine Component	2	0.0009	0.0009	0.0009	0.0006	0.0003

Failure						
Hull Failure	1	0.0010	0.0006	0.0011	0.0001	0.0001

Appendix 6

Appendix 6.1: Ship Specification

Name of the Ship: Undisclosed
Type: Roll-On Roll-Off Carrier (RoRo)
Year of Built: 1978
Length OA: 228.41 m
Breadth: 32.26 m
Draft: 57.00 m
Gross Tonnage: 54680 GRT
Engine Type: Slow Speed Sulzer Diesel Engine (9RND90M)
Power Output: 20000 kW MCR
Engine RPM: 118
Maximum Speed: 20.5 knots
Propeller Type: FPP
Propeller Diameter: 6.80 m
Number of Blades: 5
Propeller RPM: 118
Electrical Power: 4 Daihatsu Diesel Generators

Appendix 6.2: Crisp Importance Values

The Crisp Importance Values of LOC and ACC, FOC, CC, MRC and IC

	ACC	FOC	CC	MRC	IC	LOC
LOC	0.300	0.200	0.600	0.800	0.500	1.000

The Crisp Importance Values of MRC and ACC, FOC, CC and IC

	ACC	FOC	CC	MRC	IC
MRC	0.400	0.300	0.700	1.000	0.600

The Crisp Importance Values of CC and ACC, FOC and IC

	ACC	FOC	CC	IC
CC	0.500	0.400	1.000	0.800

The Crisp Importance Values of IC and ACC and FOC

	ACC	FOC	IC
IC	0.700	0.600	1.000

The Crisp Importance Values of ACC and FOC

	ACC	FOC
ACC	1.000	0.800

Appendix 6.3: Sensitivity Analysis (by Changing the Weight Values as Percentages)

CC_q Values and Rankings of All Propulsion Systems (Condition 1)

Alternative	CC_q	**Ranking**
2ST	0.0983	**01**
4ST	0.0870	**04**
RST	0.0754	**06**
MSD	0.0667	**09**
SSD	0.0506	**10**
HDGT	0.0982	**02**
ADGT	0.0925	**03**
HDGTH	0.0785	**05**
HDGTS	0.0752	**07**
AGTSC	0.0703	**08**

CC_q Values and Rankings of All Propulsion Systems (Condition 2)

Alternative	CC_q	**Ranking**
2ST	0.1030	**01**
4ST	0.0911	**04**
RST	0.0790	**06**
MSD	0.0699	**09**

SSD	0.0530	10
HDGT	0.1029	02
ADGT	0.0969	03
HDGTH	0.0822	05
HDGTS	0.0788	07
AGTSC	0.0736	08

CC_q Values and Rankings of All Propulsion Systems (Condition 3)

Alternative	CC_q	Ranking
2ST	0.1122	02
4ST	0.0993	04
RST	0.0861	06
MSD	0.0762	09
SSD	0.0578	10
HDGT	0.1123	01
ADGT	0.1057	03
HDGTH	0.0896	05
HDGTS	0.0860	07
AGTSC	0.0803	08

CC_q Values and Rankings of All Propulsion Systems (Condition 4)

Alternative	CC_q	Ranking
2ST	0.0890	01
4ST	0.0787	04
RST	0.0683	06
MSD	0.0604	09
SSD	0.0458	10
HDGT	0.0889	02
ADGT	0.0838	03
HDGTH	0.0710	05
HDGTS	0.0681	07
AGTSC	0.0636	08

CC_q Values and Rankings of All Propulsion Systems (Condition 5)

Alternative	CC_q	Ranking
2ST	0.0843	01

4ST	0.0746	**04**
RST	0.0646	**06**
MSD	0.0572	**09**
SSD	0.0434	**10**
HDGT	0.0842	**02**
ADGT	0.0794	**03**
HDGTH	0.0673	**05**
HDGTS	0.0644	**07**
AGTSC	0.0603	**08**

CC_q Values and Rankings of All Propulsion Systems (Condition 6)

Alternative	CC_q	**Ranking**
2ST	0.0750	**01**
4ST	0.0663	**04**
RST	0.0576	**06**
MSD	0.0509	**09**
SSD	0.0386	**10**
HDGT	0.0749	**02**
ADGT	0.0706	**03**
HDGTH	0.0599	**05**
HDGTS	0.0575	**07**
AGTSC	0.0536	**08**

Appendix 6.4: Sensitivity Analysis (by Exchanging the Weights)

Alternative	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
2ST	03	01	01	01	03	05	01	02	01	01	01	02	03	01	01	02	03	02	02	01	01	01	01	01	03	02	03	03
4ST	04	03	02	03	05	08	03	04	03	04	04	04	04	04	04	04	04	03	04	04	04	04	04	04	04	04	04	04
RST	07	04	03	05	07	10	05	06	06	07	06	07	07	05	06	06	07	08	07	06	06	06	07	06	07	07	06	06
MSD	05	05	08	10	04	04	09	09	09	09	09	09	05	09	09	09	09	07	09	09	09	09	09	09	09	09	05	05
SSD	06	07	05	09	06	03	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
HDGT	01	02	04	02	01	01	02	01	02	02	02	01	01	02	02	01	01	01	01	02	02	02	02	02	01	01	01	01
ADGT	02	09	09	04	02	02	04	03	04	03	03	03	02	03	03	03	02	04	03	03	03	03	03	03	02	03	02	02
HDGTH	09	06	07	07	09	06	06	05	05	05	05	05	06	06	05	05	05	05	05	05	05	05	05	05	05	05	07	07
HDGTS	10	08	06	08	10	07	07	07	07	06	07	06	09	07	07	07	06	06	06	07	07	07	06	07	06	06	09	09
AGTSC	08	10	10	06	08	09	08	08	08	08	08	08	08	08	08	08	08	09	08	08	08	08	08	08	08	08	08	08