# TECHNICAL MANAGEMENT OF VLCC/VLBC HULL STRUCTURES BASED ON SAFETY CASE PRINCIPLES

By

John Andrew Lee
BEng. MPhil.

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# A Hull Structures Perspective

*Selkirk Settler* – North Atlantic Swell (Capt. G. Ianiev)

*But in all my experience, I have never been in an accident...of any sort worth speaking about. I have seen but one vessel in distress in all my years at sea. I never saw a wreck and never have been wrecked nor was I ever in any predicament that threatened to end in disaster of any sort.* E. J. Smith, 1907 (Captain of *Titanic*).

# Disclaimer

The views and conclusions expressed in this thesis are those of the author alone and do not necessarily represent the views of the institution with which the author is affiliated.

# Acknowledgements

In his book *The Black Swan,* dealing with the impact of the highly improbable, Taleb suggests that black swan logic makes what you don't know far more relevant than what you do know. Many black swans he argues can be exacerbated by their being totally unexpected. The sudden and near collapse of world financial markets in 2008 was such a rare and unexpected event occurring during the later stages of this research. There now seems to be a consensus emerging of a general failure of the credit rating agencies in relation to the adequacy of their risk assessments performed on certain structured asset backed securities. Can the maritime industry draw any lessons from this disaster?

Although the maritime industry has suffered its share of black swans including *Erika* and *Prestige,* and this research effort has uncovered a history of certain systemic problems afflicting the current safety systems governing the design construction and operation of large bulk ship structures, the author believes that the maritime industry is currently well placed to set an example to the wider community on the effectiveness of an international regulatory system controlling maritime risks led by the IMO. The risk assessments routinely performed in relation to shipment of potentially harmful bulk cargoes across the major oceans of the world against the constant perils of the sea, rule out any room for complacency. Increasing concern for the environment and media focus has heightened societal expectations that the associated risks will be properly managed. The purported failure of self-regulation and risk assessment claimed by some commentators in the banking and finance sectors indicates that the maritime example is an example worthy of consideration.

This thesis represents the fulfilment of a deeply personal goal and has been a long voyage of learning and discovery. It represents an accumulation of personal experience both practical and theoretical, and it has been completed at a relatively late stage in life. The writer has always believed in life-long learning, and developing the qualities of curiosity and sceptical empiricism, tempered with theory. Like Taleb, he regards sterile scepticism as something about which nothing can be done. On the other hand, sceptical empiricism is considered to be laudable.

I would like to thank the members of John Moores University (LJMU), Liverpool Logistics, Offshore and Marine (LOOM) Centre, for their assistance and encouragement during the production of this work. Special thanks to Professor Ian Jenkinson, Dr Zaili Yang and Dr Steve Bonsall. I extend my sincere gratitude to Professor Jin Wang for his patience, friendship, encouragement, support and efforts over the years it took to finalise this work, and without whom this research would never have come to fruition. Finally, I would like to pay tribute to the women in my life including my mother Margaret, my wife Veruni and my daughter Ariana, whom this is really for.

Finally, tribute is paid to the worlds sea-farers and if this work makes even a small contribution to their safety, it will have been worthwhile.

# Contents

# Abstract

Recent high profile accidents involving environmental damage caused by structural failures in ageing oil tankers and bulk carriers has highlighted the importance of structural integrity issues involving these types of ships. Between 1980 and 1996, there were 186 total losses of bulk and combination carriers and 1,278 lives lost. These events have led to concerns from the public, media and within the international maritime community, about deteriorating ship structural safety standards and the environmental impact. Evidence suggests that structural failure may account for more ship losses than hitherto believed. Industry critics have complained that the quality of designs for new tonnage and effectiveness of the present control mechanisms governing structural condition for vessels in service, are inadequate.

Due to the relatively low safety margins inherent in modern commercial ship structural designs, a buyer beware policy prevails in ship procurement. A weakness in current ship design practice appears to be the difficulty of incorporating an owner's individual preferences. Recognising that to be effective, improvements in ship structural design must be implemented at the design stage, this study addresses the challenge of further improving the structural safety and performance of large bulk ships through exercising specific options related to the structural design of the ship within the remit of the buyer.

A broad comprehensive literature survey was conducted to cast a wide net around the problem. The complex web of regulatory controls affecting the design and operation of bulk ship hull structures was analysed and problems involving design, construction and maintenance of these vessels were uncovered to build evidence to justify proposing an improved method. An analysis of recent high profile tanker and bulk carrier accidents involving structural failure was performed, to determine root causes. These findings formed the basis for a proposed novel risk-based "design for safety" framework

The core of the method is the new evidential reasoning (ER) algorithm developed on the basis of a MCDA evaluation framework and the evidence combination rule of the Dempster-Shafer (D-S) Theory. A number of structural design options focused on the cargo tank mid body area of a typical double hull VLCC were evaluated. A set of quantitative and qualitative criteria were identified and articulated, leading to a structural evaluation framework for eliciting preferences for competing options. The MCDA/ER model provides a risk-based, rational, transparent methodology for rapid techno-economic evaluation of alternative structural designs, putting buyers in a stronger position to balance risks and determine the expected structural safety outcomes of different designs. The ER modelling is performed using the Intelligent Decision System (IDS) software program developed by Yang and Xu. The method was tested with an example and validated through a sensitivity study.

Finally, the evidence necessary for constructing and demonstrating the MCDA/ER structural evaluation framework was used to build the arguments for a safety case approach to hull structures using the Australian Offshore safety case model. The safety case for hull structures is built upon a foundation of existing prescriptive statutory and classification society structural regulatory requirements. The advantages of the safety case applied to oil tankers were explained, including suggestions for a new regulatory approach. The application of new technology and tools was discussed.

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# Abbreviations

| | |
|---|---|
| ABS | American Bureau of Shipping |
| AHP | Analytical Hierarchy Process |
| ALS | Accident Limit State |
| AP | Application Protocol |
| ARCO | Atlantic Richfield Company |
| ASD | Allowable Stress Design |
| ASIP | Airframe Structural Integrity Programme |
| ASQ | American Society for Quality |
| BEA | Bureau d'Enquetes sur les Accidents en Mer |
| BMA | Bahamas Maritime Authority |
| BV | Bureau Veritas |
| CA | Condition of Authority |
| CA | Critical Area |
| CAD | Computer Aided Design |
| CAIP | Critical Area Inspection Plan |
| CAP | Condition Assessment Programme |
| CAPEX | Capital Expenditure |
| CAS | Condition Assessment Scheme (IMO) |
| CATS | Cost of Averting a Tonne Spilt |
| CATSIR | Computer Aided Tanker Structure Inspection and Repair |
| CBT | Clean Ballast Tanks |
| CC | Condition of Class |
| CCS | China Classification society |
| ClassNK | Nippon Kaiji Kyokai |
| COT | Cargo Oil Tank |
| CSD | Critical Structural Detail |
| CSR | Common structural rules |
| CSR | Corporate Social Responsibility |
| CSSRC | China Ship Scientific Research Centre |
| DCF | Discounted Cash Flow |
| DCR | Design and Construction Regulations (UK) |
| DFA | Derbyshire Family Association |
| DFS | Design for Safety |
| DH | Double Hull |
| DH | Duty Holder |
| DNV | Det Norske Veritas |
| DOT | Department of Transport (UK) |
| DRDA | Defence Research and Development Atlantic (Canada) |
| D-S | Dempster Shafer Evidence Combination Rule |
| DSME | Daewoo Shipbuilding and Marine Engineering Co. Ltd. |
| DSP | Decision Support Problem |
| DTU | Danish Technical University |
| DWT (dwt) | Deadweight Tonne |
| EC | European Community |
| EFQM | European Foundation for Quality Management |
| EN | European Norm |
| ER | Evidential Reasoning |
| ESP | Enhanced Survey Programme |
| ETA | Event Tree Analysis |
| EU | European Union |
| FAA | Federal Aviation Administration |
| FEA | Finite Element Analysis |

| | |
|---|---|
| FEM | Finite Element Method |
| FPSO | Floating Production Storage and Offloading |
| FSA | Formal Safety Assessment |
| GBR | Goal Based Rules |
| GBS | Goal Based Standards |
| GL | Germanischer Lloyd |
| HAZID | Hazard Identification |
| HBL | Hydrostatic Balanced Loading |
| HCM | Hull Condition Monitoring |
| HGO | Heavy Gas Oil |
| HoQ | House of Quality |
| HRQL | Health Related Quality of Life |
| HS | High Strength Steel |
| HSE | Health and Safety Executive (UK) |
| HSMS | Hull Stress Monitoring System |
| HTS | High Tensile Steel |
| IACS | International Association of Classification Societies |
| ICIMF | Oil Companies International Marine Forum |
| ICLL | International Convention on Load Lines (IMO) |
| ICP | Independent Competent Person |
| IDS | Intelligent Decision System |
| ILLC | International Load Line Convention (IMO) |
| ILO | International Labour Organisation |
| IMO | International Maritime Organisation |
| IPSB | International Project Steering Board |
| IRR | Internal Rate of Return |
| ISM | International Safety Management Code (IMO) |
| ISO | International Standards Organisation |
| ISSC | International Ship and Offshore Structures Congress |
| ITF | International Transport Workers Federation |
| JBP | Joint Bulker Project |
| JMSA | Japanese Maritime Standards Association |
| JTP | Joint Tanker Project |
| KRS | Korean Register of Ships |
| LMIS | Lloyds Maritime Information Services |
| LOS | Law of the Sea Convention (IMO) |
| LRS | Lloyds Register of Shipping |
| MARAD | Maritime Administration (US) |
| MARPOL | Marine Pollution Convention (IMO) |
| MAUT | Multiple Attribute Utility Theory |
| MCA | Maritime and Coastguard Agency (UK) |
| MCDA | Multiple Criteria Decision Analysis |
| MCR | Main Class Renewal (Survey) |
| MEPC | Marine Environmental Protection Committee (IMO) |
| ILLC | International Load Line Convention (1966) |
| MOD | Ministry of Defence (UK) |
| MOU | Memorandum of Understanding |
| MSC | Maritime Safety Committee (IMO) |
| MSC | Maritime Sealift Command |
| MSIP | Marine Structural Integrity Programme |
| NIDDESC | US Navy/Industry Digital Data Exchange Standards Committee |
| NOPSA | National Offshore Petroleum Safety Authority (Australia) |
| NPD | Norwegian Petroleum Directorate |
| NPV | Net Present Value |
| NS | Normal Strength (Steel) |
| NTNU | National Technical University of Athens |

| | |
|---|---|
| NTSB | National Transportation and Safety Board (US) |
| OBO | Oil/Bulk/Ore Vessel |
| OCIMF | Oil Companies International Forum |
| OECD | Organisation for Economic Co-operation and Development |
| OPEC | Organisation of Petroleum Exporting Countries |
| P&I | Protection and Indemnity |
| PBD | Performance Based Design |
| PMS | Planned Maintenance System |
| POD | Probability of Detection |
| PRC | Peoples Republic of China |
| PSC | Port state control |
| PSPC | Performance Standard for Protective Coatings (IMO) |
| QA/QC | Quality Assurance/Quality Control |
| QFD | Quality Function Deployment |
| RBI | Risk Based Inspection |
| RINA | Registro Italiano Navale |
| RINA | Royal Institution of Naval Architects |
| ROA | Return on Assets |
| SBT | Segregated Ballast Tanks |
| SCE | Safety Critical Elements |
| SCF | Stress Concentration Factor |
| SCR | Safety Case Regulations |
| SDA | Structural Design Assessment |
| SH | Single Hull |
| SIM | Structural Integrity Management |
| SIRE | Ship Inspection Report Programme |
| SMP | Structure Maintenance Project |
| SMS | Safety Management system |
| SN Curves | Stress/No.Cycles Relationship |
| SNAME | Society of Naval Architects and Marine Engineers (US) |
| SOC | Statement of Compliance |
| SOLAS | Safety of Life at Sea Convention (IMO) |
| SSC | Ship Structure Committee |
| SSIS | Ship Structural Integrity Information System |
| SSMS | Ship Structural Management System |
| SSRC | Ship Safety Research Centre (Strathclyde) |
| STCW | Standards for Training and Certification of Watchkeepers |
| STEP | Standard for the Exchange of Product Data |
| SWBM | Stillwater Bending Moment |
| TAPS | Trans Alaska Pipeline Services |
| TMCP | Thermo Mechanically Controlled Processing (Steel) |
| TSCF | Tanker Structures Co-Operative Forum |
| UAE | United Arab Emirates |
| UGS | Union of Greek Ship Owners |
| ULCC | Ultra Large Crude Carrier |
| ULS | Ultimate limit state |
| UR | Unified Rule |
| USCG | United States Coast Guard |
| USD | United States Dollars |
| UT or UTM | Ultrasonic Thickness Measurement |
| VLBC | Very Large Bulk Carrier |
| VLCC | Very Large Crude Carrier |
| VLOC | Very Large Ore Carrier |
| WBM | Wave Bending Moment |
| WBT | Water Ballast Tank |
| WS | World Scale |

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# Chapter 1 - Introduction

***SUMMARY***

This chapter contains the background and explanation necessary to justify the final research objectives and sub-objectives stated in section 1.2 which have been developed through a broad and comprehensive literature survey effort. Section 1.3 justifies the work. In view of the breadth of the research attempted, section 1.7 contains a detailed account of the delimitations and scope.

## 1.1 Background to the Research

The current PhD thesis involves ship structural management, with a focus on large oil tankers and bulk carriers in particular, and is founded upon and extends the author's earlier work entitled *Technical Management of Oil Tankers Based on Safety Case Principles*, submitted to Heriot-Watt University, Edinburgh, culminating in the award of Master of Philosophy (M.Phil) by research in July 2001. The foregoing work primarily argued the hypothesis that safety case principles could successfully be applied to the technical management of hull structures for a fleet of large oil tankers owned principally by independent oil majors and national oil companies.

Following practical experience as a superintendent/naval architect with a major Middle Eastern national oil tanker owner, the writer became convinced of the need to conceptualise a practical method in which the buyer's preferences in relation to the structural design could more easily be incorporated into the design/procurement process for new VLCC tonnage. Recognising that ship owners are able to exert considerable influence on the design and safety of oil tankers in regard to specification of global loads, special materials, method of analysis, detail design etc, the search for a performance based approach to the problem continued. Initially, as a first step, a conference paper was written and presented at the Royal Institution of Naval Architects International Conference on Design and Operation of Double Hull Tankers held in London in February 2004 (Lee et al, 2004).

In this work, a detailed framework is presented including a description of the current regulatory system highlighting shortcomings arising from a passive prescriptive approach to technical management activities during design, construction and operation of large bulk ships. A critique of the current highly prescriptive safety regime is used to introduce a proposed new proactive methodology centred on a decision based concurrent design for safety approach involving the designers and the owner in a practical and effective partnership. The methodology is shown to be applicable to standard ship designs from the major ship production centres in the Far East.

The proposed method fully integrates the existing prescriptive classification and statutory systems and procedures, whilst emphasising the fundamental responsibilities of the principal stakeholders. This is consistent with the principles embodied in The UK offshore safety case approach recommended as a model worthy of consideration for the safety management of international shipping in the 1992 Carver Report into ship safety. The work herein has resulted in a number of proposals for changes to the existing regulatory system affecting the design, construction and operation of large vessels.

## 1.2 Research Objectives

Unstable supply/demand, sustained low freight rates, changing ownership patterns, diverse standards of flag State performance, elimination of in-house technical support and increasingly onerous regulatory burdens are all factors affecting today's ship owners and operators. Two recent spectacular and widely publicised oil tanker losses resulting in environmental pollution, led to a deep introspection within the industry and from industry critics, about the effectiveness of the measures currently in place. These concerns included the quality of new double hull tanker designs and the requirements for survey and maintenance of hull structures imposed by the major IACS societies in the form of the enhanced survey programme (ESP) introduced in 1993. The loss of the *Erika* due to structural failure in 1999, led directly to major regulatory changes in the European Union and in the rules of the major classification societies. The subsequent loss of the *Prestige* three years later, sent further shockwaves through the industry.

The focus of the research effort is to challenge the prevailing dominant discourses on the adequacy of current procedures for design and operation of large oil tanker and bulk carrier structures. On the one hand, progressive tightening of regulations following major accidents suggests that current measures are now adequate. On the other hand, the consequences of even minor pollution arising from a leaking crude oil cargo tank are severe enough to warrant even more proactive measures on the part of those responsible for transporting the cargoes. The original research objective began to evolve out of the realization that the maritime industry continues to rely heavily on the prescriptive minimalist approach, in spite of the widespread availability of superior technical solutions including formal safety and risk assessment methods widely used in other industries. This led to the following set of preliminary research questions related to large bulk ship structures:

- What is the true nature of these structures?
- Are the structural hazards and risks adequately addressed by a prescriptive rule approach during the design phase?
- Is the current regulatory system governing structural integrity effective?
- How is structural integrity management of these structures practiced in comparison with offshore structures?
- Can the root causes of recent structural failures in large bulk ships be identified, and is structural failure underestimated as a leading cause of accidents and environmental pollution?
- Is the quality of new double hull tanker structural designs adequate?
- How can the buyer's preferences be conveniently incorporated into the design process?
- Can multiple criteria decision analysis (MCDA) be successfully applied to the ship structures problem?
- Can the offshore safety case model be adapted to regulation of ship structures?

The above questions led to the following principal research objectives.

Principal Research Objective

***To build evidence confirming that the customer can effectively enhance the quality safety and performance of large bulk ship structures by managing risks at the design stage using a novel structural selection framework, evolving the arguments for a hull structures safety case as an outcome from the selection process, and to demonstrate how the safety case can be successfully applied to the technical management of these types of ship structures.***

Sub-Objectives

The above principal research objective was addressed through satisfying the following sub-objectives related to large bulk ship hull structures;

***Objective No.1:*** *To review the safety management systems affecting these types of hull structures, and to identify the need for an improved management of ship safety.*

***Objective No.2:*** *To analyse selected casualties in order to reveal possible root causes associated with inadequate quality in structural design or maintenance procedures.*

***Objective No.3:*** *To analyse the current approach to ship procurement and structural design quality and existing knowledge of the use of risk-based approaches to hull structures integrity.*

***Objective No.4:*** *To articulate a set of structural performance criteria as the basis for a comprehensive structural evaluation framework used to compare alternative VLCC structural design options using the new evidential reasoning (ER) algorithm developed on the basis of a multiple criteria decision analysis (MCDA) evaluation framework and the evidence combination rule of the Dempster-Shafer (D-S) Theory, and to demonstrate and validate the method using an example.*

***Objective No.5:*** *To examine the applicability of the offshore safety case approach in the context of these structures using the above structural selection framework to evolve the arguments for a hull safety case.*

Firstly, it is argued that the current levels of safety and performance of large bulk ship hull structures (including oil tankers and bulk carriers) can and should be improved by identifying weaknesses in the contemporary ship design process and in the existing regulatory systems through a comprehensive review and analysis of the hull structures question, including recent structural failures. Secondly, a risk-based design for safety approach is proposed, incorporating the customer's preferences directly into the design process, utilising a new and unique techno-economic framework for comparing alternative structural design options. A design for safety framework based on the Dempster-Shafer theory of evidence incorporating traditional multiple criteria decision analysis (MCDA) methods is developed. Thirdly, it is demonstrated that a safety case approach to hull maintenance subservient to the existing International Safety Management (ISM) Code and evolving from the recommended performance based ship structural design method is an improved paradigm, which addresses the shortcomings identified in the present systems.

## 1.3 Justification for the Research

An important factor in the safety of large bulk ships is thought to be adequate hull integrity throughout the life-time of the asset. Safe and economic operation is also highly dependent on operability involving human factors. The starting point for the achievement of a successful and safe hull stems from the design process itself and determines performance outcomes. At this time, decisions are taken that will profoundly influence levels of risk. The requisite levels of safety and quality are reasoned to be impossible to address merely through surveys and inspection activities during the progress of construction of minimum compliance designs.

Industry critics have lashed out at the perceived drop in quality of design and construction involving oil tankers, allegedly compromising safety. New goal based common structural rules (CSR) have been developed with the intent of eliminating competition on ship structural design standards. Critics have already suggested that the new rules will not result in more robust ships as claimed and the new rules, like the previous ones should be regarded as minimum standards. In this regard, purchasers of new ships would be empowered by understanding the assumptions inherent in the design. On the other hand, excessively robust ships suggested by some critics may not be cost effective or environmentally acceptable in terms of economy of construction and utilisation of finite resources.

Currently hull lifetime is dictated by freight rates, regulations, and the owners individual requirements. Hazards due to nuisance cracking caused by fatigue related problems or local corrosion resulting in cargo leakage into the sea represent relatively high risks in modern tanker design. The inconvenience of dealing with such events in a loaded tanker is believed to constitute a very sound reason to seek ways to minimise these hazards throughout the vessel lifetime. In the current economic climate, oil majors are discriminating against unreliable vessels and an outstanding *condition of class* can result in the loss of a charter. Further, even minor pollution incidents can lead to serious consequences. Environmental pollution carries a heavy financial and political burden.

UK P&I Club statistics in 1993 indicate that structural failures accounted for only 12% of the total major claims (Boisson, 1999). However, it is believed that the hull question is disproportionately important in the safety equation. Classification societies often contend that 80% of losses are caused directly or indirectly by human error. However, technical problems including structural failures in tankers and bulk carriers are conjectured to be an understated and possibly latent cause of loss of life or pollution. From 1980 to 1996, over 1,200 sea-farers died on bulk and combination carriers due to sudden and unexplained circumstances, possibly involving loss of reserve buoyancy, loss of stability or hull girder failure (Paik et al, 1998). In many cases the root cause is suspected to be linked to hull failure. Some critics unequivocally condemn the industry for not recognizing that structural failure is a leading cause of vessel casualties (Devanney, 2006).

Recent accidents involving crude oil tankers, coupled with widespread condemnation of prescriptive controls governing shipping safety performance, suggests that a high risk industry such as bulk transport of goods by sea, should seek alternatives other than exclusively relying upon prescriptive rules and services driven by recognized organisations. Leading figures in the classification industry have recently called for a re-invention of the industry's primary self-regulation system in response to these developments. A precedent has already been established for the use of goal-based standards in the UK offshore industry and a decade of positive experience has accrued.

The legal aftermath of the *Erika & Prestige* accidents has resulted in a vigorous debate and the implications are discussed. The Carver Report in 1992, contained 20 recommendations, including applying the safety case to individual ships. The UK Government conceded that the time was right for exploration of safety case principles in shipping due to the attractions of the concept. However, various concerns were raised about the transferability of the safety case from the offshore industry. In this light, an alternative form of regulation for hull structures based on safety case principles, but embodying the current prescriptive controls is proposed. The safety case approach adapted to large tankers would seem to be a paradigm worthy of further investigation and a logical step forward in the transition to a goal-based safety system built upon existing prescriptive rules. It is believed that the hull structures question deserves primary focus and is the area best suited to direct application of the safety case methodology.

## 1.4 Methodology

In table 1.1, the respective sections in which the five principal research sub-objectives listed in section 1.2 are addressed are listed. The first two objectives listed are achieved in the literature survey carried out in chapter 2. Objective no.3 which analyses the current approach to ship procurement and structural design quality and existing knowledge of the use of risk-based approaches to hull structures integrity is addressed in chapter 3 as part of a discussion on the problem associated with the contemporary ship production environment.

| Objective | Chapter |
|---|---|
| 1 | 2 |
| 2 | |
| 3 | 3 |
| 4 | 4, 5 and 6 |
| 5 | 7 |

Table 1.1. Chapters in which the Sub-Objectives are Addressed

Objective no. 4, articulates a set of structural performance criteria as the basis for a comprehensive structural evaluation framework using the new evidential reasoning (ER) algorithm based on multiple criteria decision analysis (MCDA) and the evidence combination rule of the Dempster-Shafer (D-S) Theory. Demonstration and validation of the method using an example is covered in chapters 4, 5 and 6. Finally, objective no.5 examines the applicability of the offshore safety case approach using the structural selection processes, framework and model to evolve the arguments for a hull safety case presented in chapter 7.

## 1.5 Outline of the Research

The structure of the thesis is laid out in figure 1.1 on page 11. There are eight chapters and the individual chapters are laid out as follows:

**Chapter 2**: In chapter 2, a comprehensive and broad literature survey has been conducted to cast a wide net around the boundaries of the research problem and to establish a theoretical foundation upon which the research is based as described in section 1.7. All aspects of the hull structures integrity question were examined including:

- The history and background of structural integrity management in relation to ship structures.

- The major economic and political determinants in relation to sea transportation of oil and other bulk commodities, and their impact on design and operation of ship structures.
- The importance of hull integrity in relation to the wider economic consideration in relation to the operation of large oil tankers and bulk carriers.
- The network of regulatory controls applicable to hull structures, the relationships between stakeholder and responsibilities.
- Quality aspects of contemporary bulk ship designs in terms of comments made by critics.
- A forensic examination of selected tanker and bulk carrier losses involving structural failure in order to establish possible common causes.
- Comparison of the *Erika* and *Prestige* casualties in order to establish possible commonalities.
- The principle structural hazards from the literature.
- The adequacy of the classification- driven repair process.

**Chapter 3**: In chapter 3, the current ship production environment is described. Commercial ship design is seen to be characterised by compliance with the prescriptive rules of the international classification societies. Classification rules for ship design have evolved over 150 years and they have been developed incrementally in response to failures and represent a huge accumulation of experience. The fundamental purpose of classification rules and services is to ensure that the asset is fit for the purpose with adequate levels of safety and reliability. Whilst this has stood the test of time, recent events have highlighted the need for a risk-based approach which is described in sections 3.3, 3.4 and 3.5.

**Chapter 4**: In chapter 4, problems with the current methods of ship procurement and quality are identified forming the incentive to develop a risk-based structural assessment framework intended to facilitate the buyer's input into the design process. A review of decision support methods and performance based ship design is undertaken.

A set of 35 structural assessment criteria and an assessment hierarchy construct is developed as the basis of the proposed MCDA/ER structural assessment framework.

**Chapter 5**: In chapter 5, the criteria and hierarchy constructs proposed in chapter 4 are used to demonstrate an example involving selection between competing structural options. In section 5.4, detailed examples of procedures used for calculating the main *commercial* and *technical* numeric data including net present value (NPV) and ultimate limit state (ULS) are presented and explained. Four alternative VLCC structural designs are evaluated and ranked by utility using the software supported MCDA/ER framework developed previously.

**Chapter 6**: In this chapter, a range of sensitivity studies are performed to validate the model.

**Chapter 7**: The structural assessment framework developed in chapters 3, 4 and validated in chapter 5 is used to evolve the evidence and arguments for an offshore style hull safety case based on the Australian offshore (NOPSA) safety case model. The implications of the safety case approach relative to responsibilities and regulation are discussed. The benefits of the improved approach are analysed in section 7.5.

**Chapter 8**: This chapter contains the conclusions from the study.

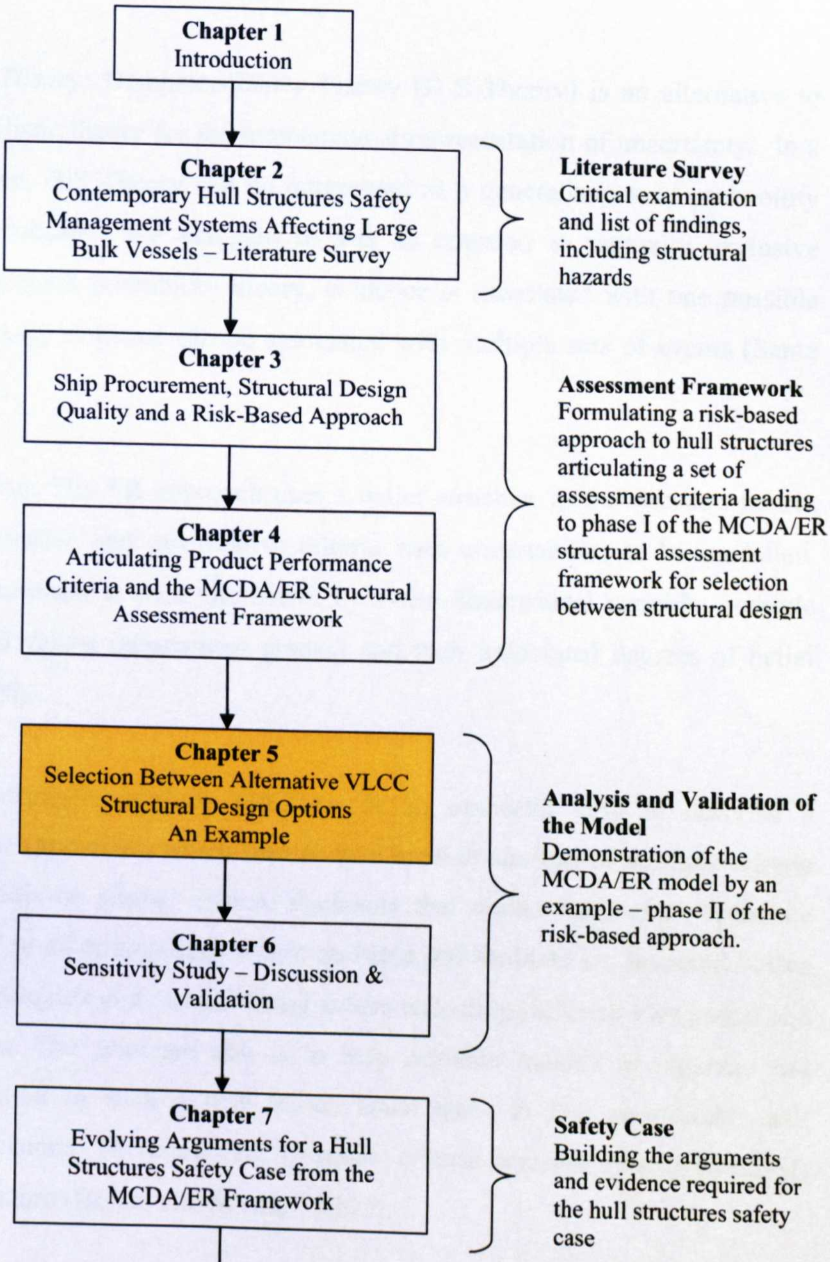


Figure 1.1. Research Methodology

## 1.6 Definitions

*Dempster-Shafer Theory:* Dempster-Shafer Theory (D-S Theory) is an alternative to traditional probabilistic theory for the mathematical representation of uncertainty. In a finite discrete space, D-S Theory can be interpreted as a generalisation of probability theory where probabilities are assigned to sets as opposed to mutually exclusive singletons. In traditional probability theory, evidence is associated with one possible event. In D-S Theory, evidence can be associated with multiple sets of events (Sentz and Ferson, 2002).

*Evidential reasoning*: The ER approach uses a belief structure in the decision matrix which allows qualitative and quantitative criteria with uncertainties to be modelled. Each criterion is assessed at each alternative by a two-dimensional variable: possible criterion referential values (assessment grades) and their associated degrees of belief (Xu and Yang, 2005).

*Multiple criteria decision analysis (MCDA):* Is an umbrella term to describe a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter such as in corporate decision making or in other situations where multiple stakeholders are involved. Often the information is complex and of conflicting nature reflecting different viewpoints and changing with time. The principal aim is to help decision makers to organize and synthesize information in such a way which leads them to feel comfortable and confident about decisions. There are over 70 multi criteria decision making (MCDM) methods in the literature (Belton and Stewart, 2002).

*Safety Case*: A written document prepared by the operator of an installation to demonstrate that the major potential hazards have been reduced to risk levels which are as low as reasonably practicable and that they will be effectively managed and controlled throughout the lifetime of the installation (Kuo, 1998).

## 1.7 Delimitations of Scope and Key Assumptions

The research objective central to this thesis is to build evidence that the customer can effectively enhance the quality, safety and performance of new oil tanker and bulk carrier hull structures. This is achieved by managing risks at the design stage using a novel structural selection framework to evolve the arguments for a hull structures safety case as an outcome from the selection process, and to demonstrate how the safety case paradigm can be successfully applied to the technical management of large oil tankers and bulk carriers.

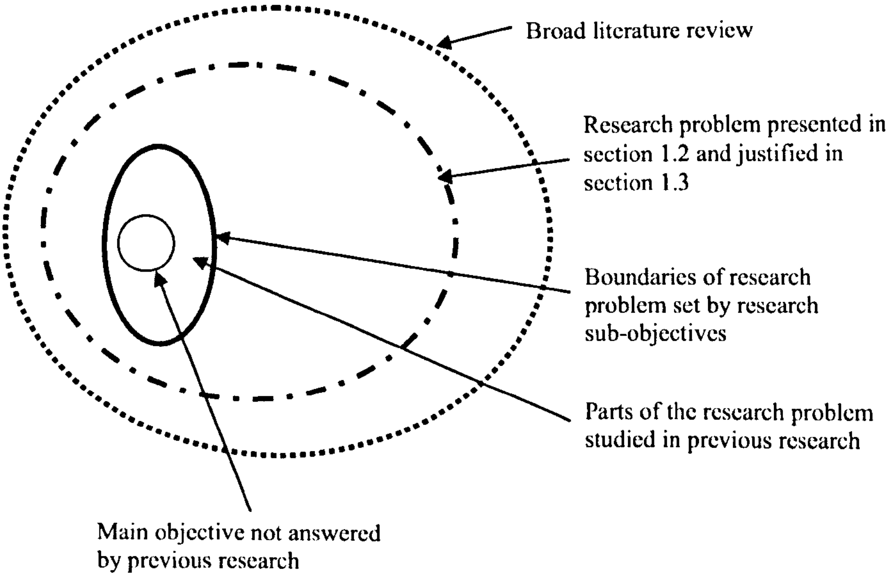


Figure 1.2. Research Boundaries

To establish a theoretical foundation upon which the research is based, a comprehensive literature review was conducted over an extended period of time with reflection on the researcher's current experience as a practicing classification society surveyor in the field. The broad literature review encompassed the field of vessel safety with emphasis on hull structures aspects for large crude oil tankers and bulk carriers, and this is indicated diagrammatically in figure 1.2. The work began in October 2002 and was completed by part-time research during a normal full-time working career. The first three years were focused on collecting published literature, studying and gathering published data, much of it available through technical journals and internet resources. The second two years were spent interpreting and synthesising data. These processes helped the researcher to determine the final research question and objectives listed in section 1.2.

Several key developments determined the direction of the research. Firstly, there was the huge controversy caused by the loss of the oil tankers *Erika* and *Prestige* in 1999 and 2002 respectively. These accidents occurred in spite of a progressive tightening of regulatory requirements for oil tanker and bulk carrier structures after the IMO adopted Resolution A.744 (18) in November 1993. Secondly, IACS, Greece and the Bahamas proposed the new goal-based common structural rules (CSR) to the IMO in November 2002, with the objective of eliminating class society competition on structural standards (Hoppe, 2007). Six years later, controversy persists as to the effectiveness of these new measures. Thirdly, the researcher's professional experience reinforced a long-held belief that tanker safety could be improved by more effectively exercising the owner's options at the structural design stage. Fourthly, the work already undertaken as part of the researcher's M.Phil (Lee, 2000), had previously explored and validated the applicability of the offshore safety case concept to large tanker structures.

Recognising the complexity of the subject and the apparent futility of attempting to critically examine hull structural standards in comparison to the magnitude of the contribution by the major class societies, the author has endeavoured to ensure that the modest effort herein was conducted critically, independently and dynamically. The work has evolved over a six year time period and has been self-funded. The temptation to restrict the scope of the study to consider only the structural assessment framework or only the applicability of the offshore safety case to tanker structures would have reduced the work, but was resisted because it was felt that the proposed structural assessment framework led naturally to the evolution of a hull structures safety case.

As a starting point, the ship structures problem was examined holistically in the overall context of design, regulatory, degradation, maintenance and other aspects including hull failure. To narrow the focus of the research, only large crude oil tanker and bulk carrier structures were considered as proposed in section 1.2, justified in section 1.3 and indicated in figure 1.2. Although the focus was on VLCCs in development of the structural assessment framework, large bulk carriers (VLBCs) are specifically included in the study due to the impact of the structural safety issues affecting this type of vessel, as demonstrated in the literature.

The boundaries of the current research problem are further narrowed to consider hull structural quality and safety aspects directly affected by the customer's preferences as indicated by the solid inner circle in figure 1.2. The objectives listed in section 1.2 not answered by previous research are justified in chapter 2. Thus the principal objective arising from the research is to examine whether ship structural quality can be improved at the design stage by the buyer's intervention and whether the improved structural design can form the basis of a hull structures safety case subservient to the mandated ISM Code safety management system.

Evaluation of structural designs is usually undertaken on the basis of engineering analysis to determine stresses and deflections based on a set of loads. A direct comparison of stress levels or fatigue factors in longitudinal strength members or in critical areas could then be used to establish preferences. Alternatively, comparison of options could be based on defining a set of structural assessment criteria, capturing the key quality characteristics of the hull design, as defined by the buyer. The method would involve assessment of information available to the customer, involving a combination of quantitative, qualitative, and sometimes incomplete data. A multi criteria decision analysis (MCDA) approach incorporating the Dempster-Shafer theory of evidence was selected as a suitable methodology for dealing with the complex array of criteria involved in the structural assessment framework. A limited amount of expert input was solicited and some discussions were held with a number of industry experts to test the validity of the chosen criteria.

## 1.8 Conclusions

This chapter lays the foundations for the research, by introducing the background to the problem, the research questions and the hypothesis. Justification for the research is presented, the methodology is outlined, a set of definitions is given, and limitations are described. The detailed research proceeds on these foundations.

# Chapter 2 - Traditional Hull Structures Safety Management Systems Affecting Large Bulk ships – A Literature Review

***SUMMARY***

*In this chapter, the safety management systems used to regulate large bulk ship hull structures are investigated with a view to identifying the need to improve ship safety. Firstly, a wide ranging literature survey was conducted to examine the hull structures safety question from a very broad perspective, including the nature of large bulk ship structures, structural degradation mechanisms, and an analysis of the current approach to structural integrity management for ship structures. Shortcomings in these control mechanisms evidenced by a number of recent high profile casualties involving structural failure are identified, and possible root causes found. This chapter represents the foundation work necessary for building the theoretical and empirical validity needed to support the principal research objective, confirming that the buyer can effectively enhance the quality, safety and performance of VLCC/VLBC hull structures by managing risks at the design stage. Building upon this foundation, the numerical and qualitative input data for a novel structural selection framework based on multi criteria decision analysis (MCDA) and evidential reasoning (ER) is further developed in the following two chapters.*

## 2.1 Introduction

As the title of this research work suggests, essentially two types of vessels have been considered, the very large crude carrier (VLCC) and the very large bulk carrier (VLBC). Bulk cargo is meant to be any cargo that is transported by sea for economy of scale. Firstly, focus is on vessels with length greater than 300m and deadweight in excess of 280,000 tonnes. This includes liquid bulk cargo vessels, the largest segment of which carries homogeneous bulk cargoes such as crude oil and products (major bulk products). Although other major bulk cargoes such as grain, iron ore, coal, bauxite and phosphate are shipped in Capesize and other smaller bulk vessels, the primary focus of this research is on the particular hazards associated with the shipment of bulk cargoes in large vessels.

In 2007, Brazilian mining giant Vale controlled approximately one third of global iron ore trade which reached roughly 800m tonnes. Vale planned to ship 100m tonnes of iron ore to China in 2008. At the time, freight rates for shipment of iron ore from Brazil to China were USD 108/tonne, almost exceeding the value of the cargo at USD 118/tonne, an increase of 500% over a two year period. Under a 25 year contract with BW Group (Bergesen), Vale ordered 6 very large ore carriers (VLOCs), 4 of which were 388,000dwt, from Bohai Shipbuilding Heavy Industries PRC, and at the time of writing these vessels are in service with BW Group. In May 2008, Vale announced further plans to construct 20 new VLOCs in China, 14 of which were to have deadweight of 400,000 tonnes. Future plans to construct 500,000 dwt vessels were also mooted (http://www.lloydslist.com, 21st May 2008). Dramatic events on Wall Street in the third quarter of 2008 and during the first months of 2009 indicate that Vale may cancel plans to build all 20 vessels (http://lloydslist.com, Friday 7th November, 2008).

Given the size of these vessels and the operational routes which include the North Atlantic, and the consequences of structural failures, VLOC structures have also been included in this study, although frequent specific reference will be made to VLCC structures by examples throughout the development of the structural assessment framework and the MCDA/ER model. For consistency, VLCC/VLBC has been used generally, and this should be understood also to refer to large oil/product tankers and bulk carriers including Capesize vessels..

The first objective of this research is to review the current safety management systems affecting the design and operation of VLCCs and VLBCs, with primary emphasis on hull structural performance aspects. State-of-the-art structural reliability studies from the civil engineering fraternity involve calculation and prediction of the probability of limit state violation for the structural system (Melchers, 1999). The number of failure modes and complexity of the load and resistance formulations for ship structures illustrates the difficulty in attempting such predictions for maximising the structural utility of large oil tankers and bulk ships. For this reason the current approach to the design and operation of ships is richly code based, with the empirical rules of the international classification societies underpinning ship design and operation and the regulatory systems which apply. To identify weaknesses in this traditional approach, a wide net has to be cast round the subject.

Firstly large oil tanker and bulk carrier structures are investigated to determine their true characteristics within the wider set of load-bearing welded plate structures including bridges, buildings, and offshore structures. Secondly, the published literature describing the principal hazards affecting ship structures is examined for the purpose of incorporating the findings into a structural assessment framework developed in the following chapters. Thirdly, the regulatory system affecting the design and operation of large ship structures is described analysed and weaknesses identified. The second objective of the research is to reveal possible root causes associated with inadequate quality in structural design or maintenance procedures arising from a review of selected, published marine casualties. Shortcomings arising from the critical assessment of the regulatory controls imposed on hull structural performance by the various stakeholders in the safety system are identified in order to determine whether failures discussed in section 2.6 can be traced to faults in design or operation. Further, structural failure is hypothesised to be an understated root cause of vessel loss.

In the second phase conducted in the following chapters 3 and 4, the evidence needed to support the principal research objective, confirming that the buyer can effectively enhance the quality, safety and performance of VLCC/VLBC hull structures by managing risks at the design stage is gathered. This forms the numerical and qualitative input data for a novel structural selection framework based on multi criteria decision analysis (MCDA) and evidential reasoning (ER), proposed, developed and validated in chapters 3 to 6 of this work

## 2.2 The Nature of Ship Structures

### *2.2.1 What Are Ship Structures?*

Ships are the largest mobile man-made structures in existence. Practitioners refer to the size, complexity and multiplicity of function of structural components and the random or probabilistic nature of the loading that characterises ship structures. In a seaway, large tanker and bulk carrier hull structures are subjected to considerable internal stresses due to wave loading and inertia forces. The residual stresses inherent in modern welded construction and the geometrical complexity of the internal structural arrangements, complicate attempts to accurately determine dynamic stress levels experienced by individual structural elements. Uncertainties in analysis methods, materials of construction and variances in the integrity of ship construction add further complexity to the problem.

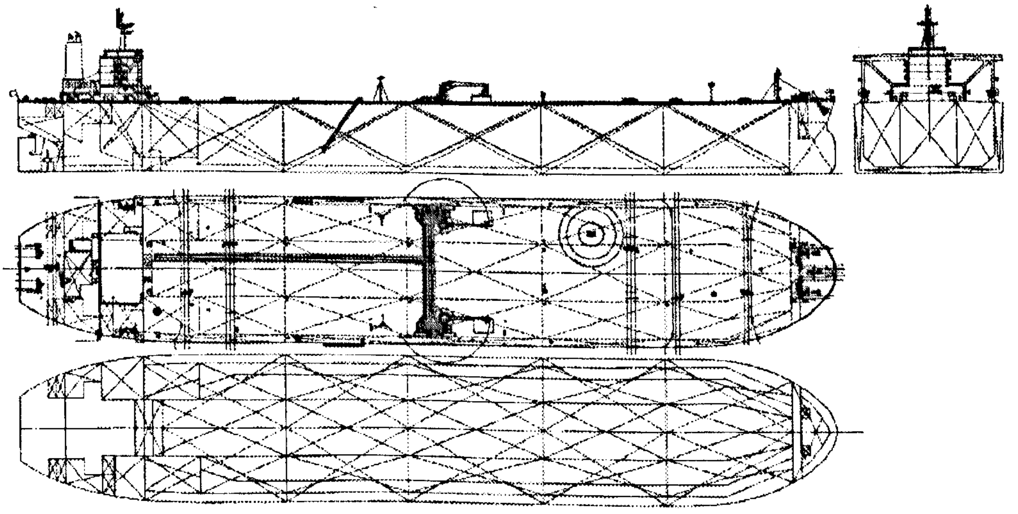


Figure 2.1 (a). Typical Double Hull VLCC (LBP 310m)

Figure 2.1(a) above shows the typical arrangements for a double hull (DH) VLCC of approximately 300m length. These vessels typically have a transverse frame spacing of 5.0m and a longitudinal frame spacing of 0.9m and contain approximately 16,500 key structural intersections formed by the penetration of relatively closely spaced longitudinal framing penetrating the main transverse structures including web frames and bulkheads at main deck, side shell, longitudinal bulkheads, inner sides, and double bottom. These are regions of high stress due to the geometry of the opening and the residual stresses inherent in fillet welded joints.

Figure 2.1 (b). Typical Capesize Bulk Carrier (Paik et al, 1998)

.Figure 2.1 (b) shows the arrangements for a typical Capesize bulk carrier of length 264m. Figure 2.2 on page 22 shows a typical penetration through a transverse member such as a web frame and the areas of increased stress indicated by the red arrows. In these locations, fluctuating local dynamic stresses are magnified considerably in relation to average global stresses, and have to be controlled to avoid fatigue failures.

Commercial steel ships are constructed fit for the purpose and are primarily designed for ease of productivity and economy (refer to section 3.2.5 for a full discussion on this topic). Ship structures are invariably fabricated from low carbon steel, grades A, B, D and E, and higher strength steels, grades AH, DH and EH, produced to IACS standards. In mild steel designs, grade-A with a nominal yield point of 235MPa is used, with no impact test requirement. In high tensile steel designs, EH-36 steel with nominal yield point of 355 MPa is required to be Charpy tested at -40C.

Figure 2.2. Typical Penetration Detail Showing Stress Concentrations (DNV, 2005)

By comparison, the rules for offshore steel structures are much more onerous. Offshore structural codes such as NORSOK (2004) require special steels where joint complexity is high and failure will have substantial consequences, defined as loss of human life or significant pollution, and this applies to joints where the geometry of connected elements and weld type leads to high restraint and triaxial stress pattern. For offshore ship structures the NORSOK Code N-004 specifies design class 4 (DC4) butt welds in the deck, recognising the substantial reserves of residual strength inherent in ship structures. The corresponding material quality is level I or III. Level I steel quality for plates (MDS Y20) implies a low carbon steel equivalent to the European standard EN 10025 S355G10+N/G10+M. This material has a nominal yield point of 355 MPa depending on the thickness, and a minimum average Charpy Impact value of 50 J at -40C.

The common structural rules (CSR) for new oil tankers define three structural categories, secondary, primary and special (classes I, II and III). These rules allow the use of grade A/AH steels up to a thickness of 20mm with the exception of class III material which has to be grade B. The CSR requires special materials only in limited zones in the mid body, including the sheer strake, deck stringer plate, the deck strake at the longitudinal bulkhead and the bilge strake. Effectively therefore, the majority of the steel structure is fabricated from grades-A/AH steels.

The fabrication of large ships structures from rolled steel plate leads to an inherently complex internal arrangement involving a multitude of structural member intersections in tanks, zones where in-service fluctuating field stresses are locally amplified. Production considerations dictate the extended use of cheaper materials and careful minimisation of welding. Such commercial constraints result in a significant departure from the more rigorous offshore requirements described above. For production reasons, ships structures are almost entirely fillet welded or at best, partial penetration welded with full penetration welding enforced only in certain areas such as the double hull lower hopper corner joint. Industry insiders have strongly criticised the designers of new tankers for allowing fillet weld throat thicknesses to be optimised to suit production constraints (Devanney, 2006).

Efficiency in the hull structural system is measured by the ratio of strength to weight. Mild steel used for decades was reliable, forgiving but low in yield strength and therefore relatively inefficient (Wilson, 1975). During the 1980s, optimisation by ship builders together with the extended use of high tensile steel (HTS) to take advantage of the improved strength to weight ratio, resulted in the lightweight of large SH tankers reduced to approximately 36,500 tonnes. This is roughly 15% less than the lightweight of the current generation DH VLCCs. However, the lighter scantlings displayed much greater sensitivity to fatigue failure since the HTS material had the same nominal fatigue life as mild steel, although the dynamic stress levels and deflections were significantly higher (Magelssen, 2004).

The foregoing considerations lead to a number of interesting preliminary findings and conclusions. Firstly large bulk ship structures are much more complex than usually thought of in industry circles, indicating a perception problem in understanding as to what really are ship structures? Secondly, there is a tendency to understate the differences between the much more rigorous offshore requirements and the requirements for large commercial ships. Thirdly the minimum requirements for disposition of special materials and the adequacy of welding design required by classification rules for large bulk ships appear to be marginal. Fourthly, the continued use of A-grade steels having no guaranteed fracture toughness and susceptibility to brittle fracture phenomena in tankers and bulk carriers appears to be a curious anomaly which has been the subject of repeated criticism from industry critics in the past and is linked to the bulk carrier problem discussed in section 2.6.1.

### *2.2.2 Structural Utilisation, Loads and Operating Environment*

Primarily, tankers and bulk carriers are intended to transport huge consignments of bulk commodities safely, including crude oil, products, iron ore, grain etc. across the major oceans of the world in all types of weather conditions. The double hull VLCC *Sea Energy*, built by Hyundai Heavy Industries in 2004, had summer deadweight of 299,998 tonnes and a lightweight of 43,969 tonnes. Filled with cargo, this represents a structural utilisation factor of 6.82 based on cargo lift relative to the lightweight mass. A Capesize bulk carrier built in Brazil in 1987, with a length of 277m had a deadweight of 151,493 tonnes. The lightweight for this vessel was 21,896 tonnes and the utilisation factor 6.92. Clearly, these structures are unique in terms of their load carrying ability relative to their own structural weight.

In their re-assessment of the loss of the OBO *Derbyshire* in September 1980 (refer to section 2.6.1), Paik and Faulkner concluded that large tankers and bulk carriers when fully laden, carry cargo 6-8 times heavier than the structure supporting it, “in seas that we are not presently designing for” (Paik and Faulkner, 2003b). This criticism of the inadequacy of a major structural design parameter driving the design of large bulk ships is surprising when it is viewed in the context of when the observations were made. The significance of this statement is that the stochastic wave loading and dynamic load response experienced by these vessels may not be properly accounted for in the design. In the following section this hypothesis will be examined.

### 2.2.3 Global and Local Strength Aspects

The ship structural design problem is essentially the prediction of dominant hull girder response in the form of vertical bending moments and shear forces in terms of the lifetime probability of occurrence, and the cyclic loads tending to cause fatigue damage. Static loads include mass and buoyancy forces, thermal and docking loads. Low frequency dynamic loads include hull pressure variations due to waves, oscillatory motions and inertial reaction forces due to the mass of the ship and its cargo. High frequency loads include hydrodynamic loads due to engine or propeller impulses, wave induced loads due to springing and whipping phenomena, and impact loads due to bow slamming (Faltinsen, 1990; Hughes, 1988; Paulling, 1998).

The principal indices of longitudinal strength for tankers and bulk ships are found in the rules of the international classification societies and the unified interpretations given by IACS In classical allowable stress design (ASD), the primary indices of hull girder longitudinal strength are the rule section modulii for deck and bottom. These are derived from a combination of the wave-induced and stillwater bending moments. For normal strength steel designs, the allowable stress level was traditionally set by the international classification societies at 175 N/mm$^{2\cdot}$ The allowable shear and wave bending stresses were limited to 110N/mm$^2$. In rule-based design, the minimum value of the section modulus was established to keep the wave bending stress within acceptable limits, as no explicit check for hull girder fatigue was carried out (Hughes, 1988).

The stillwater bending moment $M_s$ is specified in IACS UR S11.2.1.2 and is a function of the design loading conditions, which for oil tankers includes homogeneous loading, ballast, non-uniform loading and mid voyage conditions including tank cleaning operations. The value of $M_s$ can be derived from direct calculations. Earlier studies on wave induced bending moments for ships include the work of Little et al

(1998). The common acceptance of longitudinal strength standards for large ships has been the subject of much academic effort and a great deal of variance until the eleven IACS societies agreed on the basic requirements for longitudinal strength at the 22nd session of the IACS Council meeting in April 1991. This development work resulted in the S11 Longitudinal Strength Standard described in detail by Nitta et al (1992). For commercial ships under the S11 standard, the design minimum wave-induced bending moment $M_w$ is the mean value of the extreme wave bending moment which the vessel is likely to encounter during an assumed lifetime of 20 years. Until recently, the standard wave environment, assumed was typically worldwide service wave data.

$$M_{wh} = +0.19CL^2BC_b \text{ (kNm) for hogging}$$

$$M_{ws} = -0.11CL^2B(C_b + 0.7) \text{ (kNm) for sagging}$$

where $C$ = wave co-efficient (10.75 for $300m \leq L \leq 350m$), and $L$ = vessel length, $B$ = vessel breadth, $C_b$ = vessel block coefficient (Paik and Faulkner, 2003b).

The IACS wave bending moments are now incorporated in the Joint Tanker Project (JTP) rules issued by ABS, DNV and LR, and in the Joint Bulker Project (JBP) Rules discussed in section 3.4. Paik and Faulkner (2003b) have conclusively demonstrated that, in the case of the OBO carrier *Derbyshire,* short-term response analysis involving storms of a specific duration used to determine $M_w$ resulted in wave-induced bending moments 25-32% higher than the IACS standard values derived from the above formula. Because of the large size of tankers and bulk ships, the effects of bad weather on the ship's structure are not readily observed by the crew. Ship structures are mobile and assumed to avoid bad weather (Lacey & Chen, 1995). Clearly, the handling of a vessel during a severe weather event has a significant impact on the structural performance. Faulkner (2001) notes that "master mariners generally have little confidence in the safety aspects of weather routing" and the tragic loss of the OBO *Derbyshire* appears to support this conclusion.

A number of other researchers have recently reported (Stiansen and Thayamballi, 1987; Kendrick and Daley, 2007; Smith, 2007) that the wave bending moments assumed in hull girder assessment to IACS S11 standards may be routinely exceeded in service. Recently, Kendrick et al have shown that, based on a mean likelihood of $10^{-5.4}$ (hog) and $10^{-6.9}$ (sag), the expected return periods are 2.9 weeks and 1.8 years for hogging and sagging BM's respectively. The conclusion is that these average design values indicated in figure 2.3 are "not exceedingly rare" and are somewhat surprising, as revealed further in the following discussion.

Figure 2.3. IACS S11 Standard for WBM (Kendrick and Daley, 2007)

Rare wave events occurring with an annual probability of $10^{-4}$ are accounted for in the accident limit state (ALS) design of offshore structures, whereas ship structures are designed for a 20 year return period ultimate limit state (ULS). Bitner-Gregersen et al (2003) concluded that, for offshore structures, the 100 year wave load with appropriate safety factors in ULS is applied. Recent meteorological data interpreted by Magnusson et al (2006), suggests that the 100 year North Sea wave corresponds to a significant wave height of around 16.0m. These are the grounds for recent criticism by Freize and Paik (2007) and Frieze and Lin (1991) of the very different and reducing reliability levels of ships observed, compared to their offshore counterparts.

The current research into extreme waves conducted by Bitner-Gregersen and colleagues referred to earlier indicates that wave heights between 20-30m may be experienced in certain ocean areas during extreme weather events. For ship design, the US Navy assumes that the largest wave likely to be encountered is 21.4m. Smith (2007) reported that current IACS classification standards assume that about 88% of waves have periods between 7-14 seconds and significant heights in the range 1.0m to 10.9m and only 0.2% of these significant wave heights fall within the range of 11-17m. Typically, a 300m length bulk ship will be dimensioned to a wave height of approximately 10.75m. Statistically, a vessel operating in the North Atlantic will experience 55 x $10^6$ waves during its lifetime, and 99.8% of these waves have a significant wave height less than 11.0m. However, approximately 110,000 of these waves over 11.0m height could be encountered during the vessel's lifetime (Smith, 2007). In a re-assessment of the sinking of the *Derbyshire* in September 1980, Paik and Faulkner (2003b) refer to "prima facie evidence" for an in-depth examination of the adequacy of the IACS standard UR S11 for large tankers and bulk carriers.

For adequacy of global strength, the IACS longitudinal strength standard Unified Rule (UR) S7, prescribes a *minimum* midship section modulus as a function of the principal dimensions for ships with $90m \leq L \leq 500m$ fabricated from steel. According to Paik and Thayamballi (2003a), the IACS minimum value is given by:

$$Z_{\min} = C_1 L^2 B(C_b + 0.7)K \quad (\text{cm}^3)$$

where $C_l$ = wave co-efficient (10.75 for $300m \leq L \leq 350m$), $K$ = high tensile steel factor ($K$ = 1.0 for normal strength steels), and the other parameters are defined above. Typically, the actual section modulus for the deck and bottom of large bulk ships will exceed the required IACS minimum. For example, the section modulus of the deck $Z_d$ = 77.195 $m^3$ for the least cost option VLCC_2 described in section 5.3, is 13.6% above the IACS minimum requirement. This margin is typical for many tanker designs, and just exceeds the allowable 10% reduction in section modulus to allow for the effects of corrosion while the vessel is in service.

These criteria are contained in IMO Resolution MSC.105(73) adopted on 5th December 2000. The IMO standard contains the same formula given above and has now been integrated into IACS procedures. The dangers of strict adherence to an ASD approach involving small margins above IACS minimum section modulii criteria have been highlighted in relation to bulk carrier designs. Bottom structures with large plate slenderness ratios of 2.5 or more have been shown to be highly susceptible to buckling failure under vessel hogging mode, even though the ratio of section modulii at bottom to deck $Z_B/Z_D$ has been close to 1.33 as in the case of the *Derbyshire* (Paik and Faulkner, 2003b).

Whilst the global strength considerations described above drive the main scantling requirements primarily from a buckling viewpoint, a combination of global loads and lateral loads experienced by plated grillages is part of the structures problem. A detailed in-depth consideration of local strength aspects leads to further important discoveries relative to the real nature of ship structures, normally the domain of specialised naval architects. Recent independent critical analytical work performed by Daley et al (2007) involved comparative studies of ship structural design standards which was published by the Ship Structure Committee, report no SSC-446. This work examined the strength aspects of a typical bottom panel or grillage from a 50,000 dwt bulk carrier. The panel measured 10.08m length x 3.32m width having a longitudinal frame spacing of 830mm and a transverse frame spacing of 3,360mm. The combined loading consisted of the longitudinal hull (hogging) bending stress of 126 MPa and a lateral pressure on the shell plating of 210kPa. The structure was found to be capable of withstanding 2-3 times the local design pressure without any visible local deformation (buckling). The maximum lateral deflection at twice the design pressure was 2.0mm.

Recently, criticism has been directed at the lack of transparency in the rule making process for ship structures. It has been pointed out that ships are the only form of major structures world-wide not built on the basis of independent and transparent standards. Frieze and Paik (2007) refer to a "judge and jury approach" to the development of rules by the classification societies. This concern is heightened by their observation of a downward trend in reliability of ship strength accounting for the effects of corrosion and wastage. In conclusion, the review conducted in this section related to global strength aspects for large tanker and bulk carrier structures revealed a number of important findings and conclusions.

Firstly, the IACS minimum standard S11 for wave bending moment does not account for a survival design approach which has been strongly advocated in important independent research. Secondly, the ASD approach is no longer adequate for the design of large tankers and bulk carriers and has been described as "absurd" (Paik and Faulkner, 2003b). Thirdly, ships typically rely heavily on the substantial plastic reserve characteristics of plated grillages in order to create a significant strength reserve and classification rules lack a significant factor of safety against yield at the design point. These plastic reserves are invoked on a regular basis with the ship in service, although the accompanying plating deformations are not normally observed.

### *2.2.4 Political/Economic Factors*

Over the last 25 years, the key driver for the major bulk commodities market including crude oil, products and iron ore has undoubtedly been rapid urbanisation and development in China which commenced in 1976. China has currently around 20% of the world's population. The Chinese economy has grown to be the third largest in the world with a gross domestic product (GDP) of USD 4.3 trillion (2008), making it the fastest growing major nation in the world. The average annual GDP growth rate has been more than 10%, effectively doubling every 7 years. Predictions made in January 2008, indicate that 400 million Chinese are expected to populate the urban communities to be built during the next 15 years. With the worldwide economic crisis unfolding in late 2008, huge state investment into China's infrastructure and heavy industry will undoubtedly slow growth rates down to more sustainable levels, although a strong demand for commodities is expected to continue (http://www.worldyards.com, 15th January 2008). The design and operation of bulk ship structures are fundamentally driven by the commercial constraints imposed by such worldwide markets for commodities which dictate freight rates.

Increasingly, political factors such as regional strife and terrorism have influenced markets. Figure 2.4 illustrates how the oil price has been affected by major political events over the period 1947 to 2003. Tanker shipping suffered the effects of the supply/demand imbalance created during the period 1973-1977 when approximately 80 million tonnes deadweight was constructed (Osborne, 1992). More recent *black swan* events involving speculation on commodities in global financial markets have led to oil prices reaching approximately $140 per barrel in mid 2008. Historically, tanker single voyage freight rates for crude oil shipment from 1947 to 1990 show distinct spikes related to world political and economic events. Beenstock and Vergottis (1993) suggest that four basic perennial market factors affect the economics of the bulk trades, explaining the aggregate fluctuations in market conditions, viz freight rates, shipbuilding costs, 2nd hand and scrap value.

Figure 2.4. The Effect of Major Political Events on Crude Oil Prices 1947-2003 (http://www.wtrg.com, 28th July 2008)

Figure 2.5. Total Loss Ratio 1945 to 2005 (Soma, 2004)

Ships carry about 95% of international freight and shipping costs are about 25 cents per tonne mile (Faulkner, 2003). Low freight rates are said to be a factor negatively impacting safety in shipping. Faulkner suggested increasing freight rates by 40-50% over 10 years. In a recent study exploring the data interrogation approach for identification of safety characteristics in shipping organisations, Soma (2004) found an inverse relationship between freight rates and loss ratio. In figure 2.5 from Soma's study, the post World War II freight rates (solid line) are overlaid and compared to the total loss ratio trend (dotted line). Fluctuations in freight rates were tuned down using a moving average approach. Because freight rates generally increase over time and the loss ratio decreases, the freight rates are inversed. The only exception to the trend was shown to be the inverted peak in the 1980s due to a market drop which forced speculators out when speculation in buying and selling of ships was not viable.

During the most recent prolonged recession of the 1980s, asset play, or the buying and selling of vessels when the market value was less than the future value, meant that a 15 year old vessel could be purchased for approximately 30% of the new construction cost and traded under a flag of convenience for the remaining lifetime, operating on a minimum maintenance budget. These owners took advantage of high freight rates and low operating costs to maximise profits. Their reputation and safety standards were regarded to be of secondary importance, giving huge benefits for least costs. The 1980's is characterised as a period when a small number of orders for new buildings led to the extension of vessel lifetimes to 30 years. By 1987, spot trading of crude oil had reached 50%. Further, speculators driving the market were not interested in ship condition. A recent Organisation for Economic Co-operation and Development study (OECD, 2001) concluded that these circumstances led to the "sub-standard ship" syndrome. Leading shipping companies maintaining good technical condition and well qualified crews were not able to compete on this basis.

Over a decade ago, Shashikumar (1995) reported that market forces were having a direct and dramatic impact on the nature of the crude oil transportation market. In the golden years of the 1960's and early 1970's, a tanker owner did not require an administrative structure, entrusting the technical management of the ship to the master and crew. In this period, bank loans could be recovered in less than 5 years and funding was readily available. Investment in tankers was considered to be low risk. Economic planning could be carried out independently for each vessel and decisions made on an out-of-pocket and opportunity-cost basis (perfect competition). By 1989, the total tonnage owned by the oil majors had declined to 13% of the total tanker fleet. Ownership by the traditional oil majors has declined dramatically since the 1970's. On the other hand, subsidiaries of state-owned oil companies including Vela International Marine, the National Shipping Company of Saudi Arabia (NSCSA), the Kuwait Oil Tanker Company (KOTC) and the National Iranian Oil Tanker Company (NITC) have all expanded their tanker fleets.

More recently, the tanker industry has become very cyclical in nature, and there is no reliable method to pre-determine freight rates. Global oil prices have spiralled and fallen. World stock markets are currently extremely volatile in nature, leading to a near melt down of the global financial system in October 2008. In these conditions, ship owners often find circumstances changing precipitously in the down slide. Shipping is a very cyclical activity with periods in which the market cannot support operating costs. It is highly sensitive to currency exchanges which can wipe out entire trades. Seven years ago, Mikelis (2001) observed that shipping was becoming a high volume/low profit-margin business and unpredictable fluctuations were seen to be devastating. Recent events including the collapsing of freight rates and the forced lay up of thousands of smaller bulk carriers confirm this view, and highlight the forthcoming risks faced by the shipping industry and the wider international community when faced with prolonged periods of low freight rates and uncertainty following economic downturns.

## 2.3 Structural Degradation Mechanisms

### *2.3.1 The Corrosion Hazard*

Two particular challenges have been identified with respect to the fitness for purpose of double hull tankers, namely design to prevent corrosion and design to prevent fatigue as reported by several studies including (Violette, 1994; Paik and Thayamballi, 2003a;

Paik et al, 2003c; 2003g). ClassNK has observed that approximately 70% of failures of hull structural members are caused directly by corrosion and wastage and is the prime cause of the loss of bulk carriers and ore carriers (Mizukami et al, 1994a). Corrosion is stated to be the major cause of marine structural failure, leading to fatigue damages identified by many studies (Wang et al, 2003a; 2003b; Garbatov et al, 2005; Benoit, 1994; Contraros, 2003; DNV, 1999; Emi et al, 1994a; 1994b; Magelssen, 2000; Guedes Soares et al, 1996; Soares and Garbatov, 1996; RINA, 1994; ISSC, 2007; Ivanov et al, 2004) and others.

Steel structures operating in sea water are exposed to particularly severe corrosion hazards. Corrosion damage in oil tankers may lead to loss of integrity in oil/water tight boundaries causing pollution, cargo mixing or gas accumulation. Water ballast tanks represent the highest risk areas relative to corrosion in oil tanker hull structures as concluded by several studies including those of Violette (1994), Bea (1993) and Towers (1994). The repeated cycle of filling and emptying ballast tanks with sea water of varying quality creates conditions inside the tank very conducive to a variety of corrosion mechanisms. Ballast tank temperatures in bulk carriers and double hull tankers can range between 0-70° C. Ballast tanks are always wet and accumulate mud on the bottom and horizontal surfaces which facilitates microbial corrosion. In double hull tankers, the surface area of the ballast tanks has been dramatically increased 2-3 times that for an equivalent size single hull tanker. Pre-MARPOL tankers were not required to have the ballast tanks protected against corrosion. Since about 1970, classification societies allowed owners to apply coatings in order to reduce scantlings by 5-10%. Special class notations were introduced such as Lloyds Register 'cc' notation. This option is no longer allowed by the IACS member societies as reported by Towers (1994).

In crude oil tankers, cargo tanks are exposed to a number of specific corrosion hazards including general corrosion, local corrosion, pitting corrosion and weld metal corrosion. Excessive crude oil/water washing can cause erosion corrosion through impingement. Crude oils with high sulphur content can react with sea water to form acidic compounds, causing pitting corrosion. The Oil Companies International Marine Forum (OCIMF) have warned that poor quality inert gas may also pose a hazard in the vapour space of cargo tanks due to acid formation associated with condensation. "Sour" crude oil is known to cause higher corrosion rates compared to "sweet" crude. With certain crude oil cargoes, the presence of hydrogen sulphide has been reportedly associated with accelerated corrosion rates in deck structures (OCIMF, 1997).

In bulk carriers, cleaning cargo holds with sea water after carrying high sulphur coals, led in some cases to rapid corrosion affecting side frames and their end connections to hopper and top wing tanks and catastrophic loss of side structure. Structural optimisation in the upper wing tanks of certain bulk carrier designs has resulted in deck strips up to 6.0m in length, having marginal buckling capacity. Andreassen et al (1999) concluded that the presence of corrosion combined with these marginal strength reserves may have been the root cause of sudden catastrophic structural failure and loss of life in bulk carriers.

Recently, an improved understanding of the relation between structural strength and coating condition has emerged. In HTS designs involving reduced scantlings, deflections are increased compared to mild steel designs. In areas of high shear stress, buckling of plating may lead to local coating breakdown, loss of section, higher stresses, higher deflections and load re-distribution to adjacent areas, culminating in what Contraros (2003) refers to as the "domino effect". Failure to maintain coatings in vessels with up to 50% HTS, meant that steel of substantially less thickness and inherently high residual tensile stresses due to welding, was exposed directly to sea water. Stress corrosion with associated accelerated deterioration and cracking resulted in many instances. Yamamoto (2007) suggested that this was the primary reason for a reversal in the trend of HTS in VLCC hull structures from 30-40% to 80-90% in the mid 90s, and recently back again to approximately 25-30%. Yamamoto concluded that the high tensile steel ratio for new double hull tankers under the new common structural rules (CSR) would converge into one design incorporating approximately 50% HT steel due to the more onerous global and buckling loads required by the CSR.

From an engineering perspective, using a high percentage of HTS in VLCC and VLBC structures would appear to be desirable for increased economy of construction due to the reduced steel mass. In this regard, the comments from Yamamoto support the shipbuilder's viewpoint. However, the fatigue characteristics of HTS are similar to those for NS steels. Therefore, the higher stresses and greater deflections inherent in HTS designs require much stricter control of the design and execution of critical structural details including geometric stress concentrations and welded joints. In HTS rich designs, the importance of protective coatings is paramount. Higher stresses and greater deflections are conditions which can lead to initiation points for early failure of protective coating systems, leading to the "domino effect" referred to above. Exposure of steel surfaces to a corrosive environment accelerates corrosion induced fatigue phenomena, formerly a widespread problem in some HTS rich bulk carrier and tanker structures.

### *2.3.2 The Fatigue Hazard*

In the past, many studies have focussed on the fatigue problem in ship structures including ISSC (2006a), Mizukami et al (1994b), Liu et al (1981), Ma et al (1995), ISSC (2006b), Jubb (1995) and Storhaug et al (2001). Prior to 1990, classification rules contained only explicit fatigue criteria expressed as a material factor introduced in the late sixties due to the introduction of HTS (Magelssen, 2000). In 1990, a series of 3-4 year old Japanese built single hull VLCC's suffered cracking in way of the side longitudinal connections to the transverse bulkheads. In some cases the cracking led to leakage of oil into the sea through the side shell. The cracks were concentrated in the side structure from the load water line to approximately 8.0m below. Most cracks occurred in way of the cargo tanks and involved unsymmetrical longitudinal sections. The problem was found in ships built from HT32/HT36 steels and utilising the newly developed thermo mechanically controlled processing (TMCP). A full discussion of the investigations and findings performed by the Japanese classification society ClassNK is given by Yoneya et al (1993). As a result, classification societies after 1990, introduced explicit fatigue criteria, resulting in increased scantlings of the side longitudinals.

The simplified fatigue method for ship structures described by Cramer et al (1994) assumes that the long-term stress histogram of the hull structure resulting from random sea loading follows the Palmgrens-Miner Rule of linear cumulative damage and the local long term stress range response can be described with $n_i$ stress cycles in stress block $i$.

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} = \frac{1}{\bar{a}} \sum_{i=1}^{k} n_i \Delta\sigma_i^{\,m}$$

where $D$ = the accumulated fatigue damage, $\bar{a}, m$ are S-N fatigue parameters, $k$ = the number of stress blocks, and $N_i$ = the number of cycles to failure at constant stress range $\Delta\sigma_i$. If the long term stress range can be described by Weibull distributions for the different load conditions, with scale and shape parameters $q$ and $h$ respectively, the cumulative damage is expressed by:

$$D = \frac{n_d}{\bar{a}} q^m \Gamma\left(1 + \frac{m}{h}\right)$$

where $n_d$ is the number of stress cycles over the design life, and $\Gamma\left(1 + \frac{m}{h}\right)$ is the Gamma Function taken from tables in fatigue codes.

A rational design procedure was put forward by Violette (1995). Guidelines for fatigue assessment (DNV, 2005; BV, 1994) have been developed by the major classification societies, and these typically are software supported. In DNV CN 30.7 (2005), a simplified method based on fatigue tests (S-N data) and estimates of cumulative damage (Palmgrens-Miner Rule above) are prescribed. The long-term stress range can be determined by either of two alternative methods. In the first simplified approach, a postulated Weibull distribution can be assumed, with the load effects derived from the ship rules. Nominal stresses are multiplied by the various stress concentration factors to get the local notch stresses for the S-N curves. In the second more complex approach, the long-term stress range has to be calculated from a given wave climate and combined with structural FEM analysis.

Horn et al (1999) have described the methodology used for fatigue assessment in the SafeHull approach, where Weibull shape parameters for structures at various locations in the ship are in the range 0.8 to 1.1.

Figure 2.6. UK Department of Energy S-N Curves (Horn et al, 1999)

Two slope S-N curves were used, based on statistical analysis of experimental data taken at 2 standard deviations below the mean lines. Eight curves, each representing a class of welding detail were chosen according to UK Department of Energy data, reproduced in figure 2.6 above. The fatigue behaviour of different types of structural details is evaluated by constant cycle fatigue tests and the results plotted as straight lines on log-log paper. The designations B, C, D and E in figure 2.6 indicate individual S-N plots for the various structural details tested.

According to pre-CSR classification rules, the nominal fatigue life of the hull girder was given as 20 years, based on world wide wave data.

Table 2.1. Effect of Trade Route on Fatigue Life (Magelssen, 2004)

The new CSR rules described in section 3.4.3, require 25 years life based on North Atlantic wave data. Magelssen (2004) has presented a comparison of relative fatigue lives for the various routes shown in table 2.1. It is obvious that there is a remarkable difference between the respective trade routes.

Despite the initial efforts made by the classification societies to introduce explicit fatigue criteria into ship design after 1990, recent Norwegian research (Storhaug, 2007; Storhaug and Berstad, 2001) concluded that current fatigue design procedures for ships using classification society rules were insufficient to avoid fatigue cracking, since only a very limited number of susceptible areas were usually considered. The criticism was related to vibratory effects induced by springing and whipping phenomena not accounted for in current fatigue design procedures. Ship owners were advised to take precautions and use more advanced methods for both new and existing ships, similar to offshore applications. Previously held views regarding the contribution of springing and whipping phenomena to total fatigue damage were challenged.

In the 1960s the first published studies appeared on whipping and springing. In the 1970s, a number of full scale measurements were carried out on tankers including the 255,000 dwt *Esso Bonn* followed by the ARCO tanker *California* in 1995 described in section 2.5.2, and more recently, full scale measurements carried out in 1997 on a 300m length ore carrier in the trans Atlantic ore trade (Moe et al, 2005). In 2002, DNV initiated an extended workshop on springing with participants including DTU, NTNU, Marintek and CSSRC. Four different non-linear hydrodynamic codes were used to predict the observed wave loading including wave induced vibration, and the theoretical results were compared to full scale data, indicating under prediction of the actual wave induced stresses in all four codes.

Storhaug (2007) recently conducted a comprehensive and definitive study on the subject of wave induced vibrations in ships, part of his Doktor Ingenior thesis, involving a series of model tests of an iron ore carrier using a 4 segmented model, 8.7m in length. The contribution from vibration damage was found to have increased from 19% in the North Atlantic environment to 26% in world wide trade. The dominating wave and vibration damage came from waves with significant height of only 5.0m. The conclusion was that current codes are incapable of accurately predicting the effects of whipping and springing response in terms of its full contribution to overall fatigue damage for a general design. Storhaug found these discoveries indicated that the decision to remove the whipping addition from the new IACS Joint Tanker Project (JTP) and Joint Bulker Project (JBP) Rules, actually reduced the safety level.

After World War II, improvement in materials technology and attention to detail design virtually eliminated the serious fatigue and fracture problems which had plagued ship designers during and just after the war. In the late 1970s, some of the world's largest oil tankers were constructed including *Seawise Giant* of 564,763 dwt. With the introduction of HTS to take advantage of the higher strength to weight ration, these mega structures began to experience fatigue failures. Ship designers had three options, *safe-life, fail safe* or *damage tolerant* design. In *safe-life* design normally adopted for aerospace structures, fatigue cracks could not be allowed to develop during the nominal lifetime of the structure, normally 20 years for ship structures. To achieve this goal, the design fatigue life was necessarily several multiples of the target life time of the structure. In the *fail-safe* approach, fatigue cracks were allowed to develop but were controlled within a limited area (Wilson, 1975). Choosing the first option would have meant that designers could not take advantage of HTS because it was virtually impossible to economically design lightweight structures that would not display fatigue cracks inside 20 years. The fail safe/damage tolerant approach has been adopted in the current generation of large bulk ship designs, where it is assumed that flaws of detectable length (critical flaw size) will be found during regular calendar based surveys.

In conclusion, large bulk ships have been deliberately designed on the assumption that fatigue cracks will occur and that the structure will be fail-safe and damage tolerant because flaws can be detected by visual inspection before they reach critical length. The weakness in this approach lies in the practical difficulties encountered in the inspection of such huge structures (refer to section 2.5.3 for a discussion on this topic). As a further consideration, because the majority of ship structures are fabricated from material without guaranteed fracture toughness values (A-grade normal and higher strength steels), the critical defect size is much reduced, highlighting the importance and reliance on structural inspections to find flaws before they propagate in a brittle manner, as observed by Jubb (1995). The general view today is that the crack initiation period in as-welded steel joints is insignificant due to the existence of welding defects. This means that crack growth is initiated in the very early stages of the structural lifetime (Ye et al, 2007). Fatigue and buckling phenomena can become the governing failure modes driving the design (ABS, 1998).

Despite these realities and the limitations on the effectiveness of inspections to detect flaws, and to guarantee safe structures, the maritime industry has only explicitly addressed fatigue in the design of large bulk ships after 1990. There are concerns that the standard minimum compliance approach to current fatigue design may not be sufficient to ensure reliable and robust structures. Other concerns include the failure to address the combined effects of springing and whipping vibratory phenomena into the new CSR rules. This aspect has been a long standing complaint from sectors of the industry, most recently by the Greek bulk shipping community (IACS, 2006a).

### *2.3.3 Corrosion Rates & Margins*

In the recent past, crude assumptions have generally been made in relation to estimation of corrosion rates for ship design purposes. A number of sources from the literature (Wang et al, 2003b; TSCF, 1992; ISSC, 2007) contain corrosion rate estimates. TSCF typically quote 0.3mm/year general corrosion in seawater ballast tanks.

Figure 2.7. Corrosion Process Model (Paik et al, 2003c; 2003d)

From the early eighties, evidence of a more sophisticated approach has emerged, including phenomological probabilistic models representing the corrosion of steel in a marine environment such as the work done by Melchers (1994). A number of key new studies based on analysis of statistical data from thickness measurements have been presented in the literature, including the model developed by Paik et al (2003c; 2003d), shown in figure 2.7. The Paik theory shows three distinct phases in the corrosion process. In the first phase, the coating remains intact, followed by a transition period in phase two involving initial break down. In the third phase, corrosion proceeds, steel loss occurs and the process may be linear or non-linear. The following expression was given:

$$t_r = C_1 T_e^{C_2}$$

where $t_r$ = corrosion depth (mm), $T_e$ = exposure time (years) after coating break-down ($T_e = T - T_c - T_t$) and $T$ = the age of the structure (years), $T_c$ = the life of the coating (years), $T_t$ = duration of transition (years) which can be taken as zero. $C_1$ and $C_2$ are coefficients.

The coefficient $C_2$ has been estimated by curve fitting of corrosion measurement data from more than 100 bulk carriers and found to be in the range 0.3-1.5, but for practical purposes can be assumed to be 1.0. Based on a fixed value of $C_2 = 1.0$, $C_1$ can be estimated from a Weibull distribution of corrosion data. In other research work, Ivanov et al (2004) have described a linear model of the corrosion process involving four phases. A non linear corrosion wastage model based on the solution of a differential equation originally proposed by Guedes Soares and Garbatov has been validated against corrosion data contained in the ABS database in relation to deck plates of ballast and cargo tanks (Garbatov et al, 2005).

Andreassen et al (1999) quoted a range of corrosion rates for general corrosion in a number of bulk carrier types, obtained from Weibull distributions, which varied according to the structural location. The maximum corrosion rate given for the main deck plating was 0.15mm/year and for the stiffeners in the upper wing tanks it was 0.07mm/year. General corrosion rates in cargo and sea water ballast tanks in FPSOs have been studied by MacMillan et al (2004). The average rate (upper to lower zone) was 0.08 to 0.35mm/year. The average rate in cargo tanks (upper to lower zone) was 0.1 to 0.5mm/year. The authors of this study noted that a temperature increase of 10°C doubled the corrosion rate based on an ambient temperature of 20°C. A number of other factors influencing corrosion rates in low alloy steels were observed including oxygen in sea water, salinity, chlorinity, flow, sulphide pollution, humidity etc.

OCIMF (1997) studies related to oil tankers concluded that, in uncoated cargo tanks, general corrosion rates were typically 0.1mm/year, but in some cases, the corrosion rate was as high as 0.24mm/year involving ships less than 3 years old. Crude oil at high temperatures in excess of 50°C is routinely loaded in the Arabian Gulf. Double hull tankers are known to be susceptible to microbe induced corrosion (MIC) due to the insulating effect of the double bottom and sides resulting in cargo temperatures being maintained for longer periods, as reported by several studies (Thygesen, 2002; Hill and Hill, 1994). In the study referred to above, some OCIMF members reported pitting corrosion rates in the uncoated bottom of cargo tanks as high as 2.0mm/year.

In traditional ship design, corrosion allowances were based on 10 years service life. Corrosion margins were utilised as safety factors, assuming breakdown in tank coating systems. This was a reasonable assumption, since the mean nominal lifetimes of most ballast tank coating systems were approximately 10 years which has been confirmed by several researchers including MacMillan et al (2004) and Towers (1994). Assuming general corrosion rates in sea water ballast tanks described in section 2.3.3, the average wastage in an unprotected 20mm plate over a 20 year period could be as high as 45% of the original thickness. Until recently, classification societies allowed a maximum 20-25% thickness reduction in individual scantlings including plates and stiffeners as a "rule of thumb". Devanney (2006) in his critique of the tanker industry refers to 25% allowable loss in steel thickness as "horribly wasted". However, the overall section modulus of the hull girder was not allowed to degrade to less than 90% of the IACS minimum requirement given in the formula quoted in section 2.2.3. Recent studies (Paik and Thayamballi, 2002a, 2002b, 2003e; 2003f) concluded that when deck or bottom buckling was taken into account in corroded tankers and bulk carriers, these modest margins were often violated unintentionally.

Under Resolution A.744(18) adopted by the IMO on 4th November 1993, a means of monitoring corrosion through "substantial corrosion" was introduced by the classification societies. This was defined as 75% of the allowable wastage. If the wastage limit was 25% of the gross thickness, the substantial corrosion" threshold was reached at 0.25 x 0.75 = 18.75% of the gross thickness. During ultrasonic thickness (UT) measurements carried out in conjunction with Class Renewal Surveys, the substantially corroded areas were recorded. In latter developments, a "condition of class" with a strict time limit was imposed, forcing owners to carry out annual surveys, UT measurements and possible repairs. During vetting inspections, some charterers refused to accept vessels found with substantial corrosion.

With the introduction of the CSR in April 2006, the philosophy for establishing corrosion margins in tanker and bulk carrier structures changed significantly. The "net thickness concept" meant that the strength of the structural members was assessed using the structural capacity in the wasted condition, or net thickness. A general average global hull girder and primary support member wastage was assumed, such that the overall strength of these members was maintained. The corrosion values included in the new rules were obtained from a database of IACS members with more than 600,000 measurements (Yoneya, 2004). The new rules are based on specific corrosion margins stated in the rules, applied to plating and primary support members, and added to the required net thickness. In service, 0.5mm of the corrosion margin has to be retained, being the maximum predicted corrosion loss over the 2.5 year period between the main class renewal (MCR) surveys, as explained by Horn (2005).

The authors of a recent paper on the lifecycle costs of bulk carrier hull structures and the impact of the new IACS Common structural rules (Gratsos and Zachariadis, 2005), presented a impassioned argument for significantly increasing corrosion margins. Reasoning that some class societies had promoted vessel designs requiring steel renewals after 10 years, the authors believed that adequate corrosion margins have a lower life cycle cost per annum. Greek shipping industry experience was said to have indicated that corrosion margins for a 25 year lifetime in the ballast tanks of the Panamax bulk carrier example studied, should be up to 7.5mm in places (e.g. deck and side transverse web plating). This was approximately double the 10 year corrosion margins which were numerically similar to those required by the new CSR. The debate, sometimes acrimonious and with comments largely from the Union of Greek Ship-Owners, was taken to IACS and the records have been published (IACS, 2006a).

In section 5.3, four alternative VLCC designs of similar dimensions will be presented for comparative purposes. The least cost option has a total steel mass of 25,731 tonnes. By contrast, the high quality option has a steel mass of 31,965, an increase of 24.2%. The additional cost of the 6,234 tonnes of steel is roughly USD 12.5 million based on an assumption of USD 2000/tonne for new steel given in section 5.4.1.1. The corrosion margins adopted in the above VLCC designs are 3.5-4.0mm average, or approximately 25% of the gross shell plating thickness (refer to table 5.12 in section 5.4.1.2). This finding is not surprising since it generally corresponds to the IACS wastage allowance for corrosion as discussed in the foregoing sections. A doubling of the corrosion margins in the case of the least cost option VLCC_1, would result in a steel mass similar to that for the high quality option VLCC_4, and an additional cost of USD 12.5 million or about 8.3% of the capital cost of the vessel. In section 3.2.5 product quality related to large bulk ships is discussed. Quality implies performance optimisation and cost minimisation. These objectives are the result of compromise which is the essence of good engineering design. Therefore indiscriminate doubling of corrosion margins due to failure of protective coatings is not seen as good design.

### *2.3.4 Importance of Coatings*

In the 1980s a number of tankers and bulk carriers were constructed with a high percentage of HTS and reduced scantlings. Owing to a combination of mediocre flag state and class society intervention, speculative owners and poor technical management, severe structural problems were experienced (OECD, 2001). The resulting criticism, often directed at class societies, led to the introduction of many changes to the regulations including the amended MARPOL, SOLAS and other IMO conventions.

The new SOLAS Regulation II-1/3.2, applicable from the 1st July 2008, addresses the effectiveness of the corrosion prevention systems in dedicated seawater ballast tanks in all types of ships and the double skin spaces of bulk carriers. From 2000, the segregated ballast tanks of all new double hull tankers must be protected with a light-coloured hard coating such as modified tar epoxy. The Performance Standard for Protective Coatings (PSPC) is designed to provide a target coating lifetime of 15 years. The coating system shall be approved and the application and verification processes are defined in the PSPC standard. The choice of major coating system parameters above the PSPC standards, including surface preparation, number of coats, edge preparation, dried film thickness etc is specified by the buyer. Effectively therefore, the coating lifetime and hull durability is directly controlled by the ship owner (ABS, 1995a; Buxton and Cain, 1994; DNV, 1999; Emi et al, 1994a, 1994b).

These above measures intended to improve the performance of tank coating systems are currently new and there is no database of experience. However, it is expected that the envisaged controls over the application of coatings during new construction will lead to an improvement in coating lifetime which in turn will mitigate the risks of unanticipated coating failures and the subsequent onset of structural problems during the in-service phase. If corrosion is eliminated during the lifetime of the vessel, the intervention measures necessary to deal with the accelerated onset of corrosion-induced fatigue failures will be reduced.

## 2.4 The Regulatory System Affecting Ship Structures

### *2.4.1 Main IMO Instruments*

Figure 2.8 presents an overview of the international maritime system, with the 1982 United Nations Law of the Sea (LOS) Convention at its apex, which came into force in November 1994.

Figure 2.8. Overview of the Maritime Regulatory System (after Soma, 2004)

The LOS Convention provides the regulatory powers assigned in accordance with the zones where the vessel is located. Outside territorial waters, the principle of *res nullius* (belonging to no one) reigns. Under the convention, the IMO is tacitly acknowledged to be the proper body to formulate international maritime regulations for the purpose of protection of the environment and safety at sea, and its role is defined in Article 2 of the 1948 Geneva Convention. The equal and sovereign states which make up the international maritime community are signatories to the various IMO Conventions. Effectively, the law of the sea provisions divide up the regulatory powers over maritime navigation between the respective shipping states. States base their regulatory responsibilities on the principles of international law, utilising the IMO Conventions as instruments (Boisson, 1999).

At the centre of the international maritime regulatory effort is the International Maritime Organisation (IMO). The IMO is a specialised agency under article 57 of the United Nations charter. IMO as an intergovernmental organisation is financed by its 157 member states.

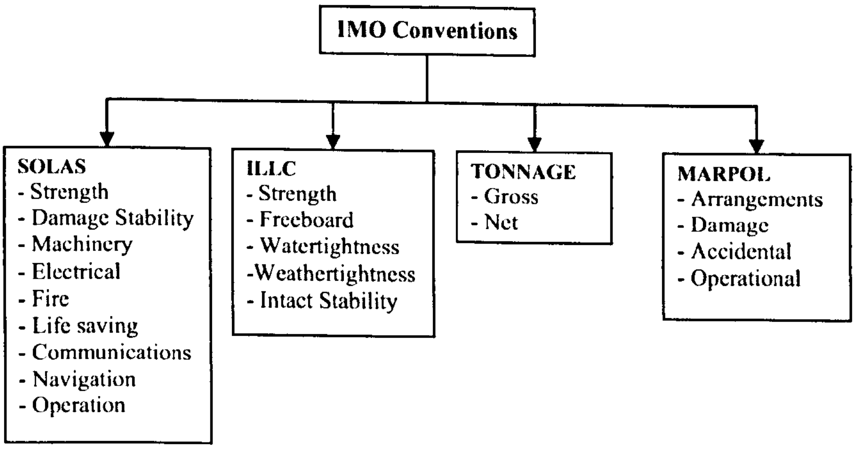


Figure 2.9. Main IMO Conventions

The basic IMO structure comprises the Assembly, the Council, the Maritime Safety Committee (MSC), the Legal Committee, the Marine Environment Protection Committee (MEPC), the Technical Co-operation Committee, the Facilitation Committee and the Secretariat. The MSC is the highest technical body of IMO and is responsible for construction and equipment of vessels (IMO, 2008). Figure 2.9 above shows the main IMO Conventions which are briefly described as follows:

#### *2.4.1.1 SOLAS Convention*

SOLAS Chapter II-1 addresses construction, structure, water tightness and stability. Although it is not widely understood, the SOLAS Convention implicitly mandates the prescriptive structural maintenance standards formulated by the international classification societies. In July 1993, IACS issued Unified Rule Z.10.2 containing guidelines on the "enhanced programme of inspections during surveys of bulk carriers and oil tankers (ESP), originally referred to as MARPOL 13G. In November 1993, the IMO adopted resolution A.744 (18) In 1995, the IMO gave explicit recognition to classification by adopting amendments concerning ships structures into the SOLAS Convention. SOLAS Convention II-1/3-1 requires that "all ships shall be maintained in compliance with the structural mechanical and electrical requirements of a classification society which is recognised by the administration".

Hence prompted by the United States, classification became compulsory from 1st June 1998, making conformance to classification rules a statutory requirement. MSC/Circ.1070 contains obligations to ship owners under SOLAS regulations I/11 and II-1/3-1 chapter IX and regulation I/1 of the 1966 ILLC. The ILLC stipulates that, in order to receive a Load-Line Certificate, a vessel must be of "adequate strength". Consequently, it is a statutory obligation to maintain the ship structure to the standards in the rules formulated by the international classification societies. Evidence of compliance with this obligation is manifested primarily in the main IMO instruments which are the vessels Classification, Safety Construction and International Load Line Certificates (Boisson, 1999).

### *2.4.1.2 MARPOL Convention*

The current MARPOL regulations have had a profound effect on the design, construction and operation of vessels with respect to tank size, and arrangements, hull configuration, subdivision and stability. For tank ships, the MARPOL 73/78 rules have become the principal driving force in the since adoption in the early eighties. Prior to the adoption of Resolution A.744(18) in SOLAS, Regulation 13G of MARPOL 73/78 (as amended) stated that "an oil tanker to which this regulation applies shall be subject to an enhanced programme of inspections during periodical, intermediate and annual surveys, the scope and frequency of which shall at least comply with the guidelines developed by the organisation". Essentially MARPOL 13G(3)(a) contained the same prescriptive requirements contained in the IACS societies survey rules prior to 1993 with three major exceptions. Detailed prescriptive requirements for close-up surveys, UTM and formal requirement for survey documentation to be kept onboard the vessel. Regulation 13G, Annex I of MARPOL, dictates a framework for the progressive imposition of double hull standards for existing tankers.

### *2.4.1.3 The International Load-Line Convention (ILLC)*

IACS can trace its roots to the first International Load Line Convention (ILLC) of 1930. The convention recommended collaboration between classification societies to secure as much uniformity as possible in the application of the standards of strength upon which freeboard is based. The 1966 International Load Line Convention (ILLC) addressed three areas of safety, survey, conditions of assignment and minimum geometric freeboard. The convention comprises a set of important prescriptive regulations which are absolutely fundamental to vessel integrity and safety of design and operation. As stated previously, the 1966 ILLC stipulates that, in order to receive a Load-Line Certificate, a vessel must be of "adequate strength". In a recent paper, Hoppe (2007) explained that "the functional requirement on structural strengths goes actually into quite some detail and has borrowed heavily from the load line provisions in there which basically says that structures will be designed with suitable safety margins to withstand environmental conditions anticipated for the ship's design life and the loading conditions appropriate for them".

### *2.4.1.4 The International Safety Management (ISM) Code*

The International Safety Management (ISM) Code is a direct result of the *Herald of Free Enterprise* and *Scandinavian Star* accidents in 1987 and 1990 respectively. A safety management system is a structured set of controls for managing the business through five basic components; policy, organisation, implementation, measurement and review.

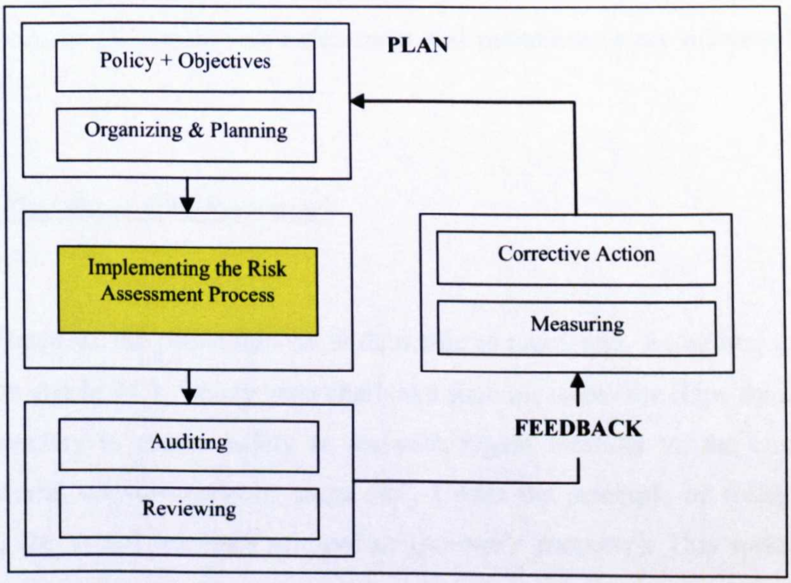


Figure 2.10. Safety Management System

Figure 2.10 above shows the typical safety management system structure. Policy and strategic objectives have to be defined by top management. Organisational structure, responsibilities and resource allocation have to be specified. The risk assessment process provides assurance that hazards are identified and associated risks controlled. Regular audits are conducted to ensure compliance with the SMS. Management has the responsibility of conducting annual reviews (Kuo, 1998; Wang and Trbojevic, 2007). A safety management system is used to ensure that the organisational goals are achieved safely and efficiently. The ISM Code is a safety management system and was introduced into the shipping industry in 1994 to provide an international standard for the safe management and operation of ships and for the protection of the environment.

The code lays down three main goals for safety management, to provide for safe practices in ship operation and a safe working environment, establish safeguards against all identified risks, and to continuously improve safety management skills of personnel ashore and onboard ships. In 1994, the ISM Code was incorporated into Chapter IX of the SOLAS 74 Convention (*Management for the Safe Operation of Ships*). ISM Code element 10 is devoted to the establishment of procedures for the maintenance of equipment and systems. This includes the hull structure, although the ISM Code does not specifically refer to how this should be achieved. Weaknesses in the ISM Code in relation to risk assessment and maintenance are discussed further in section 7.3.2.

### *2.4.2 The Flag States (The Regulator)*

The flag States are the prime movers in their role as regulators. According to the LOS Convention article 94.3, "every state shall take such measures for ships flying its flag, as are necessary to ensure safety at sea with regard interalia to, the construction, equipment and seaworthiness of ships etc". Under the principle of freedom of the high seas, the vessel becomes *res nullius* (no-one's property). This means that no territorial sovereignty can be exercised over it, only the individual powers of the flag State in relation can be applied. "Performance of inspections and surveys onboard ships, or delivery of safety or anti-pollution certificates, by their very nature, cannot be commercial activities". Flag States are able to hide under sovereign immunity under the provision of the LOS Convention, and this fact practically prevents legal action against states that are in breach of their obligations (Boisson, 1999).

Article 94.4 of the LOS Convention places an obligation on flag States to regulate the construction, equipment and seaworthiness of ships flying their respective flags, and to ensure that each ship is surveyed by qualified surveyors of ships. The generally accepted international regulations, procedures and practises contained in Article 94.5 of the LOS Convention related to the regulatory activities of the flag States, are largely satisfied by adherence to classification rules, the IMO Conventions and the individual requirements of the flag States. In figure 2.8 (p.48) , these relationships were shown and it is noteworthy that the international classification societies are commonly delegated by the flag States (the regulator) as recognised bodies responsible for the statutory certification of ships.

In summary, maintenance of large bulk ship hull structures is enforced explicitly through a system consisting primarily of the IMO's SOLAS conventions, and implicitly through IACS URZ10.1 and URZ10.2 calendar based survey rules and procedures applicable to oil tankers and bulk carriers (enhanced survey programme), although the vessel's flag Administration is the underlying guarantor of effective performance of inspections and surveys. There are a number of layers of responsibility affecting the outcomes of what Boisson (1999) refers to, as this "unique and complex system". Flag States generally delegate the authority to survey vessels to classification societies stated in SOLAS Ch.1 Reg.10. The Classification Certificate then becomes the cornerstone of the quality system for ageing ships.

The shipping industry operates in an international domain where local, federal and international jurisdictions prevail. Boisson, refers to the current diversity of sources for the setting of safety standards in the maritime history, a legacy of maritime history. Lack of uniformity, imprecision, complexity and loopholes in regulations are all characteristics of the worldwide maritime regulatory system. They are the product of a difficult compromise between divergent or contradictory interests which pose a threat in the form of future potential unilateral action from individual states.

**Condition Assessment Scheme (CAS):** Following the *Erika* and *Prestige* disasters in December 1999 and November 2002 respectively (refer to section 2.6.2), a number of measures were introduced to improve the maritime regulatory system. Revised regulation 13G of MARPOL 73/79, Annex I adopted by MEPC by Resolution MEPC.95(46) and amended by Resolution MEPC.111(50) entered into force on 5th April 2005, imposing specific requirements on single hull oil tankers. Regulation 13G(6) required that category 2 and 3 oil tankers of 15 years and over after their date of delivery should be subject to the Condition Assessment Scheme (CAS).

The intention behind the statutory requirement of the CAS survey was to independently supplement the requirements of the IACS ESP survey regime required under Resolution A.744 (18) as amended. The CAS survey had to be conducted in conjunction with Main Class Renewal (MCR) Surveys carried out by the classification societies. Following the CAS survey, class surveyors were obliged to issue an Interim Statement of Compliance (SOC) valid for five months, subject to verification by the flag Administration who issue the final CAS Statement of Compliance. In this way, the flag States have been encouraged to arbitrate over the structural condition of the vessel.

### *2.4.3 Classification Societies and IACS Procedures*

In new construction, the classification society is contracted by the builder to provide classification services. Classification services include design review, survey during construction and possibly consulting services across other business areas. Classification rules are generally adopted by ship builders effectively as design codes. This common practice has been criticised (Spencer et al, 1998), a view supported by IACS on its official web site, containing the following restriction: "classification rules are developed to assess the strength and integrity of essential parts of the ships hull etc. Classification rules are not intended as a design code and in fact cannot be used as such". Classification rules include sub-sections containing the prescriptive rules for ship operation and maintenance.

Classification rules are a vital part of the statutory legislation under SOLAS Ch II-I, and compliance with both the ship classification rules of the IACS major societies and the various IMO Conventions is considered essential to provide a safe ship. The condition of the steel structure of ships is subject to the requirements of the international classification societies on the one hand, and to statutory regulations specified in the IMO resolutions on the other hand.

The technical skills possessed by the classification bodies aided by their world-wide service networks has led governments to delegate the public service role of enforcing the regulations contained in the IMO international conventions related to pollution prevention and safety at sea (Boisson, 1999). As a consequence, class societies have become key players in the maritime safety regime, and are often expected to fulfil the duties of the regulator in enforcing the regulations ensuring minimum acceptable structural standards. This dual role played by classification societies in providing classification and statutory services appears to be commonly misunderstood

### *2.4.4 Port State Control (PSC), Voluntary Measures and Insurance*

Increased public and media focus on the environment and recent casualties involving oil tankers has highlighted the phenomenon of substandard shipping. Gray (2000) traces the origins of port State control (PSC) in the United States with the break up and spill of 30,000 tons of fuel oil from the *Argo Merchant* off Nantucket Island in 1976. This was followed by the grounding of the oil tanker *Amoco Cadiz* off Brittany spilling 220,000 tons of crude oil, leading to the first true PSC agreement known as the Paris MOU. In International law and under the dual arguments of the right of self protection and the international policing of navigation, the port States exercise their duties to enforce the application of international conventions on safety at sea and prevention of pollution. Knapp (2004) has outlined the various coastal State safety regimes currently in effect in table 2.2. Negligence and leniency by flag States has led some coastal States to act, resulting in harsh policing of substandard ships and owners (Boisson, 1999).

Table 2.2.Coastal State Safety Regimes (Knapp, 2004)

The Parliament of the Commonwealth of Australia (1992) published a land mark report entitled *Ships of Shame*, in response to the mysterious loss of six bulk carriers in quick succession off the Australian coast in the period January 1990 to August 1991.

According to Hare (2003), this study was the catalyst for maritime authorities around the world to "sit up and take notice of the malaise permeating the industry". The 1982 Paris MOU required each contracting authority to conduct inspections on 25% of foreign merchant vessels calling at its ports, acting under detailed guidelines regarding inspection procedures and detentions. Detention lists were published and PSC has evolved as the principal indicator of classification society performance in terms of detention rates. In a recent paper, Gray (2000) concluded that in-port inspection of ships during cargo operations by PSC officers revealed "next to nothing about structural condition". A number of voluntary measures have evolved in response to shipping accidents and the sub-standard ship syndrome referred to earlier, including the condition assessment programme (CAP) and vetting inspections described in the following:

**CAP Surveys**: In ISSC (2007), the background for the introduction of the condition assessment program introduced by DNV in 1989 was discussed. CAP surveys were introduced prior to the enhanced survey program (ESP) in response to a requirement by the industry for an independent estimation of ship condition. CAP was a systematic means of quantifying a vessels condition in accordance with a rating scale. This was a service performed by classification societies, independent from and complementary to classification. CAP could be applied to vessels which may or may not have been classed by a society. CAP covered hull, machinery, electrical, cargo and ballast systems. CAP normally included a fatigue assessment. CAP was intended to evaluate and report on the vessels condition in relation to the minimum class standard. The scope was more comprehensive than that for class surveys with respect to analysis of thickness measurements, structural strength evaluation, and reporting. CAP surveys were covered by a separate contract with the owner.

**Vetting Inspections:** The pattern of tanker ownership changed during the 1970s-1980s. The move away from independent ship-owners with substantial fleets resulted in a drop in quality of vessels. The Oil Companies International Marine Forum (OCIMF), commenced with ship vetting inspections at that time, based on OCIMF developed inspection guidelines. The intention behind vetting inspections was to provide OCIMF members with a reliable view of a vessel's suitability for charter purposes (see the loss of the oil tanker *Erika* in section 2.6.2). The ship inspection report programme (SIRE) was also developed as a project under OCIMF supervision. For some years, the vetting inspectors proactively enforced additional controls on the industry. In the event that "conditions of class" imposed by classification society surveyors were found during routine vetting surveys, a vessel on the spot market was occasionally prevented from loading due to the vetting inspector's report.

**Insurance:** The role of underwriters and insurers is of particular importance. Without insurance, vessels could not sail or enter foreign ports. P&I Clubs covering ship owners' third party liability applied premiums based on claims records. Risk profiles were usually linked to the premium levels and "deductibles". The largest insurers set up their own vessel inspection systems to verify the quality of ships they were about to insure. In 1993, the joint hull committee of the London Underwriters established clauses JH115 and JH115A in their "structural condition warrantee (JH722). Eighty percent of surveys conducted by the Salvage Association surveyors on behalf of the underwriters in 1993 resulted in major repairs (Boisson, 1999).

### 2.4.5 Problems With Current Regulatory Controls

The international maritime industry is characterised by an extreme diversity in stakeholder interests including insurance companies, intergovernmental organisations, maritime legal institutions, professional bodies, maritime universities, maritime unions, meteorological and hydrographic organisations, and society itself. The emergence of flags of convenience, some of which appear to have failed to live up to their obligations under the international conventions, has tended to aggravate this phenomenon. In her study, Knapp (2004) criticises the complexity of the maritime safety regime. The legal framework is said to be created by the UN, ILO and IMO, supported by country specific legislation. Classification societies provide technical expertise during construction and operation of the vessel. "The line between the ship owner, operator or technical manager of the vessel is not completely clear in shipping and therefore complicates enforcement of the legal instruments". It seems clear that compliance with classification rules and statutory conventions is a prescriptive and minimalist approach.

Prescriptive regulation is seen to be commercially safe providing a degree of assurance for a given design. Compliance is also easier to verify. A major motivating factor in devising new prescriptive regulations has been based on analysis of past marine accidents. In a recent paper, Vassalos (2007) observed that the tendency to make compromises over economy and technical performance means that safety is often restricted to rule compliance only, and is therefore a constraint in the design process. This approach is seen to be associated with two major misconceptions, that investment in safety compromises financial returns and compliance with prescriptive rule minimum standards is deemed to be appropriate. In a recent critical review following the *Erika* disaster, the OECD (2001) summarised the weaknesses in the current regulatory system. In particular, the failure of charterers and shippers to accept liability for oil pollution damage involving oil tankers was identified as a leading case of substandard vessels (see section 2.6.4 for post *Erika* developments in this regard).

## 2.5 Structural Integrity Management

### *2.5.1 SIM in the Context of Ship Structures*

Structural integrity management (SIM) is a term borrowed from the offshore oil industry. The SIM approach to offshore structures is contained in the ISO standards 19901 (2002) and 19902 (2004), which recommend structural integrity management systems for major structural components of all types of offshore structures and vessels ISSC Committee III.2 (2006). ISO 19904 covering floating offshore structures used for the petroleum and natural gas industries is currently under development and the version reviewed was a draft international standard (ISO/DIS 19904, 2004). ISO 19904 is significant, as it contains lengthy guidance on condition monitoring, based around a structural integrity management system. The SIM system then becomes the framework within which fitness in service is monitored and maintained.

Structural integrity management of ships is usually thought of in terms of classification rules. Early studies (Liu and Bakker, 1981) investigated technical and economic aspects of hull structural repairs from a first principles approach. In shipping, it is commonly believed that SIM aspects are covered explicitly by compliance with classification society rules, and implicitly through compliance with the IMO statutory conventions relating to hull integrity, covered in section 2.4.1. In 1993, the implementation of IMO Resolution A.744 (18) for bulk carriers and introduction of the ISM Code requiring ship owners to formalise onboard maintenance procedures was the incentive for the trend towards a planned maintenance system for the hull structure in excess of the minimum regulatory requirements, and this is described further in section 7.3.1.

Prior to the early 1990's, voluntary owner-driven SIM systems for ships were virtually unknown, and despite the current widespread availability of the technology, only a few owners had implemented truly integrated proactive SIM measures, as discussed by Bea (1992) in SSC-365. Two studies which appeared in the public domain one year ahead of the mandatory enhanced survey programme (ESP) introduced by IACS in 1993 are described in the following section.

### *2.5.2 Review of Selected SIM Studies*

**Brooking & Barltrop (1992)**: Brooking & Barltrop considered structural safety of ships as a concern given the prevailing commercial pressures leading up to the early 1990's, including "low freight rates and fierce competition", ahead of the introduction of IMO Resolution A.744(18) in 1993. They proposed a ship structural management system (SSMS) designed to provide constant assessment of ship structures in order to identify defects and failures to ensure that a minimum level of structural safety was maintained. Figure 2.11 shows the structure of the SSMS.

Figure 2.11. Ship Structural Management System (SSMS)
(Brooking & Barltrop, 1992)

**Melitz, Robertson and Davison (1992)**: In the early 1990s, Melitz, Robertson and Davison introduced a risk-based approach using fatigue and fracture mechanics principles, incorporating offshore technology in a ship structures application. All of the co-authors were employed by BP Shipping Limited and members of the fleet technical department. The authors recognized "an opportunity for developing a strategy to more comprehensively and more objectively examine the structural ageing process in a class of vessel". Work was commenced in about 1990. The concept of a full-scale structural monitoring system was said to have developed in 1989. The strategy consisted of three main components: enhancement, inspection and monitoring.

Experience with structural problems across a mixed fleet of tankers and other types of vessels, and largely founded on a "new method" proposed by Bishop and Price, a core "risk-assessment procedure" was formulated. The structural design basis was classification society rules and a wave bending analysis including dynamic loading, a corrosion sensitivity study, a fatigue durability study and evaluation of crack growth rates for sensitive structural locations using fracture mechanics. Complex risk analysis procedures were not considered to be appropriate. Longitudinal member scantlings were based on rule values. A 3D FEM analysis was conducted against classification rules using a 1.5 tank length structural model and conventional static considerations for transverse member strength assessment. The authors described a new approach to wave bending analysis involving quasi-static wave bending, dynamic response of the hull girder to wave frequency loading ("springing") and to bow impact events. Melitz et al were overtaken by events after 1993 when the major international classification societies introduced sophisticated computerised structural assessment systems capable of conducting the types of structural evaluation attempted. This was confirmed during an interview with Melitz in 1997.

**Bea et al, University of California at Berkeley (1990-1995):** During the period 1990-1995, the Department of Naval Architecture and Offshore Engineering at the UCAL, conducted the *Structural Maintenance for New and Existing Ships Project* under the direction of Professor R.G. Bea. Sponsors included the SSC and the USCG. The technical objectives were to develop practical tools and procedures for analysis of ship structural repairs and to provide guidelines for cost effective design and construction of "lower maintenance" ships structures to facilitate inspections, maintenance and repair. Part of the objectives was to provide an open forum for the industry to develop new and innovative strategies for the design and maintenance of ship structures. Most of this research effort involving hundreds of pages of published work was made available on the SSC website. The project had three phases, SMP I, SMP II and SMP III. Table 2.3 outlines the objectives in each study.

In 1992, the Ship Structure Committee (SSC) published report no SSC-365, describing a procedure for the development of a marine structural integrity program (MSIP) for commercial ships, with particular emphasis on oil tankers. This substantial work was said to be the fruit of many interdisciplinary groups, national and international meetings with key individuals, and field trips to ship construction and repair yards. The motivation was said to be "the result of recent extreme political and public pressures being brought upon regulators, owner's operators and classification societies, along with environmental concerns relative to crude carriers".

Table 2.3. Scope of MSIP Studies (Bea, 1992)

Citing extreme cost cutting and manpower reductions in the maritime industry, a legacy of the 1980's economic slump, Bea refers to a crisis in terms of poor structural performance of tankers, succumbing to the combined effects of fatigue and corrosion (Bea, 1992, 1993, 1994a, 1994b). In order to formulate a framework for an advanced MSIP, Bea carried out an in-depth assessment of the airframe structural integrity program (ASIP) in the United States for both commercial and military aircraft. A number of ASIP applications to MSIP were identified (Dry et al, 1996; Schulte-Strathaus and Bea, 1994b). The components of the advanced MSIP are shown in figure 2.12.

Bea's vision for a comprehensive owner-driven SIM system based on a common platform appears to have been overtaken by events. New software products recently developed by the leading classification societies described in sections 2.5.5 and 7.5.1, now appear to offer equivalent solutions. The development of these tools has been achieved in a relatively short time frame following the *Erika* and *Prestige* disasters, driven by outside pressure and industry self-recognition that the quality of procedures required to monitor hull structures in service needed to be improved..

Figure 2.12. Components of the Advanced MSIP (Bea, 1992)

**USCG Critical Area Inspection Plan (CAIP):** Due to the high frequency of fatigue cracks found in the vessels operating on the Trans-Alaska Pipeline (TAPS) service, the United States Coast Guard introduced a requirement for a critical area inspection plan (CAIP) specifically for these vessels (USCG, 1999).

**Chevron Shipping**: Chevron Shipping recognised the need for an owner's computer aided maintenance system in the early nineties when they developed their own in-house system, computer-aided tanker structure inspection and repair system (CATSIR). Ternus (1991) in describing the CATSIR system, states that classification rules "cannot be used as a guide for a maintenance program which will ensure that a ship can be operated for an extended number of years at reasonable cost."

**Lacey and Chen (1995):** In mid 1992, Arco Marine initiated a structural monitoring program in conjunction with Ocean Systems Inc. This involved a fleet of 10 tankers engaged in the Alaska to US crude oil trade to US west coast ports. The focus of the Arco investigations was primarily on the transient response phenomena associated with hull slamming and hull girder response (springing and whipping), with possible reduction of hull girder fatigue life. The Arco study concluded that slam induced high frequency whipping vibrations could significantly amplify mid ships wave bending moments, exceeding the class rule allowable value in typical seas under normal loading conditions. Further, slam-induced high frequency stresses were found to be an important contributor to structural fatigue damage, reducing the nominal fatigue life by up to 30%. This subject has been extensively discussed in section 2.3.2. It was noted that classification rules did not explicitly account for slam-induced loads and hull springing phenomena when computing fatigue life. The safe operating envelope concept developed by Arco provided ships captains with valuable operating guidelines reflecting company policy and actual operating experience obtained on a particular ship.

**Witmer & Lewis (1995):** Witmer & Lewis published the findings of a four year study involving structural monitoring for the Trans Alaska Pipeline Services (TAPS) tankers shipping crude in the North Pacific and Gulf of Alaska, from Valdez to North Pacific east coast ports and Hawaii. These six ships commissioned in 1977-1979 were constructed by Avondale Shipyards and included the *SS Thompson Pass*, *SS Keystone Canyon*, *SS Atigun Pass* and *SS Brooks Range*. The vessels were built entirely from AH-36 steel under ABS class. The Witmer & Lewis study is actually an extension of the BP Shipping effort commenced by Melitz et al (1992) referred to earlier. The objectives of the study were related to the structural monitoring aspect of the previous work. The authors stated that the hull stress monitoring system (HSMS) installed on the Atigun Pass tankers, had become an integral part of the company's tanker fleet structural management program. "The units have greatly increased the awareness of the ship's officers regarding their role in helping to control the amount of structural damage done to the ships. A substantial effort was made through the study and investment in technology intended to provide feedback and guidance to the master & crew in relation to improved ship handling and weather avoidance as a means of mitigating structural damage".

### *2.5.3 Structural Surveys of Large Vessels*

Structural surveys routinely performed on VLCCs or VLBCs represent a hugely challenging and almost impossible task for a single surveyor to effectively survey the vast internal structures in the time available. The difficulties involved in inspecting large bulk ship structures have been described in a number of studies including

Thygesen (2002) and Demsetz et al (1996). A VLCC has typically 15 centre cargo tanks each measuring approximately 50m in length, and 30m depth, and 10 wing ballast tanks, each 50m in length and 30m depth. Cargo holds in VLOCs are of similar scale. In tankers, crude oil sludge is difficult to remove, depending on the characteristics of the cargo. Crude oil and hot water washing are used to improve the cleanliness of tank surfaces prior to conducting Main Class Renewal (MCR) Surveys. In ballast tanks, mud and scale are difficult and expensive to remove. If corrosion is not removed from corroded surfaces by hydro or grit blasting, the surface condition makes ultrasonic thickness measurement impossible or unreliable due to the build up of heavy corrosion scale, possibly up to 5-10mm thick.

The Demsetz study referred to earlier used benchmarked inspection data, and found that inspection performance varied greatly, depending upon the location in the vessel, indicating the importance of access, lighting and cleanliness. Poor lighting was thought to affect the "readily detected" crack size based on Probability of Detection (POD) curves. Jubb (1995) identified the absence of a quality system for visual inspection of bulk carrier structural condition and noted the differences between inspection philosophies for commercial aircraft compared to commercial ships, pointing to a lack of understanding of the importance of visual inspections and structural welding details in the maritime industry.

Re-capping from section 2.3.2, the *fail-safe/damage tolerant* approach is the basis for contemporary large bulk ship structural designs, wherein it is assumed that undetected flaws of small size will not lead to significant structural consequences. The underlying assumption in fail-safe design is that cracks of detectable length (critical defect size) will be found during regular calendar based surveys in tanks (every 2.5 years). Because the crack initiation period in as-welded steel joints is insignificant due to the existence of welding defects, crack growth is initiated in the very early stages of the structural lifetime. The weakness in the *fail-safe/damage tolerant* approach lies in the practical difficulties encountered in the effective inspection of large ships structures, and this difficulty has been borne out by the number of incidents involving undiscovered structural failures reported in the literature survey conducted in chapter 2.

### *2.5.4 Assessment Criteria*

The calendar based prescriptive requirements for survey of oil tanker and bulk carriers structures can be found in the rules of the IACS classification societies. The rules detail the scope and extent of overall and "close-up" (arms length) surveys and hull thickness measurements required in tanks during Annual, Intermediate and Main Class Renewal Surveys (Special Surveys). The survey scope increases with the age of the vessel and after the second Special Survey (10 years of age), the scope increases substantially, depending on the condition of the tank coatings. In table 2.4 the IACS UR Z10.4 close-up survey requirements are listed for a double hull tanker at the third Main Class Renewal (MCR) Survey (IACS, 2006b). These criteria have been explained in a study by Hoppe (2002).

Table 2.4. DH Tanker, Minimum Requirements for Close-Up Surveys
(DNV, 2008)

The IACS criteria also list the thickness measurement requirements associated with the respective MCR surveys. After the *Erika* disaster, the Intermediate Survey scope for oil tankers more than 10 years of age was increased to a similar extent to that of the Renewal Survey, so effectively major hull surveys are conducted at nominal intervals of 2.5 years. Although the IACS survey scope has progressively increased in response to recent accidents including the *Erika* and the *Prestige*, these calendar-based surveys are considered to be minimum standards in relation to effective hull maintenance (Ternus, 1991).

### *2.5.5 New Developments in SIM Products*

In the early 1990s, a number of the leading IACS classification societies introduced computerised rule formulations and software-supported structural assessment systems, allowing easy public access to these powerful solutions. Nearly two decades on, these tools are increasingly being adopted by the industry, and afford a means for rapid preliminary structural design assessment based on the data contained in the key structural drawings including the Mid Ship Section. These software tools at the most basic level, contain routines for rule check of section scantlings, buckling analysis, ultimate limit state (ULS) check of hull girder capacity and fatigue analysis.

***Mars Rule 2000*** from Bureau Veritas, is intended for calculating scantlings of plating and ordinary stiffeners of any transverse section based on Bureau Veritas Rules for Classification of Ships and IACS CSR for bulk carriers and tankers. Mars Rule 2000 includes fatigue checks for structural details. The program is available as freeware on the internet (http://www.bureauveritas.com).

***Nauticus Hull*** from DNV Software is DNV's solution for strength assessment of ship-structures, both for design and verification. Nauticus Hull contains a basic rule check package with the option of advanced systems for wave load and finite element analysis. Nauticus hull features Brix Explorer as the main entry point to Nauticus Hull programmes and the FEM package contains the user interface GeniE (http://www.dnv.com).

***Poseidon ND*** from GL is intended for fast modelling of the hull structure through the program module *Hull Wizard* which automatically generates the typical structural topography of mid ship sections by selecting key parameters defined by the user. Poseidon ND automatically determines scantlings based on rule requirements applicable to the respective vessel parameters, rule requirements, class notations, global loads and sea pressures. *Poseidon ND* automatically generates an FEM model of the ship structure defined by the modelling and scantling phases. The FEM analysis is performed by the programme *GL-FRAME* (http://www.germanlloyd.org).

***PrimeShip-HULL*** from ClassNK is described as a revolutionary new way to conduct advanced ship strength structural assessments. *PrimeShip-HULL* covers direct strength analysis, fatigue strength and ultimate hull girder strength assessment. The background to the development of *PrimeShip-HULL* and the description of the effort by ClassNK to propose rational, accurate and practical methods of strength assessment and to simplify the set of design loads have been published previously (Yoneya et al, 2004).

***RULESCALC 2008*** is the latest version of a software tool intended to enable ship designers to rapidly assess structural designs against Lloyds Register rules and regulations for ship classification and the IACS CSR. In 2006, LR released *RulesCalc* and *ShipRight* structural design assessment (SDA) tools in conjunction with the official publication of the IACS CSR. *RulesCalc* and *ShipRight,* ensuring compatibility with LR's software interface tool, claimed to allow designers to seamlessly import industry standard structural data such as from NAPA and Tribon (http://www.lr.org).

***SafeHull*** . The development of the ABS *SafeHull* system has been fully described in several published works including (Chen et al, 1998), (ABS, 1997). The first part of the system is the newly developed strength criteria. The second part is said to be the software supported development of initial scantlings preceding the more detailed strength assessment. A finite element solver is fully integrated into SafeHull. Alternatively, other FEM programmes such as *NASTRAN* can be linked directly to the *SafeHull* application, allowing seamless integration into established shipyard design and production systems. *SafeHull* is said to be a fully integrated structural design system (http://www.eagle.org).

### *2.5.6 Information Resources*

Prior to 1993 when radial changes took place in the developments associated with the regulation of ships structures discussed in section 2.4, and preceding the advent of the internet in 1989, information relevant to ship structures was obtained largely through published papers and journals. Today, virtually unlimited access to published information is available through the web and electronic media. In late 2008, the researcher is struck by the sheer volume of information on ship structures technology available to the industry in the form of published material, technical material produced by The IMO and non-governmental institutions.

The Ship Structure Committee (SSC) was formed in 1943, principally to research the brittle fracture problem which plagued welded ships during the WWII years. The SSC (http:///.www.shipstructure.org) is one of the most prolific sources of information available today with over 503 published reports dating back to 1946, most of them available on line. The SSC currently comprises eight member organisations: ABS, the US Maritime Administration (MARAD), the Maritime Sea Lift Command (MSC), NAVSEA Structures, the Canadian Defence Research & Development Atlantic (DRDA), Transport Canada, the USCG and SNAME. A second major source of information is the IACS member societies. These organisations provide important research papers, often published in international journals.

In section 2.5.2, Bea, one of the most prolific workers in the field of ship structural integrity research in recent times, in summing up the results of a 5 year long intensive research effort conducted by the University of California at Berkeley, stated, "the primary problems associated with the commercial ship industry are not fundamentally technical. Basically the industry has the technical background to do what is required to achieve durable and reliable ship structures. The primary problem is that in the majority of cases, this technology is not being wisely used or applied" (Bea, 1993).

## 2.6 Significant Structural Failures

### *2.6.1 The Bulk Carrier Problem*

Although a few industry spokespersons have publicly defended the safety record in the maritime industry including Iarossi (2003) and Curry (1998), the twenty year period from the late 1970s through to the late 1990s was characterised by a number a casualties involving bulk carriers. With media focus primarily on the safety of the environment and oil tankers, catastrophic accidents involving bulk ships often leading to considerable loss of life, appeared to pass relatively unheeded. Some industry insiders campaigned against these negative trends. Jubb (1995) remarked that "hundreds of seamen have died and continue to die in bulk carriers subject to hull failure. This is a scandal which merits public discussion and international pressure to bring these losses down to a minimal and acceptable level" Subsequently, the full impact of this serious problem became more apparent when accident statistics from various sources were published in the literature.

Table 2.5. Bulk Carrier Casualties 1978-2001 (Vassalos et al, 2002)

In a study on the impact of IACS Unified Rule UR21 on existing hatch covers, Vassalos et al (2002) observed that from 1978 to 2001, a total of 43 bulk carrier casualties involving hatch cover failure in heavy weather were recorded, 13 of which resulted in 325 fatalities, as summarised in table 2.5. Citing Lloyds Maritime Information Services (LMIS) from September 1980 to end 1991, Boisson (1999) concluded that there were approximately 280 bulk carrier accidents with the loss of over 800 lives. In a study on strength and reliability of ageing bulk carrier structures, Paik and Thayamballi (1998) reported 1,278 lives lost and a total of 186 bulk/combination vessels from 1980 to 1996.

In the early 1990s, a sharp peak in losses heightened concerns about the safety standards for these types of vessels. In 1992, following the crude tanker *Kirky* disaster, an Australian government inquiry (Parliament of the Commonwealth of Australia, 1992) concluded that unilateral and international efforts were necessary to improve the safety of shipping and reduce the risk of damage to the environment. The catalyst for the inquiry was the loss in close succession over a 19 month period between January 1990 and August 1991, of six bulk carriers including *Mineral Diamond* off the Western

Australian coast. Frequent bulk carrier losses in the early nineties led the IMO to initiate a number of procedures intended to improve the ship inspection regime, resulting in a new chapter XII in the SOLAS Convention. IACS also initiated a number of research programmes after 1991, and a set of unified rules were developed, including UR S17 for longitudinal strength and UR S12 for the side structures of single skin bulk carriers. In the following, the loss of the *OBO Derbyshire* will be discussed due to its significance.

***The Derbyshire:*** The *Derbyshire* (ex *Liverpool Bridge*), ship no.57, the last of a class of six vessels built by Swan Hunter at Wallsend Yard in 1970-1976, was a UK flagged Capesize Oil/Bulk/Ore carrier. The vessel was of double hull construction and remarkable size, being 281.94m in length, 44.20m breadth with nine cargo holds. In 1980, loaded with 158,000 tonnes of fine iron ore concentrates distributed in seven of the nine holds and en route from Canada to Japan, severe weather (typhoon *Orchid*) was encountered, and the vessel was lost with all hands (44 people) near Shikoku Island, Japan. As the vessel was lost in deep water and there were no survivors, much speculation surrounded the loss of the *Derbyshire* and in 1986, the UK Department of Transport issued a report, concluding that the most likely cause was "total structural failure". Structural problems affecting several ships of the same class led to further speculation fuelled by rumours of poor construction practises (Faulkner, 2001).

Led by the Derbyshire Family Association (DFA), and supported by the International Transport Workers Federation (ITF), a series of underwater surveys were conducted the first of which was in May 1994. In 1995, Lord Donaldson was appointed to lead a formal inquiry with the goal of finding the possible cause in the interests of ship safety and further underwater surveys of the wreck site in April 1997 were conducted. A detailed independent forensic analysis of the loss of the *Derbyshire* has been published by one of the appointed UK assessors in the survey of the wreck site (Faulkner, 2001). He concluded that the loss of *Derbyshire* could be attributed directly to a weakness in the structural design of the hatch covers. His findings included a recommendation for a substantial revision of the 1966 ILLC requirements related to hatch cover strength in view of the deficiencies discovered in the design hatch coaming loads and safety factors. Faulkner concluded that the use of Grade A steel could lead to brittle fractures in structures under dynamic wave conditions, a view supported by Jubb (1995).

Historical weaknesses in the structural designs of bulk carriers are well documented in the literature (Grove et al, 1998; Faulkner, 2001; IMO, 2002b; IMO, 2003; Paik and Faulkner, 2003b). In a FSA study on bulk carriers carried out by Japan under MSC/75/5/2, data from ClassNK, suggested 68 instances of hull structural failure in bulk carriers under 20,000 dwt, during the period 1990-1997. Paik et al (2003b) in a re-assessment of the *Derbyshire* sinking recommended a 20-30% increase in the IACS UR S11 standards for wave bending moments. The revelation that the "surprisingly weak bottom structure" of a Capesize bulk carrier may be inadequate in hogging response exposed the dangers in relying solely on allowable stress design, raising the spectre of "jack knife" collapse of the hull girder as a possible cause for the loss.

Figure 2.13. F-N Curves for Bulk Carriers (IMO, 2002)

With the above examples of flaws in the design of bulk carriers, the further deleterious effects of fatigue and corrosion in these already sensitive structures are obvious. The main problem areas have been identified as the hold side frames, cross deck structures, corrugated transverse bulkhead, fore and aft transition zones and hatch covers.

The flexibility of the bulk carrier structural design having no longitudinal bulkheads to support the double bottom differs radically from that of the much more rigid tanker structure. The criticality of the no.1 hold side frames and the consequences of water ingress leading to a domino like collapse of the corrugated bulkheads are well documented in many sources in the literature including Contraros, (2003). In figure 2.13, reproduced from the Japanese FSA study into bulk carrier safety MSC 75/5/2, the F-N curves show that the safety performance particularly for Capesize bulk carriers appears to be quite marginal.

### *2.6.2 Recent Tanker Disasters*

Tanker loss statistics from 1991-1995 show that more than 80% of accidents involve ships more than 15 years old. Fires and explosions accounted for almost half of all accidents (Boisson, 1999). The safety focus on oil tankers is usually related to oil pollution and environmental damage. The first major oil spill in history was caused by the Liberian tanker *Torrey Canyon,* which grounded as a result of a navigational error off the coast of Cornwall near the Scilly Isles on 18th March 1967. The amount spilled was 119,000 tonnes and it caused severe environmental damage on the UK and French coastlines. The worst ever oil spill from a tanker was that involving the *Atlantic Empress* off Tobago West Indies in 1979 with a spill of 287,000 tonnes.

In 1983 the *Castillo de Bellver* spilled 252,000 tonnes of oil off Saldanha Bay South Africa. On 16th March 1978, the Liberian tanker *Amoco Cadiz* grounded off Porsall in Brittany due to steering gear failure, spilling 223,000 tonnes of oil. In March 1989, *Exxon Valdez* grounded in Prince William Sound in Alaska. Although the amount of oil spilled was only 10% of that involving *Amoco Cadiz,* eleven years earlier, the massive media attention sent shockwaves through the maritime industry and resulted in an amendment of the MARPOL Convention. In 1990, *Surf City* exploded and sank off

Dubai with loss of life and environmental damage. In 1991, there were 3 large oil spills involving tankers. The *ABT Summer* spilled 260,000 tonnes about 700nm off Angola. The *Haven* spilled 164,700 tonnes off Genoa and the previously mentioned *Kirki* was responsible for 20,300 tonnes of oil spilt off Western Australia.

Table 2.6. Selected Major Oil Spills Involving Structural Failure
(Devanney, 2006)

Devanney (2006) concluded that a number of accidents involving oil spills from ships allegedly related to hull failure, and these are listed in table 2.6. More recently, the *Erika* and *Prestige* spills have been the latest incidents.

The tanker industry often suggests that 99.9986% of all oil cargoes loaded into tankers arrives safely (Slater, 2000; Iarossi, 2003) and that the industry is fundamentally a safe one. Despite the convincing evidence showing that the safety performance of the bulk shipping segments continues to improve, public, media and some industry insider perceptions apparently continue to decline. According to the International Union of Maritime Insurance, since 1993, only 12% of major ship casualties were said to be traceable directly to structural integrity problems (Boisson, 1999). This claim was contested by some industry insiders including Devanney (2006), who hypothesised that structural failure is a major and hidden cause of vessel losses. In the following, a number of high profile accidents involving structural failure in tankers are forensically examined to test this assertion further.

***Betelgeuse***: In 1979, the *Betelgeuse* was discharging cargo at Gulf Oil's Bantry Bay terminal when it exploded and broke into two. A sworn public inquiry was conducted under a high court judge, eventually blaming the owners, Total Oil and the classification society BV, for the accident. The *Betelgeuse* was said to be in an appalling condition. An inspection of the tanker nine months before the explosion revealed 37 cracks in its crude oil tanks. A major oil leak had been reported to the ship's owners one week before the disaster. Ballast tanks were so badly corroded they could have been a possible cause of the explosion. The tribunal revealed that "the cause of the disaster was the buckling of the ship's structure at about deck level; followed by explosions in the permanent ballast tanks and the breaking of the ship's back" (Irish Examiner, 8th January 2004). "Horribly corroded segregated ballast tanks and lack of an inert gas system contributed to the accident" (Devanney, 2006).

**The *Surf City*:** In February 1990, just prior to the invasion of Kuwait, the US flagged 81,283 dwt tank ship *Surf City* loaded with naphtha and automotive fuel outbound from the Arabian Gulf, exploded and burned north of Dubai UAE. The conflagration claimed the lives of the master and chief mate who had entered the No.4 (S) ballast tank immediately prior to the accident. The spill volume was estimated to be 28,000 tonnes and the vessel was declared a total constructive loss. The subsequent official National Transportation Safety Board (NTSB) report stated that naphtha vapour was found in way of No.4 (S) ballast tank (supported by 3 independent crew observations), and that the most likely source was through a fracture in the common transverse bulkhead between No.5 (S) cargo tank and No.4 WBT. According to the report, USCG inspectors involved with re-flagging the vessel during the Iran-Iraq war, had observed a generic problem affecting the structural integrity of 4 sister vessels including the *Surf City*. The problem was related to repetitive cracking found in No.2 and No.4 WBT's. Two months prior to the accident, the former chief mate testified finding 3 fractures in 12.5mm plating of No.4 (S) tank stringers at bulkhead No.52 (NTSB, 1990).

**The *Erika:*** The *Erika*, (Ex *Shinsei Maru*, 1975 and ten previous names) was a 37,283 dwt products/crude carrier built by Kudamatsu Shipyard of the Kasado Dock Co. Ltd. (hull no.284) in Japan (1975). Second in a series of 8 oil tankers built between 1974 and 1976, *Erika* was used to carry heavy oil. The vessel had multiple owners and several flags, generally open register. On December 11th 1999, during loaded passage from Dunkirk to Leghorn (Italy), approximately 30 miles south of the Pointe de Penmarc'h in Brittany, the vessel suffered a catastrophic structural failure and sank in

120m of water. At the time, the vessel was loaded with 30,884 tonnes of No.2 heavy oil.

Figure 2.14. Loss of The *Erika*

At the time of the accident, the vessel was 24 years of age (approaching the 5th special hull survey). As built, the *Erika* was fitted with 15 cargo tanks (13 + 2 slop tanks). Only no.3 centre tank was a dedicated ballast tank. In view of the construction date (1975), the vessel was considered as pre-MARPOL (i.e. single hull without segregated ballast tanks). In 1990, No.2 (P+S) cargo wing tanks and No.4 (P+S) cargo wing tanks were converted to clean ballast tanks (CBT). In 1993, No.2 (P+S) CBT's were converted to segregated ballast tanks (SBT's). In 1998, No.4 (P+S) CBT's were converted to SBT's at Bijela Shipyard (BEA/MER , 1999).

From the official French agency Bureau d' Enquetes sur les Accidents en Mer (BEA) report, structural surveys had been carried out by class immediately prior to the loss of the vessel. The BEA report states that three different flags (Panama, Liberia and Malta), 8 different vessel names, 4 different class societies (NK, ABS, BV and RINA) and 4 different ship managers had been involved since 1975. The last major steel repairs in tanks were carried out during the special survey required for transfer of class from BV to RINA at Bijela Shipyard in June-August 1998, 16 months before the loss of the vessel. The total amount of steel replaced was 100 tonne (approximately 1.4% of the vessel's lightweight). Some of the main deck plating of original thickness 16.0mm was renewed using 14.0mm thick plating (12.5% less than the original thickness). According to the official findings of the BEA/MER report, the total loss of the *Erika* could be attributed to the following:

- The rupture of an element of the LBHD between No.3 centre tank and No.2 S ballast tank.
- The subsequent weakening of one on more transverse webs in No.2 S ballast tank, leading to the appearance of cracks in the side (shell) plating.
- The appearance of cracks in the deck plating resulting from the weakening of the transverse web frames.

These events are thought to have brought about a gradual collapse of the side structure in way of No.2 S ballast tank. This is hypothesised to have led to the collapse of the bottom structure, buckling of the main deck and eventual fracture of the hull girder at the aft part of no.2 tanks. The *Erika* had undergone 8 port State control inspections during the 3 years prior to her sinking. In no case did the PSC inspectors enter the tanks to assess the condition. "The "appalling condition" of her tanks went undetected, as port State control Inspectors do not enter tanks" (Devanney, 2006).

**The *Prestige*:** (ex *Gladys*) was an 81,564 dwt oil tanker built by Hitachi Zosen-Sakurajima Shipyard in Osaka Japan (1976). The *Prestige* broke in two and sank on Tuesday 19th November 2002 approximately 130 miles off the north west coast of Spain, while on a loaded passage from Ventspils (Latvia), southbound. The vessel contained approximately 76,972 tonnes of heavy fuel oil with a density of 0.9906 tonnes/m$^3$. The resulting spill caused extensive environmental damage to the coastline of the Basque region in Spain. The *Prestige* disaster occurred almost 3 years after the *Erika* accident in apparently similar circumstances. Following the loss, a major inquiry was conducted by concerned groups including IACS, the flag State and the vessels classification society. A number of reports were subsequently published including IACS's ad hoc audit report (IACS, 2003), ABS's Technical Analysis of the casualty (ABS, 2003) and the Bahamas Flag Administration's official report (BMA, 2004). The loss of the Prestige was surrounded by enormous media interest and public controversy related to the perceived inadequacy of shipping safety.

Figure 2.15. Sinking of the *Prestige*

Cargo Distribution on Departure

Figure 2.16. Cargo Distribution in *Prestige* During Final Voyage
(ABS, 2003)

In figure 2.16, the tank arrangements and the cargo distribution on the final voyage of the *Prestige* are depicted. The vessel was rated as category I under MARPOL 13 G, and was approved for either hydrostatic balanced loading (HBL) as a crude tanker, or as clean ballast tank (CBT) with 30% side protection as a product tanker. The vessel was operating in conformance with CBT requirements at the time of the casualty. Structural repairs were carried out in Guangzhou China, 18 months prior to the loss of the vessel. Following completion of the hull repairs in which 362 tonnes of steel were replaced, the vessel's Interim Classification Certificate was renewed without conditions of class relating to "substantial corrosion" (IACS, 2003).

It may be possible to hypothesise on the fate of the *Prestige* based on the published findings referred to earlier and from the maritime press and publications summarised in IMO's library services on the *Prestige* (IMO, 2008). Both the flag Administration and the classification society involved, stated that the initiating event appeared to be structural failure. This view was supported by a statement from a member of the crew: "it started with an explosive sound, followed by a shudder that was felt throughout the ship" (Fairplay, 18th January 2007, Vol.35g, No.6413, p.6). This observation appears to be consistent with a sudden catastrophic structural failure. The official report stated the sequence of events thus; "At 1510, the ship was struck by a large wave and a loud bang was heard. The ship shuddered as she rolled to starboard and the butterworth covers were displaced from the vessel's tanks." The vessel rolled to starboard reaching a 20 deg. list within 10 minutes of the event (BMA, 2004). The above sequence of events suggests that structural failure possibly led to flooding of one of the empty starboard side wing tanks, either No.2 aft or No.3 wing tank. Given that the majority of the steel repairs carried out in China in 2001 involved the No.2 aft and No.3 (port and starboard) wing tanks, there would seem to be a probability that the search for an initiating event should start in these tanks.

### *2.6.3 Regulatory and Legal Consequences of the Erika and Prestige Accidents*

After the sinking of the *Erika*, a number of significant changes were made to IACS Z.10.1 requirements and these changes were made applicable from 1st of July 2001, three years before the loss of the *Prestige* in November 2002 (the so-called *Erika* measures). These changes intended primarily to strengthen the ESP rules were as follows:

- All ballast tanks sharing a common plane boundary with cargo tanks with any means of heating shall be examined internally on an annual basis after the ship has reached 15 years.
- Intermediate Hull Surveys of ESP ships over 15 years of age shall be enhanced to the same extent as the scope of the preceding renewal survey etc and a Bottom Survey (afloat or in dry dock) shall be carried out in conjunction with the Intermediate Survey, and after 1st of July 2002, the Intermediate Bottom Survey has to be carried out in a dry dock.
- Any damage in association with wastage over the allowable limits (including buckling, grooving, detachment or fracture) or extensive areas of wastage over the allowable limits which affects or in the opinion of the surveyor, will affect the vessel's structural, watertight or weather tight integrity is to be promptly and thoroughly repaired.

There were additional requirements for two exclusive surveyors and onboard verification of UTM readings. Specifically one of the post-*Erika* initiatives introduced by IACS for oil tankers age 15 years and over, was for any water ballast tank adjacent to a cargo tank with heating coils to be examined internally at Annual Surveys. The main consequences of the *Prestige* accident described in IMO (2008) can be summarized as follows:

- Fierce controversy over ports of refuge debate amongst EU members.
- Incarceration of the vessel's master in Spain.
- Questions regarding quality of tanker safety.
- Banning of pre-MARPOL SH tankers in European waters.
- The owner's withdrawal from the oil tanker market.
- USD 700 million law suit by the Government of Spain versus the classification society (ABS) in a US court, and counterclaim against Spain by ABS.
- Move by Spain to have the class society revoked by the EU.
- Intensive public scrutiny of the classification industry.
- Questions regarding quality of repairs carried out in Chinese shipyards.

As a direct consequence of the *Erika* accident followed by *Prestige* three years later, the phasing out of SH tankers was accelerated in amendments to IMO Regulation 13G of MARPOL Annex I. The amended regulation allowed for a certain amount of trading provided that a Condition Assessment Scheme (CAS) described in section 2.4.2 was satisfactorily carried out. One year after the *Prestige* accident, the EU initiated a set of legislative changes. There was an immediate ban on SH oil tankers with deadweight above 20,000 tonnes carrying heavy gas oil (HGO) in European waters. Category I tankers (pre-MARPOL) built on or before 5th of April 1982, were effectively banned from trading past 5th of April 2005. Non DH category 2 oil tankers with deadweight above 20,000 tonnes were given a final cut off date of 2010.

Early in 2007 the *Erika* legal case, the biggest trial of its type, commenced in Paris, involving 15 organisations and individuals including Total, the vessel's charterer and the world's fourth largest oil company. The other defendants included two of its subsidiaries, the ship's captain, the management company, four French maritime officials and the Italian classification society RINA. Sixty nine witnesses took part in the proceedings. The prosecution alleged that the principle cause of the vessel's loss was cost-cutting over repairs done in conjunction with the special hull survey in Bijela Montenegro. The naval architect Jean-Paul Christophe, told the court that only 35 tonnes of steel had been replaced instead of 209 tonnes need to conduct a satisfactory repair. After seven years of disputes and investigations, on 17th January 2008, the Paris court announced its verdict and Total was found guilty of "carelessness" in chartering the *Erika*, and fined a maximum penalty of USD 560,000. The vessel's classification society RINA was fined the maximum amount "for issuing certificates without undertaking the necessary checks"(www.shippingtimes.co.uk, 27/4/2007). Durr (2007) from the University of Capetown, has recently discussed the liability aspects of classification services including the *Prestige* case.

### 2.6.4 Critique

Changes to the MARPOL Regulations in the late 1990's,meant that 25 year old SH tankers of 20,000 dwt or more were required by MARPOL 73/78, Annex I, Reg.13G to comply with Reg.13F i.e. be fitted with double hull. Alternatively a 5 years grace period (30 years) was allowed under Reg.13G (4) and Reg.13G (7). Regulation 13G(4) accepted wing tanks as double bottoms not used for the carriage of oil, meeting the width and height requirements of 13 E(4), covering at least 30% of the cargo tank length (full depth). As a further alternative, pre-MARPOL tankers compliant with IMO guidelines contained in MEPC-64 (36), permitted HBL (Robinson, 1999).

Such arrangements were required to be approved by the flag Administration (or their delegates). Ships operating in the HBL mode would in fact be operating in conditions different from previous modes of operation. It was stated to be a requirement for candidates for HBL to be screened at the 5th special hull survey. For *Prestige*, This would have coincided with the Guangzhou Survey in April-May 2001. According to the Bahamas investigation, when operating in HBL mode, *Prestige* could carry cargo in No.3 wings (P+S) under MARPOL Reg.13 G(7). However, when operating in CBT mode, No.3 wings (P+S) were designated as clean ballast tanks, in accordance with Reg. 13G (4) of MARPOL, Annex I. At the time of the accident, No.3 (P+S), wing cargo tanks were empty, coinciding with the employment of the vessel in CBT mode. However No.1 centre cargo tank was noted to be 58% full. The transcripts of the official Bahamian report and the ABS investigative report referred to earlier, indicate that the vessel was restored to satisfactory condition at the conclusion of the special hull survey in China in May 2001. Approximately 360 tonnes of steel was replaced mainly in way of No.2 Aft (P+S) ballast tanks and No.3 (P+S) cargo wing tanks. No structural conditions of class (CC's) were apparently issued at this time and no "substantial corrosion" was recorded.

The conversion of the vessel to CBT as required by Reg. 13G (4) of MARPOL Annex I, meant that No.3 (P+S) cargo wing tanks were utilised as ballast tanks. However, these same tanks were uncoated. Only No.2 aft (P+S) wing tanks were designated as segregated ballast tanks (SBT's) and coated with *Fair* Condition. The consequences of failure to mandate coating of cargo tanks designated as ballast tanks in CBT vessels have been pointed out by various critics including Devanney (2006). A period of 18 months transpired subsequent to the major repairs to *Prestige* followed by loss of the vessel. The classification society reported that, under normal conditions, corrosion wastage during the period May 2001 to November 2002 would not have been substantial (ABS, 2003). However, the BMA report states that rates of corrosion in uncoated ballast tanks (i.e. No.3 S) "may be exacerbated if heated cargo is carried in adjacent tanks", which was the case with *Prestige.* According to the IACS Ad Hoc report, all steel repairs were executed satisfactorily. However, it was noted that No.2 (P+S) ballast tanks had not been surveyed in conjunction with the last annual survey carried out in Dubai, May 2002. The report noted that this was a requirement arising from the *Erika* disaster 3 years earlier.

There are many similarities between the *Erika* and *Prestige* accidents. Both vessels were proceeding southbound in the same area and at the same time of the year, carrying heavy gas oil (HGO) cargo. The vessels were of similar age and both were Pre-MARPOL, with cargo tanks converted to SBT's. Both suffered damage initiated on the starboard weather side of the vessel. Both were fitted with heating coils in the cargo tanks and had loaded high temperature cargoes. The ballast tank coating condition for both vessels was less than *good.* The *Erika* disaster demonstrated the risk presented by old ships and the need to tighten up the existing regulatory framework beyond the level of the minimum IMO standards. In an analysis of substandard shipping, the OECD (2001) concluded that the *Erika* had been built with a light mass approximately 1000 tonne less than for similar designs. Four of the seven sister vessels had experienced serious structural failures in the early 1990s. It was alleged that some hull surveys had been carried out without all the cargo and ballast tanks gas-freed to permit safe entry.

Devanney (2006), in the book *The Tankship Tromedy – The Impending Disasters in Tankers,* is unequivocal about the contribution of hull failure to loss statistics for tankers. "In terms of spill volume, hull structural failure is by far the most important cause of tanker casualties. Structural failure is by far the most likely reason a loaded inerted cargo tank would catch fire. It's a safe bet that just about all tank explosions/fires on loaded tankers are structural related. The *Erika* and *Prestige* are only the latest in a long line of structural failures". Other industry figures disagree with this view. "Tankers rarely suffer from structural failure with the exception of the poorly maintained and badly operated fringe elements of the industry, just a few bad apples" (Slater, 2000). At the time of writing, the European Commission has approved USD 777,000 towards a 2 year project investigating dangers which accumulate from repairs throughout a ship's life (Fairplay, 18th January 2007, Vol.359, No.6413, p.6). The debate over the *Prestige* continues and the legal issues including ports of refuge and classification society liability are unresolved.

## 2.7 Conclusions

A primary objective of this research was to build evidence confirming that the customer can effectively enhance the quality, safety and performance of large bulk ship structures by managing risks at the design stage. In the first phase, a comprehensive literature survey was conducted by casting a wide net around the problem to examine the safety management systems affecting these types of hull structures and to identify the need for an improved management of ship safety. In the second phase, selected casualties were examined in order to reveal possible root causes associated with inadequate quality in structural design or maintenance procedures. This has led to the following main conclusions:

- Large bulk ship structures are subjected to considerable random stochastic environmental loads, and they are heavily utilised in terms of their load carrying ability, which places them in a class of their own when compared with most civil structures of comparable size.

- Large bulk ships belong to a class of welded plated steel structures which display a high degree of redundancy and yet are remarkably sensitive in terms of the risks posed by relatively minor structural failures. Their inherent nature, involves thousands of complex structural intersections with a high degree of restraint. Triaxial stress conditions and residual stresses in fillet welded joints significantly increase the risk of fatigue failure. The reduction in scantlings associated with the use of high tensile steel, leads to increased deflections often associated with pre-mature breakdown in coatings, resulting in accelerated corrosion conditions, sometimes referred to as the domino effect. They are unique, sensitive, highly utilised structures, exposed to particularly severe environmental loadings.

- Ships rely on the plastic characteristics of plated grillages in order to create a significant strength reserve. Due to the lack of significant factors of safety against yield at the design point, these plastic reserves are invoked on a regular basis with the ship in service, although the effects are not normally observed.

- These structures may be exposed to loads exceeding the assumed design load values, depending on the vessel's route and speed, largely under the control of the owner. An assumption in the design of ships is that the vessel will take avoidance action and reduce speed in heavy weather conditions to mitigate the risk of structural damage.

- Corrosion and fatigue are the twin and interrelated hazards causing the majority of structural problems involving large bulk ships, as amply demonstrated in the literature. Water ballast tanks in oil tankers and bulk carriers represent the highest risk areas and the integrity of coating systems is of paramount importance in ensuring structural integrity. HTS rich optimised structural designs are particularly sensitive to the corrosion and fatigue hazards and require more intensive maintenance effort. Until recently, the mean lifetime of ballast tank coating systems was typically 10 years.

- Attempts have been made recently to introduce a theoretical approach to prediction of corrosion rates in bulk ship structures. These models have generally been calibrated against thickness measurement data bases compiled by the classification societies. In ballast tanks, a corrosion rate of 0.3mm/year is usually assumed. In cargo tanks corrosion rates as low as 0.1mm/year have been assumed. Much higher corrosion rates have been recorded in both ballast and cargo tanks and accurate prediction of corrosion rates remains an area of controversy.

- Corrosion margins are considered as an additional safety factor in the design of large bulk ship structures, with recent practise assuming a margin of up to 25% of the gross plating thickness after breakdown of coatings. In some cases, these margins were invoked when market conditions dictated restraint on maintenance spending. However, the dangers in this approach have become apparent due to the difficulty in predicting the combined effects of corrosion and fatigue in HT rich designs, and the rapid degradation of structural integrity. Members of the Greek Bulk shipping community recently suggested that the newly adopted CSR corrosion margins should be doubled in Panamax bulk carriers.

- Lack of intervention in the form of maintenance of coating systems can lead to accelerated structural degradation and rapid loss of hull girder section modulus to below 90% of the required IACS UR S7 minimum value. The onset of corrosion and accelerated fatigue damage is difficult to predict and control. This threat is thought to be a possible cause of unexplained losses of oil tankers and bulk carriers. Hull failure is postulated to be a leading cause of vessel loss, often concealed in statistics, where the root causes are often not correctly identified.

- The *fail-safe/damage tolerant* approach has been adopted in the current generation of large bulk ship designs. Large bulk ships have been deliberately designed on the assumption that fatigue cracks will occur and that the structure will be *fail-safe* and *damage tolerant* because flaws can be detected by visual inspection before they reach critical length. The weakness in this approach lies in the practical difficulties encountered in the inspection of such huge structures, as discussed in section 2.5.3. As a further consideration, because the majority of ship structures are fabricated from material without guaranteed fracture toughness values (A-grade normal and higher strength steels), the critical defect size is much reduced, highlighting the importance and reliance on structural inspections to find flaws before they propagate in a brittle manner. The crack initiation period in as-welded steel joints is insignificant due to the existence of welding defects. This means that crack growth is initiated in the very early stages of the structural lifetime. Fatigue and buckling phenomena can then become the governing failure modes driving the design.

- The maritime industry has only explicitly addressed fatigue in the design of large bulk ships after 1990. There are concerns that the standard minimum compliance approach to current fatigue design may not be sufficient to ensure reliable and robust structures. Other concerns include the failure to address the combined effects of springing and whipping vibratory phenomena into the new CSR rules. This aspect has been a long standing complaint from sectors of the industry, most recently by the Greek bulk shipping community (IACS, 2006a).

- Commercial and political factors such as freight rates, shipbuilding costs, second hand prices and scrap value hugely influence ship design. Commercial ships are designed and constructed within these constraints. The structural design of large bulk ships is a largely a trade-off between economic constraints and environmental risk.

- The oil and bulk trades and the charter market operated in a highly competitive atmosphere. Finding the cheapest vessel was an essential part of the operation. In the recent past, the cheapest available tonnage offered by the oldest ships dictated prices. It was therefore difficult to create a situation where quality paid. This phenomenon posed a significant risk to safety.

- The regulatory system controlling the design and operation of ship structures comprises a chain of responsibilities, starting with the UN Law of The Sea (LOS) Convention of 1982, administered by the flag States under their obligations enshrined in UN conventions detailed in IMO and ILO specialised instruments to safeguard life at sea and for protecting the environment. Regulatory control for the safe design and performance of ship structures is enforced primarily through the IACS member society rules, as required by the SOLAS convention and addressed implicitly by the 1966 International Load Line Convention and reflected in the vessel's Classification, Load Line and Safety Construction Certificates. However, these requirements represent a minimum standard.

- Port state control (PSC) is regarded as the last line of defence in the safety chain, as viewed by a number of observers, chiefly because PSC does not involve tank inspections and structural condition is therefore not normally a part of the PSC intervention procedures.

- Experience with the operation of large bulk carriers in the trans Atlantic ore trade within the last decade and reports of fatigue cracking of the main deck structure within one year of operation has confirmed long held suspicions that these phenomena may be partly responsible for rapid structural degradation of hull structures of bulk carriers and tankers. Further, the contribution towards accumulated structural damage in the ballast mode due to hull girder vibration effects, currently disregarded in ship design practice, has been estimated as similar in magnitude to the wave induced fatigue damage.

- Following the loss of the oil tankers *Erika* in December 1999 and the *Prestige* in November 2002, the operations, engineering and management sectors involved in tanker safety have been subjected to intense scrutiny and criticism from the media and the public. Leading figures in the industry have called for a complete overhaul and re-invention of the industry's primary self-regulation system in response to these developments. In the post ESP era, these two spectacular and widely publicised accidents involving hull structural failure and pollution of the environment, have led to a deep introspection within the industry and from industry critics, about the effectiveness of the measures currently in place.

- Owner driven SIM systems were virtually unknown prior to the 1990's, and despite the widespread availability of the technology, only a few quality ship owners were seen to have implemented truly integrated proactive SIM measures. In 1993, the implementation of IMO Resolution A.744 (18) for bulk carriers and introduction of the ISM Code requiring ship owners to formalise onboard maintenance procedures was the incentive for a planned maintenance system for the hull structure in excess of the minimum IACS and IMO regulatory requirements. Underpinning these developments has been the progressive tightening of the IACS enhanced survey programme (ESP) requirements.

- The controversy associated with recently observed failures, coupled with widespread condemnation of safety performance by critics, suggests that major bulk transport by sea continues to dependent largely upon a framework of minimalist prescriptive rules and services driven by the service providers. Traditionally, safety is thought of in terms of the prescriptive regulatory approach. Recent systematic failures suggest that those responsible for the safety system governing bulk transport by sea (a high risk industry), should seek alternatives.

In summary, a number of specific findings have been identified concerning deficiencies in the current safety management systems responsible for the design, construction and operation of large bulk ship structures. In chapter 3, a concise summary of problems associated with the current approach to design and procurement oil tankers and bulk carriers is presented, building upon many of the findings referred to above. The concept of a construct which will permit the buyer's preferences to be conveniently incorporated in to the design process will be explored further. The research performed in chapters 2 and 3 provides a suitable foundation of evidence as the basis for a proposed novel and unique structural assessment framework which will be developed in chapters 4, 5 and 6. The use of formal safety assessment (FSA) and a goal based approach to hull structures will be explained. A structural hazards and risk assessment is given as a prelude to detailed articulation of a set of numerical and qualitative assessment criteria in chapter 4 as input for the model demonstrated by an example in chapter 5 and validated in chapter 6.

# Chapter 3 - Ship Procurement, Structural Design Quality and a Risk-Based Approach to Hull Structures Integrity

***SUMMARY***

*In the first phase, research sub-objective no.1 in section 1.2 was to review the safety management systems affecting the design of large bulk ship structures and to identify the need for an improved management of ship safety. Sub-objective no.2 was to analyse selected casualties in order to reveal possible root causes associated with inadequate quality in structural design or maintenance procedures. In this chapter, the third research sub-objective no.3 in section 1.2 will be dealt with i.e. to analyse the current approach to ship procurement and structural design quality, and the existing knowledge of the use of risk-based approaches to hull structures integrity. This forms the second phase of the evidence building needed to support the principal research objective, confirming that the buyer can effectively enhance the quality, safety and performance of VLCC/VLBC hull structures by managing risks at the design stage. This leads to satisfying research objective no.4 which is to formulate the numerical and qualitative input data for a novel structural selection framework based on multi criteria decision analysis (MCDA) and evidential reasoning (ER), proposed, developed and validated in chapters 4 to 6 of this work. Arising from the foregoing studies, objective no.5 which is to examine the applicability of the offshore safety case model to the hull structures question will be first considered here and subsequently fully developed in chapter 7.*

## 3.1 Introduction

The findings from the comprehensive literature survey conducted in chapter 2, revealed significant problems in the way large bulk ship structures have been designed, managed and regulated. Forensic examination of recent high profile tanker and bulk carrier casualties unveiled a direct and often understated link between structural hazards and failures. As critics have suggested, the current approach to contracting, designing and building new tanker tonnage is inadequate. Prescriptive rules and classification society minimum standards have been the defacto standard for many years. A risk-based design-for–safety approach has been strongly advocated in recent times. Formal safety assessment (FSA), originally developed by the nuclear industry in the 1950's, has recently been adopted by the IMO and applied to the bulk carrier structures safety problem. Recognizing historical problems with declining performance of ship structures designed to minimum prescriptive rules, the IMO initiated a goal based standards approach to ship structures, resulting in new rules published by the IACS societies in 2006. In a parallel development, the SAFEDOR Project was set up by a European consortium, with the objective of integrating safety into the design process to minimise risk. This chapter deals with all the above developments in ship structures technology, advocating a risk-based approach driven by the customer, the first step in a performance based framework.

Traditional naval architectural texts describe the design process as iterative, starting with definition of mass, volume, principal particulars, underwater form, speed, power, propulsion, intact stability, architecture, sea keeping and so forth, and converging to a solution in a "design spiral" as described by Rawson and Tupper (1994a). The aim in ship design practice is to deliver a vessel that performs in accordance with the expectations defined by the owner's operational or functional requirements, while complying with statutory rules and regulations (rule based design). Those operational or functional requirements may be contained in an outline specification. In contemporary ship design practice and for large tankers and bulk carriers in particular, ship yards in the Far East offer standardised designs. These are optimised for production and the timeline is generally very short, giving an owner very limited opportunity to positively influence the quality outcomes. Rapid changes in technology are leading to the possibility of a virtual design environment where the buyer may play a more definitive role.

The FSA method and the hull safety case paradigm are assessed for relevance to the ship structures problem. Examples will be given where the offshore safety case has been recommended for ships but has so far not been seriously considered by the industry as a model worth adopting. Goal based standards introduced by the IMO and applied to the development of ship structures standards are discussed. Moves to introduce a risk-based approach to ship design holistically through the SAFEDOR project are described, and the first steps towards a risk-based design for safety approach to hull structures are outlined, through a structural hazard identification process outlined in section 3.5.

## 3.2 Statement of the Problem

### *3.2.1 Ship Production and the Product Model*

Commercial ship design and production in today's world represents a quantum leap from the time honoured approach. Modern commercial shipbuilding practise is characterised by one-of-a-kind designs, fluctuating workloads and strong competition on price, delivery and quality. Up to 70% of the value creation in ships is based on vendor items and services. The tremendous changes which have taken place during the last two decades in relation to the widespread use of computer aided design (CAD) methods and electronic media has resulted in a data explosion and consequently problems managing data in all organisations globally. The ship design process involves a large number of often disparate software design tools, and in many cases involving duplication of effort. The first discussions related to product information systems in ship building occurred in 1980, with the definition of the product model as "a logically structured product oriented database" (Whitfield et al, 2003). The product model offers a collaborative approach to design (Bong et al, 1994; Bronsart et al, 2004).

In the mid 1990s, the Standard for the Exchange of Product Data (STEP) application protocols (AP), were adopted by the industry and these efforts were described in detail by Howard et al (1995), documenting the initiatives taken by Lloyds Register to develop a common standard for data exchange to maintain their competitiveness from a classification viewpoint. STEP was intended to be a complete and unambiguous representation of the product (vehicles, aircraft, offshore platforms or ships) in a computer interpretable neutral format intended for the product lifetime. The application protocols in STEP were intended to subdivide the product into recognisable and useable parts.

Figure 3.1. Shipbuilding Application Protocol (AP)
(Howard et al, 1995)

A seven part application protocol model described by Howard consisting of "islands of AP's" jointly developed in 1985 by the US Navy/Industry digital data exchange standards committee (NIDDESC) and other groups including the Japanese Maritime Standards Association (JMSA) was agreed in 1993 and shown in figure 3.1 (Note: the mission systems functional area has been removed, as it is considered more applicable to naval vessels). This work was continued by the International Standards Organisation (ISO) through the STEP ship team. Various AP standards including AP 215 (ship arrangements), AP 216 (ship forms model), and AP 218 (ship structures model) have been developed as described in detail by Whitfield et al (2003).

In 2008, the product model using STEP AP's is in widespread use by the leading classification societies. The primary intention behind the effort by classification societies, ship builders and other industry stakeholders to develop the 3D product model was to provide a mechanism for concurrent engineering development and virtual prototyping. The future may involve a paradigm shift in the techniques presently used to enable the distributed design of ships using a continuous product model, eventually using technology from the computer games industry. The product model database serves as a framework and repository for information concerning all phases of the vessel lifetime including operations, and hence the planning for surveys and all survey input can now be carried out a common data base.

The goal of a comprehensive ship structural integrity information system (SSIS) envisaged by Bea and modelled on commercial aviation industry best practises (discussed in section 2.5.2), has effectively been realized. However, the development of multiple databases and systems across the major classification societies was perhaps an undesirable and unexpected outcome. With the announcement of common structural rules (CSR), The Joint Tanker and Joint Bulker Projects (see section 3.4.2), it was anticipated that there may be a common approach to software development in the industry. Recently however, the major classification societies have stated that mutually exclusive software development as described in section 2.5.5 is beneficial to the industry. Effectively therefore, the international classification societies have become the keepers of their own databases, and this includes structural maintenance activities.

### *3.2.2 The Outline Specification*

Negotiations with prospective ship builders usually commence with a general outline specification. The outline structural specification is the basis for the owner's input into the design as illustrated schematically in figure 3.2, and should contain all the relevant technical requirements. The form of the general outline specification may be based on one previously written by an owner's technical department, or on "templates" such as the one produced from a Maritimt Forum (1992) project. This specification for a crude oil tanker was said to have followed ship owners' recommendations and information supplied by Norwegian manufacturers and vendors, and consisted of 10 chapters, chapter 2 being devoted to hull.

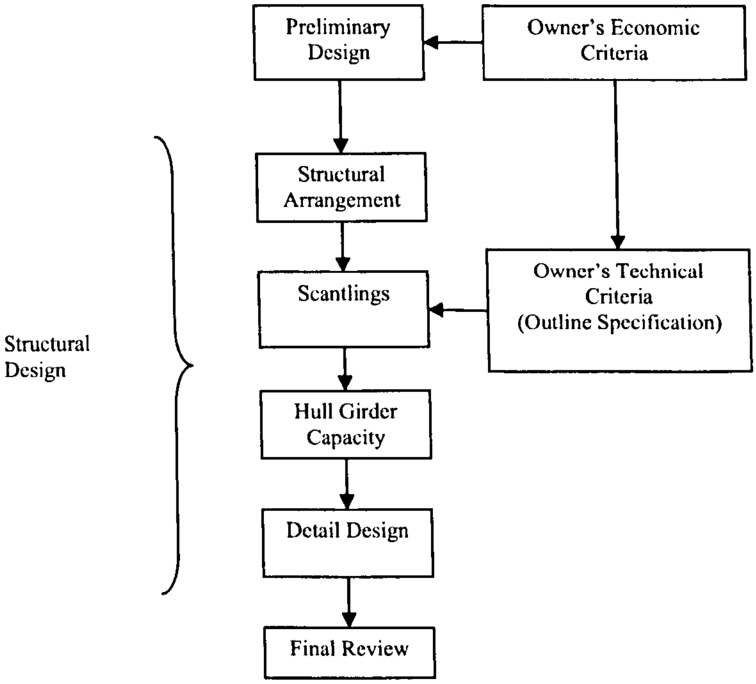


Figure 3.2. The Outline Structural Specification

Chapter 2 of the Maritimt Forum template dealt with hull materials and material protection (coatings), the major structurally related owner's requirements are listed below:

- The vessel shall be designed for carrying oil in all centre tanks. Due consideration shall be given for the ship partly loaded and with tanks reinforced for sloshing.
- Minimum use of ballast water in part loaded condition to be applied.
- One centre cargo tank to be arranged as "heavy weather ballast tank" and coated accordingly.
- All steel shall be new and of good quality mild steel well suited for this type of vessel and certified by the class.
- Use of high tensile steel (HTS) shall be a bare minimum.
- All welds to be double continuous in the main hull structure and in areas where humidity can occur.

- Reduction of scantlings based on corrosion control not to be used for the hull structure.
- Steel thicknesses to be increased.......% or .....mm over thicknesses given by classification requirements in the following parts of the steel structures....... (Note: intentionally left blank).
- The structural work shall be executed in accordance with good shipbuilding practice.
- The ship to be equipped with instruments for early warning of abnormal hull stress levels during operation in waves and bad weather, and during loading/unloading operations.

The above broad requirements contained in a mere 5/141 pages of detailed specifications devoted to machinery and equipment, suggests that the hull specification was potentially poorly considered by ship owners procuring new tonnage. As a rule of thumb, roughly 30% of the initial cost of a large bulk vessel is attributed to steelwork. However, evidence suggests that unplanned costs due to early hull degradation, followed by major unscheduled steel replacement, exceed any short term gains achieved by imprudent trade offs in the structural design and integrity of the vessel.

### *3.2.3 Responsibilities (Builder, Class and Buyer)*

In delivering a ship, the builder's obligations are diminished normally after one year, and the transfer of responsibility is as follows. Firstly, the owner generally assumes responsibility following the end of the guarantee period. Secondly, the vessel has to be operated within the parameters set by the ship designer and classification society. Thirdly, it has to be maintained according to the standards set by the classification societies. The responsibility for ensuring that these requirements are met clearly rests with the ship owner (DNV, 2008). Critics have suggested that the warrantees provided by ship builders are totally inadequate. Devanney (2006) has noted that the standard 1 year warrantee for a VLCC is "similar to that for a toaster". Experience during the past three decades with the operation of large tankers suggests that the risks associated with corrosion or fatigue hazards during the nominal 20 year service life are excessively high as discussed in detail in sections 2.3.1 and 2.3.2. The consequences of even minor structural failures in crude tankers are well documented. A crack in the side shell of a single hull tanker can lead to leakage of crude oil into the sea. A crack in the inner containment system of a double hull VLCC can lead to cargo leakage into the ballast tanks with the risk of explosion.

### *3.2.4 View of Critics*

Large tankers and bulk carriers represent unique, made-to-order products. New tonnage is ordered across a spectrum of owners requirements ranging from standard builders' designs to fully bespoke specifications from high quality owners. Recently, much discussion has taken place in the maritime press in relation to the quality of design and construction of tank ships and the alleged deterioration of new building standards. During the tendering process, the customer has an opportunity to submit bespoke requirements and this usually takes the form of an owner's written specification. Ship builders appear to be less willing to consider bespoke requirements which negatively impact production schedules. Owners may be forced to accept ship yard terms, which often translate to reduced specifications and compromised quality. Yards sometimes take advantage of the limited timeframe in which owners can effectively leverage the design process. This usually manifests itself in substandard structural performance.

Over 30 years ago, Wilson (1975) remarked that the average customer has no interest in supporting tool-sharpening or in advancing the status of marine technology. He wants as much ship as his money can buy". This focus on least cost in commercial ship design has arguably led to unacceptable quality levels, a view confirmed by leading figures in the industry (Carlsson, 2000; Devanney, 2006; Devanney and Kennedy, 2003; Mikelis, 2001; Woinin; 2000, 2001; Papachristidis, 2001). Critics have deplored the lack of customer involvement in the ship design and construction process, and Devanney and Kennedy (2003) suggested that collusion between the yards and the classification societies was driving the "down ratchet". Some owners described their experience with having to re-engineering ship designs leading to significant conclusions regarding contemporary ship building quality. In a full page Lloyds List article, Papachristidis (2001) made a number of critical observations relative to how large tankers are designed:

- Ships are designed for economy of construction, not quality.
- No tolerance is made for corrosion or fatigue.
- Yard specifications are generally too low.
- Construction procedures generally undermine quality.
- The task of the yard is to build a ship as quickly and cheaply as possible.
- Yards bear virtually no responsibility for the quality of their product.
- Classification societies set minimum standards.

Other high profile critics, some of them industry insiders (Bea, 1993a; Woinin, 2001; Carlsson, 2000), lent support to his views. Due to the lack of standards and consensus by the rule-making bodies, the primary structural variables were often said to be decided on the basis of production considerations, driven by the ethos of least cost designs. Mikelis (2001), formerly principal surveyor to Lloyds Register, director of Lyras Shipping in London, and Intertanko chairman, observed a noticeable drop in quality of tonnage built during the eighties, stating that minimum specifications barely covered the requirements of the authorities and the class societies. Rules and regulations were said to be “minimum requirements”. He raised a number of issues related to the balance between cost, competition and enhanced safety summarized below:

- Fatigue life based on 20 years.
- Design hogging and sagging moments.
- Design ballast configuration.
- Corrosion margins.
- Negative plate rolling tolerances.
- Cargo tank coatings.
- Class involvement in coating application.
- Access arrangements.
- Level of supervision.
- Choice of classification society.
- Guarantees.

- Operational factors.

Mikelis (2001) concluded that new building standards for tankers were in need of improvement, and that owners were not aware of the implications. Tankers, he said, were "lacking in robustness and longevity".

### *3.2.5 Product "Quality"*

Perceptions of quality vary, and there appear to be many definitions in common usage. Because quality is used over such a wide spectrum of applications including products and services, there can be no one definition to fit all situations. Deming suggested that quality is defined by the customer and has many measurement scales, one for each of the characteristics deemed important by the customer (Wikipedia, 2008). Juran viewed quality as "fitness for purpose" with each product having multiple characteristics of two types: 1-customer-desired product features and 2-freedom from defects (ASQ, 2008). Crosby (1979) defined quality as conformance to requirements based on a set of specifications defining the product. The ISO 9000 definition of quality (ISO, 2005) relates to the degree to which a set of inherent characteristics fulfil requirements. The American Society for Quality (ASQ) states that quality is a subjective term for which each person has his or her own definition, but in technical usage means the characteristics of a product or service that bear on its ability to satisfy stated or implied needs or a product or service free of deficiencies.

When referring to the quality of a vessel design, and in particular to the structural aspects, it is considered essential to define what quality actually means in the particular context. When dealing with a complex engineered product such as a large bulk ship, a common definition is sought from an engineering reliability viewpoint. Lewis (1994) links quality to reliability and safety in the following definition: "In very general terms, quality may be defined as the totality of features and characteristics of a product or service that bear on its ability to satisfy given needs". This interpretation is identical to the ASQ definition given earlier. Further and importantly, Lewis believes that quality also implies performance optimisation and cost minimisation. The above discussion leads firstly to an understanding that product quality in the context considered here, relates to a set of performance characteristics which are highly optimised to meet customer needs, linking quality, safety and reliability. Secondly, these performance characteristics should not be susceptible to variability (defects in the manufacturing environment or process, defects in the operating environment or deterioration from wear or ageing).

Figure 3.3. Target Safety Level (Skjong, 2007b)

The general relationship between cost and quality in terms of property, life and the environment for a range of ship types has been demonstrated by Skjong (2007b), based on a formal safety assessment cost benefit approach, taking into account the cost of property, safety of life and the environment as shown in figure 3.3. The target safety level is plotted as the log of the probability of failure (safety index). This would imply that an optimum target safety level exists for different vessel types.

The European E3 tanker initiative described by Gutierrez-Fraile et al (1994), was a result of collaboration between 5 major European ship builders. The goal was to design a new generation of safe, environmentally friendly, high quality DH VLCC's. To the author's knowledge, few of these vessels were ever constructed. When considering quality related to crude tankers, Hayer (1994) reviewed 18 VLCC specifications from twelve prospective yards tendering for a five ship project, questioning whether a USD15 million premium related to additional options constituted a "quality" design. In relation to the hull, Carlsson (2000) defines quality as value for money, long reliable service and voluntary quality and safety measures such as extra corrosion protection in tanks, but concedes that the industry is lacking a transparent and comprehensive yardstick for quality. Recounting Hellespont Shipping's experience with quality issues when placing an order for four ULCC's with Korean Yards in 1999, chief executive Papachristidis (2001) listed the following changes which were negotiated by the owners relative to the original structural specification offered by the builder, resulting in a 20% increase in the light weight (more than 48,000 tonnes):

- A 50% increase in the design sagging and hogging bending moments.
- A 10% margin on top of classification stress and buckling factors.
- Unrestricted tank filling.
- A 40 year fatigue life instead of the yard's standard of 20 years.
- A limit on the high tensile steel content of 35%.
- No thermo mechanically controlled processing (TMCP) steel to be used.

The views of critics in relation to perceived deficiencies in the quality of design and construction of tank ships discussed in the preceding sections indicates a gap between customer expectations and observed levels of product performance. This is especially evident in the failure of the product to perform according to the required levels of reliability, evidenced by the number of corrosion and fatigue failures reported in the literature in chapter 2. More spectacular structural failures previously discussed in section 2.6 emphasise these shortcomings. However, the argument for improved quality should be balanced against the need to optimise the product performance characteristics. The stated objectives of ship builders are to improve productivity through computer-based least-cost structural optimisation of the kind described in by Hughes (1988). This optimisation is not necessarily at odds with the performance expectations of the product from the client's viewpoint, provided that the specifications for design and construction are robust enough to ensure that the target safety levels are optimised as indicated in figure 3.3.

It will be contended that the documented failures in structural performance are related to three main factors. Firstly, there is the lack of a procedure for ensuring that the customer's stated performance objectives are adequately integrated into the structural design process. Secondly, there is the failure of some ship owners to exercise their options in the structural design. Thirdly, this is recognition by the industry that prescriptive rules are a minimum standard for structural design. In section 3.4.2, the new goal-based common structural rules (CSR) are discussed. The new rules are claimed to offer an improved basis for product quality (Horn et al, 1999; Kim et al, 2007). However, the design of robust bulk ships must be based on a combination of a risk-based approach, founded upon the CSR baseline prescriptive standards as a starting point. This assumption is central to the proposed structural assessment framework, which relies on the various risk-based measures forming layers on top of the basic underlying prescriptive foundational elements of the system.

## 3.3 Formal Safety Assessment (FSA) and Hull Structures

### *3.3.1 Design for safety*

Maritime safety is currently in a transition phase from a prescriptive certification regime to a goal-based one (Billington and Caruana, 2002; Wang, 2002; Wang, 2006a). Over a decade ago, Wang and Ruxton (1997) argued that safety aspects should be systematically integrated into the design process for large made-to-order products such as ships and offshore platforms, as indicated in figure 3.4. Design for safety (DFS) means identifying hazards, estimating and evaluating risks, and conducting design reviews to reduce the risk. Ship safety when viewed as a top-down process, is governed by a handful of factors, that can be managed individually or in combination, comprising a manageable set of design scenarios with calculable probabilities of occurrence and consequences, involving the major accident categories, derived from formal hazard studies (Vassalos, 2007). The most important phase in a design for safety approach for large marine artefacts is in the design itself. Effective intervention in the design process is thought to have the most impact on the satisfactory safety and structural performance of the vessel. Failure to ensure adequacy in design means that quality and safety cannot be inspected into the product during the construction process.

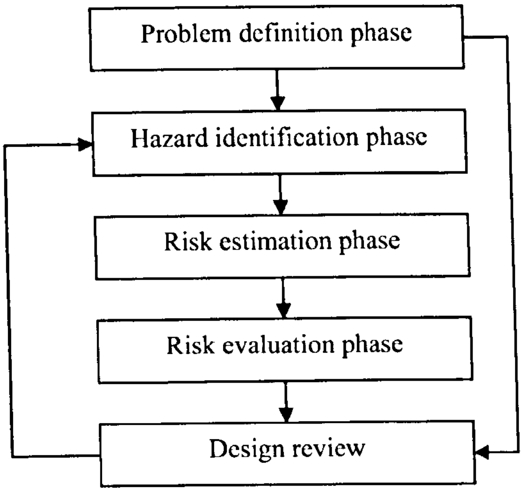


Figure 3.4. The Design for Safety Process

### *3.3.2 Formal Safety Assessment (FSA)*

Following the *Herald of Free Enterprise* disaster in 1989 and according to White (2002), the UK Government rejected a proposal from Lord Carver's 1992 House of Lords Select Committee Report for the safety case regime to be applied to shipping, based on preliminary safety goals administered through the IMO by the flag States. The concept of FSA was said to have evolved from subsequent research efforts. Attraction in the concept was the potential to prioritise safety issues and derive cost-effective regulations. In 1997, preliminary FSA guidelines were agreed by IMO. Over the last decade, formal safety assessment (FSA) has developed and is now an acknowledged safety management method based on risk assessment techniques. It consists of systematic identification of hazards, risk assessment, risk management, cost benefit analysis and making decisions from a set of options (Wang and Trbojevic, 2007). The design for safety approach and formal safety assessment are essentially similar, although FSA is intended as a more generic approach, and it incorporates a cost-benefit analysis which sets it apart from DFS. FSA was developed by the UK nuclear industry, predating the safety case.

Figure 3.5. Formal Safety Assessment (Skjong, 2007a)

The UK Civil Aviation Authority utilise FSA in the design construction and operation of air traffic control systems. The UK Navy has used FSA methods to operate its submarine fleet (Pudduck, 1997). Wang and Trbojevic (2007) maintain that maritime safety applications of FSA methods have been generally extensively researched and satisfactorily demonstrated. FSA methods are now being tested in the shipping industry for classification rule development and application to a number of specific problems such as bulk carrier strength, Ro-Ro stability and code development for dynamically supported craft. Kormatzis et al (2000) from DNV, has described the adoption of FSA as the basis for a comprehensive review of all classification rules. FSA leads to "useful insights" into the nature of risks. FSA is viewed as having the potential to be of benefit to classification societies, ship-owners and society as a whole.

In figure 3.5, Skjong (2007a) has described the basic structure of the FSA process in relation to hull structures applications. Although the principles for FSA and the safety case are the same, FSA is intended to be applied to generic safety issues across various ship types and the safety case is ship specific. However the use of FSA by the regulators to drive rule development and the safety case by the individual ship owner is entirely consistent (Wang and Trbojevic, 2007). Background information on maritime applications of the FSA method can be found in IMO (1997), Sekimizu, (1997) and RINA (2002). Kuo (2002) proposed enhancing FSA with a safety management system (SMS).

### *3.3.3 Applications To Hull Structures*

At the 70th session of the IMO's MSC in December 1998, the United Kingdom proposed that a FSA study of bulk carrier safety be conducted in accordance with the guidelines adopted by the organisation. An international Project Steering Board (IPSB) was established including a broad cross section of the dry bulk industry stakeholders. A series of five work packages were defined and distributed. In parallel with this work, the Japanese classification society ClassNK and the Shipbuilding Research Association of Japan conducted their own study. An overview of the structure of the project can be found in Luntz et al (2002). In September 2002, the Royal Institution of Naval Architects (RINA) conducted an international conference on FSA, publishing many of the findings of the bulk carrier FSA study (RINA, 2002).

Arima (2002) investigated water ingress through hatch covers and structural failures using an event tree analysis (ETA) approach, commenting on the need for the industry to develop acceptable risk evaluation criteria. The Cyprus Bureau of Shipping and consultants carried out a study (Lockett, 2002) into safety of bulk carriers less than 150m in length using a risk matrix approach, identifying five major hazards and ranking of risk control options. BV developed a risk estimation approach using risk contribution trees for hull envelope failure, enabling a breakdown of causal factors (top events). The BV study identified the most significant high level event to be side shell failure due to fatigue/wastage (Astrugue et al, 2002).

The Ship Stability Research Centre (SSRC) of the University of Glasgow and Strathclyde UK, investigated existing hatch cover structural failure in relation to IACS UR S21. A first principles non-linear FEM calculation of the fore hatch of a Capesize bulk carrier was carried out. It was concluded that the probability of failure in the design condition to the requirements of the ICLL 66 with B minus 60 freeboard and 20 years severity was 100% (Vassalos et al, 2002). In the same conference proceedings, the ship design laboratory of the National Technical University of Athens (NTUA) conducted a cost-benefit study into the safety of double skin bulk carriers, using a fault tree approach. Under the IMO guidelines, the FSA method has tested over a period of years, first with high speed craft and later with bulk carriers as explained above. Experience with the application of the FSA method including IMO (2002) opened the way for a much wider adoption of risk-assessment principles in shipping, coinciding with the remarks of Wang and Trbojevic (2007).

### *3.3.4 The Offshore Safety Case Model*

The Flixborough disaster in the United Kingdom in 1974, resulted in the requirement for onshore facilities to submit a safety report consisting of a hazards assessment, a review of preventative measures, safeguards and mitigation, risk management and emergency response procedures. After the loss of *Alexander Kjelland* and *Piper Alpha* in the North Sea, the UK and Norwegian governments instituted a system of performance based safety controls, which in the UK was known as the safety case regime (Pitblado and Smith, 2000). The first draft of the offshore installations (safety case) regulations (SCR) was produced in 1992 and for existing installations, came into force in November 1993, affecting more than 250 offshore facilities in the UK sector.

Safety cases are required for all fixed and mobile installations operating in British waters and the UK Continental Shelf. Health and Safety Executive (HSE) acceptance is in the form of a written notification to the duty holder (DH) that they are satisfied with the case. The fundamental difference between the safety case and prescriptive rules is that the safety case embodies goal setting: ie a first principles approach to safety. According to Aupec Ltd (1999), the UK regulatory framework is recognised as among the best in the world, offering a balanced combination of clear structure, sophistication, rigor and flexibility associated with a goal-setting approach. The UK offshore safety case model has been widely adopted in aviation, rail safety and software development around the world.

In Australia, a ministerial council on mineral and petroleum resources in 2002, made the decision to adopt a consistent national approach based on the UK safety case regulatory model, using a clear legislative framework. This led to the formation of the new safety regulator, the National Offshore Petroleum Safety Authority (NOPSA) on 1st January 2005. The SCR were subsequently applied to approximately 57 fixed facilities in Australian waters (Clegg, 2005). Proponents of the safety case (Heiler, 2006) have argued that the merits of a SCR regime applicable to the Western Australian mining industry should be examined based on NOPSA experience. According to the NOPSA model, a safety case has to have three basic elements: a description of the facility, a formal safety assessment (FSA) and a safety management system (SMS). The NOPSA safety case must demonstrate to the satisfaction of the regulatory authority by its contents and supporting material, that the operator is aware of both technical and human activities and how safety is managed accordingly. Further, the safety case has to identify methods for monitoring and review of all activities to ensure continual improvement in safety performance.

### *3.3.5 A Safety Case Approach for Ship Structures*

Safety case regulations were introduced into the UK offshore industry as a direct result of failure of prescriptive systems identified by the Cullen Inquiry following the *Piper Alpha* disaster in July 1988. Subsequently, the 1992 House of Lords select committee or *Carver Report* into shipping safety, observed that modern science and technology were not being applied to ships' safety and that the systems to enhance safety at sea were not conducted on a scientific basis. The Carver Report recommended applying the safety case to individual ships due to the attractions of the concept. Concerns were raised about the transferability and practicality of the safety case in relation to its offshore context. Firstly, agreement on the parameters of the safety case for shipping, and secondly a perceived lack of uniformity in implementation and policy (White, 2002). As a consequence, the main protagonists of the safety case, the UK Maritime &

Coastguard Agency (MCA), proposed to the IMO in 1993, that an alternative approach (formal safety assessment) should be applied to ships to facilitate safety and pollution prevention.

Following the loss of the tanker *Braer* in the Shetland Islands in 1993, *New Scientist* magazine reported that the business director of the UK Atomic Energy Commission's safety and reliability consultancy had suggested that shipping should adopt a safety case approach, in line with the Cullen Report, referring to the MOD requirement for a safety case for nuclear submarines (Hamer, 1993). In the same article, the head of Lloyds Register Safety Technology Department was quoted as supporting this view, with reservations. After the *Erika* disaster, a DNV spokesperson reportedly confirmed that the society was sympathetic to the idea of a safety case for tankers. Rawson, formerly chief naval architect of the UK MOD, Professor of Naval Architecture at University College London and Brunel University, and a strong advocate of the safety case approach for tankers, refers to the "sensible discipline of the safety case" and the adoption of prescriptive standards in the safety case format. "A safety case may have drawn attention to the potential losses of oil tankers by a reduction in their strength through corrosion and misuse which are not embraced by prescriptive formulations. It could have identified critical areas for survey and examined the increase in perceived risk with age" (Rawson, 1994b).

A safety case approach has been implemented in branches of the UK MOD. Under the letter of delegation, DNV has full authorisation to issue a "Certificate of Safety – Structural Strength" on behalf of the MOD Naval Authority for patrol craft, survey craft, ice patrol ships, landing craft, royal fleet auxiliary ships and other support ships". Full delegation provides DNV with authorisation to certify the compliance of the ship against the specified rules, standard or conventions, and where there is a discrepancy, accept equivalence to the intent of the rules. Due to perceived failings in the prescriptive approach, O'Reilly (2008) asserts that the Canadian Navy should also adopt a "goal setting" approach, citing the example of the UK Health & Safety Executive offshore safety case model.

The safety case model would seem to be a worthy paradigm in relation to the hull structures question. The NOPSA philosophy is considered to be a simple and suitable framework. The envisaged safety case could be developed to cover safety aspects related purely to the design, construction and operation of the hull structure for large tankers. The safety case would be subservient to the safety management system (ISM Code) already in place. The safety case would cover both machinery and hull and address weaknesses existing in the current ISM Code. This concept will be further explored in the succeeding chapters, by first establishing a performance based framework for design involving the buyers input.

## 3.4 Goal Based Standards for Hull Structures

### *3.4.1 Goals & Functional Requirements*

Goal based standards were introduced into the maritime sector from the UK civil aviation industry. Goal based standards already exist in SOLAS Chapter II-2, 2000 amendments, with provisions allowing for alternative arrangements for fire fighting systems. In November 2002, goal based ship construction standards were introduced at the 89th session of the IMO Council, put forward by IACS-Bahamas-Greece in a joint submission. The aim was to set clear and demonstrable goals against which ship safety can be verified at design and construction stages and during ship operation. The goals could be achieved either by compliance with published technical standards or by alternative solutions providing an equivalent level of safety."(Hoppe, 2007; 2008). Figure 3.6 represents the framework of the new five tier goal based standards for hull structures. The first three tiers represent the standards to be developed by IMO and tiers IV and V contain provisions to be developed by classification societies, industry participants and other recognised organisations. The major tier I goal (safety objective) for all types of new ships is:

> Ships are to be designed and constructed for a specified design life to be safe and environmentally friendly, when properly operated and maintained under the

specified operating and environmental conditions in intact and specified damage conditions, throughout their life.

Figure 3.6. Goal Based Standards (GBS) under MSC 78/6/2 (Hoppe, 2007)

| 1 | **DESIGN** | |
|---|---|---|
| | II.1 | Design Life |
| | II.2 | Environmental Conditions |
| | II.3 | Structural Strength |
| | II.4 | Fatigue Life |
| | II.5 | Residual Strength |
| | II.6 | Protection Against Corrosion<br>II.6.1 Coating Life<br>II.6.2 Corrosion Addition |
| | II.7 | Structural Redundancy |
| | II.8 | Watertight & Weathertight Integrity |
| | II.9 | Human Element Considerations |
| | II.10 | Design Transparency |
| 2 | **CONSTRUCTION** | |
| | II.11 | Construction Quality Procedures |
| | II.12 | Survey |
| 3 | **IN-SERVICE CONSIDERATIONS** | |
| | II.13 | Survey & Maintenance |
| | II.14 | Structural Accessibility |
| 4 | **RECYCLING CONSIDERATIONS** | |
| | II.15 | Recycling |

Table 3.1. Functional Requirements (Tier II)

The design life of new oil tankers and bulk carriers was set at not less than 25 years and the environmental conditions adopted were the North Atlantic and relevant long-term wave state scatter diagrams. The tier II functional requirements shown in table 3.1 are applicable to new oil tankers and bulk carriers and comprise design, construction, in-service and recycling considerations. The structural strength requirements are contained in II.3 and are given below:

- To withstand at net scantlings in the intact condition, the environmental conditions anticipated for the ship's design life and the loading conditions appropriate for them which should include full homogeneous and alternate loads, partial loads, multi-port and ballast voyage, and ballast management condition loads and occasional overruns/overloads during loading/unloading operations, as applicable to the class designation.
- Appropriate for all design parameters whose calculation involves a degree of uncertainty, including loads, structural modelling, fatigue, corrosion, material imperfections, construction workmanship errors, buckling and residual strength.

Tier III includes an appropriate verification framework to ensure that the technical procedures and guidelines in tier IV comply with the functional requirements in tier II. Prior to the introduction of the new GBS for hull structures outlined above, the pre-existing requirement for hull structures within the IMO was in SOLAS chapter II -1 which stated that "ships should be constructed according to the requirements of the classification society which is recognised by the organisation". IMO membership was split on the philosophical issues concerning the introduction of GBS by the IMO (Hoppe, 2007). Half of the members were in favour of a complex holistic risk-based safety approach and half wanted a prescriptive/goal based approach for tankers and bulk carriers. In the end, it was agreed that both methods should be developed in parallel, but the risk-based approach was to be used for tankers and bulk carriers.

### *3.4.2 JTP/JBP and Common Structural Rules (CSR)*

The background to the development of the new common structural rules (CSR) for oil tankers has been published recently. This was known as the Joint Tanker Project (ABS, DNV, LR, 2005; Card et al, 2004; Chen et al, 1998; Liu et al, 1998). In 2002, LR, ABS and DNV agreed to jointly develop goal based structural rules for tankers (JTP). The IACS members undertook the development of a set of common structural rules for bulk carriers, or Joint Bulker Project (JBP). The first drafts of the new rules were published in June 2004. The project goals included eliminating competition between class societies on structural standards, to embrace IMO goal-based standards, to develop a single standard resulting in the same structural requirements irrespective of which society classes the vessel, to ensure that ships would be at least as safe, robust and durable as would have been required by any of the existing rules, to reduce the cost of dealing with similar but different rule sets, and to ensure common scantling requirements.

The CSR rules are mandatory for tankers with L>150m, and consist of 13 sections and 682 pages. The rules came into force on 1st April 2006. The CSR rules are mandatory for bulk carriers with L>90m and comprise 13 chapters and 558 pages. The development of the above rule sets for tankers and bulk carriers by the IACS member societies represents a remarkable effort in terms of the collective will to complete this hugely complex task. This development took place in parallel with IMO's efforts to develop broad reaching goal-based standards (GBS) referred to earlier. Undue complexity of structural design standards has been criticised on the grounds that it requires additional effort to generate outcomes and increases the risk of possible misunderstandings or undetected errors (Kendrick and Daley, 2007). Given that practical use of the CSR rule sets for tankers and bulk carriers is considered almost impossible without member society software support, it is clear that the rules are equally if not more complex than the rules which they replace. The CSR now resemble the familiar prescriptive codes from the past, albeit with a great deal more complexity. Prior to common structural rules for tankers and bulk carriers taking effect in April 2006, IACS responded to written concerns expressed by the Union of Greek Ship owners (UGS). The detailed somewhat acrimonious IACS response to UGS, is an indication that some sectors of the industry had deep reservations regarding the outcome of the new JTP/JBP rules (IACS, 2006a). As discussed in section 2.3.3, the adequacy of the corrosion margins adopted in the new rules proved to be a particularly thorny subject (Gratsos et al, 2005). The UGS allegations may be summarized as follows:

- The CSR corrosion additions are clearly inadequate for the stated lifetime of 25 years.
- Mandatory coating performance standards were not included in the CSR.
- The CSR rules require a software-based approach using different versions of proprietary software.
- The use of FEA using different software systems permits the approval of designs of varying scantlings against the intent of the CSR.
- Robust ships will not result from the CSR rules which relax existing rules in many crucial areas, reduce minimum thicknesses, relax welding requirements, do not correct known defects, neglect scientific knowledge etc.
- The CSR will not produce significantly heavier vessels (more steel).
- The CSR Rule wave bending moment was not changed to reflect 25 years instead of 20 years.
- Wave induced vibrations which may contribute up to 50% of fatigue damages were not considered.
- No real safety margin and spurious assumptions are incorporated in fatigue analysis as the damage records indicate.
- Fillet welding is extensively allowed in ship design, except for certain limited areas where full penetration welding is specified.
- Capesize bulk carriers with 11.0mm web thickness will soon be permitted again.

All of the above allegations by UGS were vigorously refuted by IACS in a detailed written response published on the web. The background to the technical discussions can be found in (IACS, 2005; 2006a; 2006b; 2006c). One of the more serious issues, namely the failure to include wave induced vibration into the new rules has since been substantiated by Storhaug's recent research findings, discussed in section 2.3.2.

### *3.4.3 CSR and Design Quality*

Only relatively modest increases in steel weight due to the implementation of the CSR have been reported for large bulk ship structures. In a consequence assessment of the impact of the CSR carried out by ABS, DNV and LR (2005), two VLCC designs were assessed and the average total scantling increases in the mid body cargo zone were +3.0% and + 4.0% for each case. For an Aframax and Panamax tanker, the increases were +5.0% and +3.0% respectively. According to Daewoo Shipbuilding & Marine Engineering Co Ltd (DSME) who delivered over 80 VLCC's, the average total increase in steel weight resulting from the introduction of the CSR is 5 to10% (Kim et al, 2007).

In some quarters, it is believed that the post CSR designs will not be any more "robust" than the previous ones. Clearly, others expect CSR designs to out perform their non CSR predecessors. To draw a conclusion from these developments, although the net increase in steel weight is marginal in most cases, it is reasonable to accept that incremental improvements in hull structures will arise from the adoption of risk-based principles, goal based standards and a holistic approach to safety management adopted by the IMO described in the preceding sections. This optimism should be tempered by caution due to the lack of failure data, and the CSR should continue to be regarded as a minimum standard.

Commercial ship design has unquestionably been an exercise in design optimisation and profitability (Hughes, 1988). In the past, empirical methods based on accumulated experience were relied upon and structural failures drove the development of prescriptive codes. Ship yards designing and building the product were focussed on minimisation of capital cost. By reduction of work content including simplifying the geometry of the hull and standardisation of plate and stiffener dimensions, fabrication costs were reduced. The introduction of cheap and available computing allowed rationally-based structural design procedures to be used in which the objective function was maximised, as per the methods advocated by Hughes.

The problem with the foregoing rationally-based, computer-aided approach during the introductory phases of this new technology (the last 25 years), has been the underestimation of the impact of the actual loads acting on large bulk ship structures and the severity of the degradation mechanisms in relation to highly optimised ship structures. In reality, the separation between the probability distributions for structural load and capacity was not always known or sufficient, giving a higher probability of failure. Despite this, the argument for improved quality should always be balanced against the need to optimise performance characteristics in accordance with good engineering practise and wise use of scarce resources. This optimisation is not necessarily at odds with the performance customer's objectives, provided that the specifications for design and construction are robust enough to ensure that the target safety levels are met.

In essence two extremes can be envisioned. On the one hand, a structural design has been optimised to the extent that the reliability, robustness and safety have been seriously compromised. On the other hand, a design has been selected which is grossly wasteful in terms of additional steel and cost required due to an unnecessarily large separation between load and capacity probability distributions. In reality, the boundary for the first extreme needs to be clearly defined such that the minimum standard can be used as a reference and baseline for the structural selection problem. This is the fundamental reason why emphasis should be directed at exercising the buyer's input into the design using a layered risk-based approach, founded upon the minimum classification and statutory standards including the goal-based CSR. This is the essential philosophy behind the proposed multi criteria decision analysis (MCDA) and evidential reasoning (ER) structural assessment framework developed tested and validated in chapters 4, 5 and 6.

## 3.5 Risk-Based Hull Design

### *3.5.1 The SAFEDOR Project*

In rule based design, safety is often thought of as simplistic rule compliance and a design constraint. Investment in safety was sometimes seen as compromising returns.

The developers of SAFEDOR envisaged a modernised risk-based regulatory system linking performance prediction with risk assessment. SAFEDOR was conceived to focus on ship design and ultimately modernise the maritime industry through a new risk-based regulatory framework for the rule-makers (Vassalos, 2007). The 1995 SAFEDOR project was led by Germanischer Lloyd (GL) and funded partly by the EC and 53 consortium partners. Sames (2007) has described SAFEDOR's origins in the first EU thematic network Safer Euro, as aimed at promoting a new design philosophy under the theme "design for safety", integrating safety and cost effectively, in such a way that safety would "drive" ship design and operation. A formal state-of-the-art design methodology (risk-based design) was envisaged to support and nurture a safety culture paradigm by treating safety as a design objective.

The primary intention behind SAFEDOR was to deliver a vessel that performed in accordance with the owners operational and functional requirements. Although SAFEDOR was intended primarily for individual ship designs of a novel nature having significant economic value for Europe including mega cruise vessels, the SAFEDOR philosophy was said to be directly applicable to standard ship designs. Safety goals were associated with company values, policies and safety considerations. In SAFEDOR, Hazards could be identified using systematic and rational hazard identification techniques such as those described by Skjong (2007a), and include what-if/checklists, hazard and operability analysis, failure mode & effect analysis, failure modes, effects & criticality analysis and fault tree methods. From the list of hazards, specific functional requirements and evaluation parameters could be formulated. Additional classification notations could be applied e.g. for bridge ergonomics. Established optimisation tools and techniques allow the designer to explore a wider set of possible design solutions during concept development, as described by Vassalos in the reference quoted earlier.

SAFEDOR acknowledged that approval of risk-based designed ships required a new approval paradigm, involving qualitative and quantitative assessment of innovative concepts and knowledge of current risk levels (Sames, 2007). SAFEDOR was also envisaged to embrace approval and operational phases for risk-based designed ships. Risks identified during the design process were intended to be mitigated in operation.

Where the initial design assumption were invalidated (by changes to route speed etc), periodic assessment of risks during the in-service phase were intended to be carried out onboard ship.

Figure 3.7.Comparison Between SAFEDOR and IMO's Goal Based Standards
(adapted from Vassalos, 2007)

Similarities between the SAFEDOR risk-based design approach and the IMO goal-based procedure are shown diagrammatically in figure 3.7 as explained by Vassalos (2007). The goal-based verification of compliance criteria shown in tier III of the GBS procedure discussed in the previous section 3.5.1 is linked to a corresponding tier III set of procedures in SAFEDOR, shown in the left hand side of the figure. SAFEDOR effectively fulfils the design for safety approach outlined by Wang et al over a decade ago (Wang and Ruxton, 1997). At the time of writing, SAFEDOR has matured and is due to be completed in 2009 and the findings of SAFEDOR workshops and proceedings have been published and are available on line (www.safedor.org).

### *3.5.2 Risk-Based Approach to Hull Structures*

The broad objectives of the SAFEDOR project described in the previous section approach the design problem holistically, and the initial published data from SAFEDOR dealt with defining risk criteria. To date, few specific risk-based structural studies have emerged from this work. However, the published findings from the IMO FSA study on bulk carriers detailed in section 3.3.2 contain many references to the risk-based design methodology applied to ships. Very recently, industries worldwide have adopted a risk management approach. The marine classification societies have been transformed into universal providers of risk management services, publishing guidelines for risk assessment including those from the American Bureau of Shipping (ABS, 2000). The shipping fraternity appears to be a latecomer in adopting formal risk management techniques, although it is probable that the concept of risk management has its roots in shipping. A clear tendency is emerging, with a move away from prescriptive to performance-based approaches to safety internationally, and this in turn, is paving the way for drastic evolutionary changes in design, where safety is dealt with as a central issue with serious economic implications rather than basic compliance with minimum prescriptive standards (Sames, 2007).

In section 3.2, the current approach to ship procurement was described. In sections 3.3 and 3.4, application of new risk-based safety procedures such as formal safety assessment (FSA) and the goal-based common structural rules (CSR) into the development of ship structural standards were discussed. These initiatives were noted to be at the very formative stages since most of the recent FSA studies on bulk carriers were done after 2000 and the CSR rules were introduced only in 2006. While increased involvement of the IMO in ship structural standards and the wider use of risk-based techniques for the development of class and statutory rules will undoubtedly steadily improve the performance of hull structures, there is no evidence of any improved scope for the buyer's influence in the design. In the following sections a methodology is presented which is intended to overcome this deficiency.

### *3.5.3 Structural Hazard Identification*

To properly address safety explicitly, a consistent and transparent framework is necessary and the most flexible means of establishing such a framework is through the concept of risk. Using risk assessment, ship design becomes a multi-objective, multi-criteria optimisation problem (Vassalos, 2007). Risk-based approaches involve a systematic and rational assessment of threats (hazards). The primary structural hazards affecting bulk carriers and oil tankers are undoubtedly corrosion and fatigue. Together, these two serious and interrelated hazards are believed to be responsible for over 80% of ship structural failures as discussed extensively in the literature survey sections 2.3.1 and 2.3.2. The contribution from yielding and buckling phenomena is of far less importance; however these additional hazards need to be properly addressed. There is considerable evidence to support the hypothesis that a number of mysterious structural failures involving the sudden loss of bulk carriers and in some cases, pollution by oil tankers, can be attributed directly to the effects of undetected or uncontrolled corrosion as the loss of the tanker *Erika* attests.

Figure 3.8. Prioritization Process for CSD's
(adapted from Ma et al, 1997)

Risk-assessment applied to hull structures is complex owing to the lack of data and difficulty in calculating failure probabilities. Ma et al (1997), in conjunction with the University of California at Berkeley, proposed a priority rating approach based on categorisation of critical structural details (CSD's) depicted in figure 3.8. Although this concept was originally intended to identify structural areas subject to risk-based inspections (survey), the method is equally valid for categorisation of structural areas at the design stage for evaluation purposes, which is the aim of this work. Ma et al experimented with priority classification based on a risk index approach: $P = S.C$, where $P$ was the priority rating, $S$ is the susceptibility rating and $C$ is the criticality rating. The calculated defect criticality ratings for the four categories were given as *Extreme* ($10^8$), *High* ($10^6$), *Moderate* ($10^4$) and *Low* ($10^3$). In table 3.2, the susceptibility ratings used by Ma et al and attributed to ASME 1991 are reproduced.

Table 3.2. Structural Defect Susceptibility Ratings (Ma et al, 1997)

In Ma et al's study, notional criticality ratings were given due to the difficulty in obtaining representative data of this type.

Figure 3.9. Structural Categorisation Used in RBI Prototype
(Lee et al, 2006)

Since their work, a significant amount of published data relative to acceptable risk criteria for marine pollution has appeared, including the 2005 SAFEDOR Risk Evaluation Criteria Project findings IP-516278 (Skjong et al, 2005b). In section 3.5.5 a risk matrix approach for critical structural detail assessment will be developed using data from these findings. As a prelude to developing a multi-level risk-based inspection strategy or to create a baseline of relevant critical structural details for design evaluation purposes, a list of structural areas needs to be established. As an example, the structural categorisation for a wing cargo tank is shown in figure 3.9 on the previous page, from a recently developed prototype computerised risk-based inspection (RBI) system intended for FPSOs (Lee et al, 2006).

The objective behind the above multi-level risk-based approach described by Lee et al, was to offer an alternative to the simplified deterministic method afforded only by the use of classification rules. In describing the philosophy behind this novel approach, the major contribution or "foundation of experience" provided by classification rules was acknowledged by the authors. ABS described an initial screening assessment involving the use of SafeHull Phase A & B to provide a set of strength and fatigue results in the form of class renewal thicknesses and deterministic fatigue lives forming the basis of a simplified risk-assessment using a risk matrix approach. Risk scores calculated based on the product of likelihood and consequence were determined by the software, for risk ranking or prioritisation.

A primary objective of this study was to search for a construct in which the buyer is able to perform rapid preliminary techno-economic assessments to compare alternative structural design options in a limited time frame. As a starting point, a procedure for ranking and identifying structural hazards was defined. Since Lee et al's approach differed significantly in complexity, scope and intent, the categorisation of critical structural details proposed here was based on a relatively simpler definition of generic critical structural areas (zones) within the transverse cross section of the hull. In table 3.3, a list of the defined critical areas is shown. Each of the areas is considered to be a zone containing longitudinal and transverse sub-elements. For instance, the main deck would include deck plating, longitudinal stiffeners and attached girders including transverse web frames. Similarly, other zones are defined and collectively sub-divide the hull structure transversely in a convenient way. Frame numbers can be used to describe longitudinal extent of the structural elements.

| No | Generic Critical Areas |
|---|---|
| 1 | Main deck |
| 2 | Side shell |
| 3 | Bottom |
| 4 | Inner Bottom |
| 5 | Sloping Hopper |
| 6 | Inner side |
| 7 | Longitudinal Bulkhead |
| 8 | Transverse Bulkhead |
| 9 | Bulkhead Stringers |
| 10 | Swash Bulkhead |

Table 3.3. Generic Critical Areas

This type of construct allows threats or hazards associated with the individual structural zones and elements to be systematically categorised. In the following section, the procedure for listing corrosion and fatigue hazards associated with the individual structural zones will be outlined.

### *3.5.4 Ranking & Prioritizing Hazards*

The proposed risk-based structural assessment framework formulated for the benefit of the buyer relies on identification of critical structural details, then assessing the risks associated with those elements. As acknowledged by Ma et al, corrosion and fatigue are the most pervasive types of structural problems experienced by ship structures. Therefore, these combined hazards are addressed with priority. In table 3.4 a list of corrosion threats (hazards) and consequences has been presented. In row one, the threat posed by aggressive environmental conditions associated with oil cargoes in the vapour spaces of cargo oil tanks is listed. The specific associated consequences can be identified and documented as shown. The information required to compile the data in the table can be readily obtained from the literature. A valuable source was the *Tanker Structures Co-Operative Forum* publication TSCF (1992). Numerous references were also provided in sections 2.3.3 and 2.3.4. Such a list could also be derived using a team approach based on the structured what if technique (SWIFT). Practical use of this technique has been described by Skjong (2007). This is an opportunity to utilise the combined input of experts, consultants and ship operators to identify ship specific or fleet wide hazards.

| CORROSION THREAT | |
|---|---|
| **THREAT** | **CONSEQUENCE** |
| Aggressive environmental conditions associated with the nature of certain oil cargoes in vapour spaces of cargo tanks. | Accelerated and possibly undetected corrosion damage to critical main deck structure including deck plating, weld connection between deck longitudinals and at penetration with deck web frames, compromising structural integrity of the deck. |
| Conditions for Microbes in cargo tanks. | Rapid localized pitting attack in inner bottom plating resulting in risk of leakage of cargo into the double bottom ballast tanks. |
| High saline content, humidity and high temperatures in upper parts of segregated ballast tanks. | Risk of coating breakdown and accelerated failure of ballast tank coating system. |
| Poor surface preparation in way of major hull block joints at the erection stage. | Risk of failure of tank coating system and early onset of corrosion damages in a localized band around the girth of the vessel, which if undetected, can have serious consequences. |
| High temperature cargoes in cargo tanks. | Increased risk of pre-mature and accelerated localized failure of ballast tank coatings in way of existing damages. |
| Designs featuring more than 30% High Tensile Steel (HTS) such as HT-32 or HT-36. | Localized spalling of coatings due to increased flexibility and larger structural deflections associated with these designs, leading to risk of pre-mature coating failure and accelerated structural degradation through corrosion and fatigue. |
| Use of TMCP steel. | Possible increased risk of corrosion due to the use of TMCP steels. |
| High velocity fluids under suction bell mouths in tanks. | Rapid accelerated localized pitting and reduction of thickness of inner bottom and bottom shell plating. |
| Excessive tank water washing. | Excessive water washing in cargo tanks can increase the rate of corrosion damage. |
| Excessive Crude Oil Washing (COW) or leaking COW guns. | Can cause localized structural degradation in cargo tanks. |
| High flow rates through drain holes in longitudinal members in cargo or ballast tanks. | May cause localized thinning of the web of longitudinals which is costly to rectify, since it involves a large number of structural inserts which is a high cost repair method. |

Table 3.4. List of Corrosion Hazards

High quality hazard identification sessions require the combined efforts of a multi-disciplinary team, and this could include a naval architect, members of new building project teams, marine engineers, and ship board operational staff including mates, captain and chief engineer.

| FATIGUE THREAT | |
|---|---|
| **THREAT** | **CONSEQUENCE** |
| High stress concentrations at penetrations between longitudinal elements and transverse primary structures (web frames and transverse bulkheads). | Risk of cracks/fractures at connections leading to the possibility of fractures progressing into primary structures or tank boundaries. |
| Poor quality fillet welds or insufficient throat thickness of fillet welds in welded joints between cargo containment system and Segregated Ballast Tanks. | Risk of leakage of cargo into ballast tanks with associated high clean up costs or risk of explosion. |
| Poor design of critical areas. | Heightened risk of failure of critical areas including lower hopper connection, with serious structural consequences, including leakage of cargo into ballast spaces. |

Table 3.5. List of Fatigue Hazards

Similarly, an initial general list of generic fatigue hazards can compiled from the hazard identification sessions as per the examples illustrated in table 3.5 above. In row one, high stress concentrations between longitudinal elements and transverse structures, typically transverse web frames and deck longitudinals in the transverse bulkheads have been identified. The captioned table is intended only to demonstrate the general procedure. The references given earlier in relation to table 3.4 (p.125) are appropriate here also. Having established the main categories of corrosion and fatigue damage mechanisms, detailed hazard sessions and feedback from vessels in operation may reveal specific areas prone to damage and these should be identified as illustrated in table 3.6. In row one, the connection of the inner bottom (tank top) to the hopper slant plate has been identified as susceptible to fatigue damage. The information used to compile the sample data presented in table 3.6 on the following page was obtained from a number of published papers including TSCF (1992), ABS (1995b), Bea (1993), Liu and Bakker (1981) and Ma (1995). Feedback from fleet experience with other similar vessels may also be a source of valuable data.

| Zone | Specific Fatigue Damages |
|---|---|
| Inner bottom | Connection of the hopper plate to the inner bottom |
| Inner side | Connection of hopper plate to outside longitudinal bulkhead |
| Transverse bulkhead | Connection of longitudinals to transverse bulkhead |
| Double bottom | Connection of longitudinals to ordinary floors |
| Inner bottom | At stiffener connection to bottom and inner bottom longitudinals |
| Inner bottom | At toe of web frame bracket connection to inner bottom |
| Cross Ties | At cross ties and their end connections |
| Main deck | At cut-outs around transverse bracket ends |
| Main deck | Connection of transverse web tripping brackets to longitudinals |
| Transverse bulkhead | Transverse bulkhead stringers to transverse web frames |
| Main deck | Ends of deck transverse girder |
| Main deck | Deck longitudinal tripping bracket at intercostal deck girders |
| Main deck | Deck plating in way of deck pipe support stanchions amid ships |

Table 3.6. Specific Fatigue Damages

The literature survey conducted in chapter 2 revealed the extent of information readily available in the public domain on ship structures problems, and the variety of sources of data used to compile the threat consequences tables, including the Ship Structure Committee (SSC). Refer to section 2.5.6 for a summary of information sources from the published literature review. Having documented corrosion and fatigue hazards as indicated in the foregoing tables 3.4 and 3.5, the hazard identification exercise may be extended to include other threats, including operational, as listed in table 3.7 on page 128. Here the emphasis is placed on operational threats leading to structural consequences only. As an example, the data provided in row one of table 3.7 will be discussed.

In section 2.5.2, Lacey and Chen (1995) and Witmer & Lewis (1995) reported the benefits in providing hull stress monitoring systems (HSM) onboard vessels to provide feedback and guidance to the vessel's master in relation to improved ship handling and the avoidance of structural damage to the ship in heavy weather. In row one of table 3.7, the consequences of not fitting the HSMS can be seen. Again, the data provided is incomplete and intended to serve only as an example of the decision making processes necessary for collating real data, although the data sources may be similar.

| OPERATIONAL THREATS | |
|---|---|
| **THREAT** | **CONSEQUENCE** |
| Lack of a feed back system giving information to the crew associated with navigation during adverse sea conditions. | Risk of severe structural damage including local deformation, fractures and a significant reduction in the designed fatigue capacity of the hull structure due to wave induced impact phenomena. |
| Loading cargoes outside the range of cargo densities approved in the design. | Risk of sloshing related damages cargo tank structural elements. |
| Incorrect cargo/ballast loading sequence. | Risk of damages to structural elements including cross ties due to excessive shear forces and stresses. |
| Filling of ballast in cargo tanks. | Risk of exceeding total design bending moment and shear force limitations on the hull girder if cargo tanks not rated for 1.025. |
| Excessive berthing forces. | Risk of deformation and fractures in side shell plating and side ballast tank internal structures. |
| Uncontrolled conditions during dry docking. | Risk of bottom plating and internals and docking brackets set-up during routine dry docking and associated additional off-hire and repair costs. |
| Tank overpressure during operation. | Risk of major structural damage to tanks with associated off-hire and repair costs. |
| Excessive sloshing forces in cargo tanks. | Risk of major structural damage to tanks with associated off-hire and repair costs. |
| Lack of Swash Bulkheads in cargo tanks. | Risk of major structural damage to tanks with associated off-hire and repair costs. |
| Partial filling of ballast tanks during Normal Ballast condition. | Risk of major structural damage to Forepeak Tank including fracture of horizontal stringers with associated off-hire and repair costs. |
| Falling objects (e.g. during crane operations). | Risk of major structural damage to deck with associated off hire and repair costs. |
| Vibration caused by machinery or propeller. | Risk of cracks or fractures in SLOP tank or adjacent cargo/ballast tank structures. |
| Excessive impact pressures in the bow area. | Risk of major structural damage to foredeck or loss of equipment with significant off hire and repair costs. |
| Doubler plates or enclosed structures (e.g. piping fixtures such as hand rails). | Increased risk of accidents (explosion hazard) during subsequent hot repairs. |

Table 3.7. List of Operational Threats (Structural)

### *3.5.5 Risk-Assessment*

Having developed a list of hazards using techniques similar to the ones described in the previous section, the risks associated with those hazards can now be assessed. The consequences of structural failure in bulk ships are well known and could involve:

- Unscheduled off-hire to effect temporary repairs.
- Unscheduled dry docking repairs.
- A refusal from ports to offload a tanker due to oil leakage into the sea.
- Offloading of cargo due to a crack in the shell (single hull tankers).
- Catastrophic hull failure caused by corrosion and fatigue and major oil pollution involving severe economic consequences.
- Explosion, fire and possible loss of the vessel due to leakage of cargo into the ballast spaces in a double hull tanker.

The consequence or "criticality" ratings are difficult to establish. It is important to distinguish between failure consequences caused directly by human error, such as collision and grounding as opposed to failures directly related to root structural causes, which is the focus of this study. It is acknowledged that this separation is not always clear, since the structural integrity is heavily influenced by the way in which a vessel is operated, which has been highlighted previously in section 2.2.2. In other cases the initiating event (e.g. explosion and fire, or unexplained loss) may have been structural and this has not always been correctly identified as the root cause, as discussed in section 2.6.

Acceptable risk criteria associated with human life have been presented as part of the SAFEDOR initiative, although development of appropriate risk criteria within the IMO is a work in progress (Skjong, 2007). In order to properly associate consequence ratings with structural assessment, economic consequences have to be linked to the risk of failure. To do this, the consequences of environmental pollution or off-hire due to unscheduled repairs have to be converted into financial risk. The Norwegian Petroleum Directorate (NPD) has released risk acceptance criteria related to oil spills on the Norwegian continental shelf (Wang and Trbojevic, 2007). The SAFEDOR project released risk acceptance data related to oil pollution recently. It was claimed that 85% of spills were of less than 7 tonnes. Collisions and groundings accounted for more than 60% of all spills of more than 700 tonnes. Clean up costs ranged from USD 1,300/tonne in The Middle East to USD 33,000/tonne in Asia, with a global weighted average of USD 16,000/tonne. The cost elements considered in the development of appropriate risk acceptance criteria were said to be a combination of environmental clean up costs, safety (cost/human life) and monetary costs (property, off-hire etc). Skjong (2005b) describes the cost of averting a tonne spilt (CATS) criterion where CATS < F x USD 40,000, and F is an insurance factor between 1.0 and $F_{max}$.

From an FSA viewpoint, such criteria will eventually be used to set a socially acceptable level of risk (i.e. through the courts). In this study, a simpler approach is adopted, where consequence is derived from an assumed cost of an oil spill which is directly linked to the structural failure event. Past events have proven that the total costs of major oil spills may exceed one billion dollars, as was the case for *Exxon Valdez*. In table 3.8, costs exceeding this level establish the very high consequence category. Spills involving > 700 tonnes may exceed USD 1 million as the SAFEDOR data implies (i.e. at the lower limit for the Middle East USD 1,300/tonn x 700 = approximately USD 1.0 million). Medium spills are set by USD 100,000 and above, based on 3 days off-hire at current daily break even rates for VLCCs of approximately USD 30,000/day. Similarly the lower limits are given using this approach to establish reasonable consequence categories.

| **Consequence** | **Cost USD (ship-year)** |
|---|---|
| Very Low | 1 |
| Low | $10^3$ |
| Medium | $10^4$ |
| High | $10^6$ |
| Very High | $10^9$ |

Table 3.8. Consequence Criteria – Cost of Oil Spills

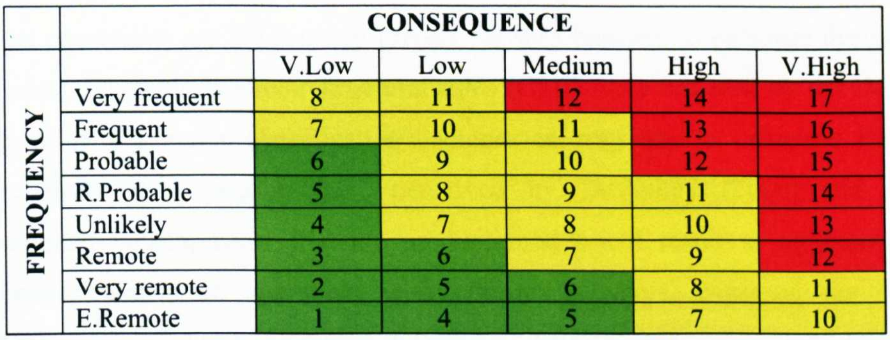
Annual target reliabilities for marine structures have been published by DNV as far back as 1992, shown in table 3.9. The target reliability indices associated with the annual probabilities of failure are indicated in brackets. The difficulty in using this type of information for preliminary assessments of the kind attempted here has been pointed out by Ma et al (1997). "Assigning a susceptibility rating is usually considered more difficult than assigning a criticality rating unless substantial in-service experience records are available". For this reason, the susceptibility criteria given in Ma et al's study are notional (see table 3.2, p.122).

Table 3.9. Annual Failure Probabilities for Marine Structures (DNV, 1992)

In this study the seven frequency indices proposed by Skjong (2007) are adopted and shown in table 3.10. The criteria range from *very frequent* (100) to *extremely remote* (0.00001) failures/ship/year. These frequency criteria are used to construct a 7 x 5 risk-matrix shown in table 3.11.

Table 3.10. Frequency Indices (Skjong et al, 2007)

The risk criteria in matrix form are the product of the frequency indices listed in table 3.10 multiplied by the consequence criteria listed in table 3.8. The results are presented above in simple standardised risk matrix format and the coloured zones represent the views of the decision maker regarding high, medium and low risk acceptance categories.



| | | CONSEQUENCE | | | | |
|---|---|---|---|---|---|---|
| | | V.Low | Low | Medium | High | V.High |
| FREQUENCY | Very frequent | 8 | 11 | 12 | 14 | 17 |
| | Frequent | 7 | 10 | 11 | 13 | 16 |
| | Probable | 6 | 9 | 10 | 12 | 15 |
| | R.Probable | 5 | 8 | 9 | 11 | 14 |
| | Unlikely | 4 | 7 | 8 | 10 | 13 |
| | Remote | 3 | 6 | 7 | 9 | 12 |
| | Very remote | 2 | 5 | 6 | 8 | 11 |
| | E.Remote | 1 | 4 | 5 | 7 | 10 |

Table 3.11. CSD Risk Matrix

The methodology for the risk-matrix approach is covered in many textbooks including Wang & Trbojevic (2007). The risk matrix approach is recommended for preliminary screening assessments of critical structural details which form part of the structural assessment framework developed further in chapters 4 and 5.

In the above sections, a methodology has been presented for documenting threats and consequences associated with the main structural damage mechanisms affecting large bulk ships (corrosion and fatigue). A formal risk assessment approach has been suggested as a preliminary procedure for screening critical structural details (CSDs). In chapter 4, a multi-level set of structural assessment criteria will be developed including the (level 3) sub-criterion *Strength*. In turn, this criterion will be shown to be composed of a number of (level 4) sub-criteria including *Critical Areas*. In section 5.4.4 it will be demonstrated how the sub-criterion *Critical Areas* can be assessed based on the approach outlined above. These processes form part of a multi-layered risk-based methodology, forming the input for the proposed MCDA/ER structural assessment framework which will be developed fully in chapters 4 and 5.

## 3.6. Conclusions

The current economic environment in which ship owners interested in procurement of new bulk ship tonnage find themselves, is challenging. Productivity considerations and least cost constraints are the primary drivers for ship builders to optimise designs and lower costs. The new common structural rules (CSR) were initiated by the IMO and developed by the major classification societies in response to criticism from the industry over "the down ratchet" perceived by Devanney (2006) and others. Technological developments like the product model will result in an increasingly collaborative web-based approach to the design of ships, engaging the builder, classification societies and vendors in the product development. Buyers may either take a passive role in these developments and accept a baseline product or exercise their options in the design process to improve the quality based on their own stated performance expectations. A number of conclusions naturally arise from this chapter:

- Large bulk ships represent unique made-to-order products. New tonnage is ordered across a spectrum of owners' requirements ranging from standard designs to full bespoke designs of "high quality". Industry perceptions of quality are widely different, and the definition has to be linked to the buyer's expectations. Numerous industry critics have expressed serious concerns over the current quality of new oil tankers and bulk carriers.

- Commercial ship design has unquestionably been an exercise in design optimisation and profitability. Empirical methods based on accumulated experience were traditionally relied upon, and structural failures drove the development of prescriptive codes. Ship yards designing and building the product were focused on minimisation of capital cost.

- The problem with the rationally-based, computer-aided approach to ship structural design has been the underestimation of the stochastic loads acting on large bulk ship structures and the severity of the degradation mechanisms in relation to highly optimised ship structures which were not adequately maintained.

- In an engineering sense, quality also implies performance optimisation, cost minimisation and wise use of scarce resources. This optimisation is not necessarily at odds with the customer's objectives, provided that the specifications for design and construction are robust enough to ensure that the target safety levels are met.

- A balance has to be struck between structural designs optimised to the extent that the reliability, robustness and safety have been seriously compromised and designs which are grossly wasteful in terms of additional steel and cost required. In reality, the minimum standard can be used as a reference and baseline to work up from for the structural selection problem.

- Least cost minimum standards bulk ship designs are sensitive structures which rely on increased levels of maintenance effort over the lifetime of the vessel in order to compensate for the reduced safety levels incorporated in the design (assumed loads, materials, increased scantlings etc). This connection between quality and maintenance effort appears to be poorly understood. Historically, the phenomenon of speculative interests operating ships has been associated with failure to maintain vessels adequately.

- Post CSR oil tanker and bulk carrier designs may not be any more robust than the previous ones. As the net increase in steel weight is marginal in most cases. However, it is reasonable to accept that incremental improvements in hull structures will arise from the adoption of risk-based principles, goal based standards and a holistic approach to safety management adopted by the IMO, although the CSR should continue to be regarded as a minimum standard.

- Emphasis should be directed at exercising the buyer's input into the design using a layered risk-based approach, founded upon the minimum classification and statutory standards including the goal-based CSR. This is the essential philosophy behind the proposed multi criteria decision analysis (MCDA) and evidential reasoning (ER) structural assessment framework.

- A balance of views is always necessary between the position of the strident critic and the vested interests. However, the sensitive nature of large bulk ship structures, combined with the threats of a poorly specified and executed structural details, rapid hull degradation due to unmitigated corrosion and fatigue, and a minimum compliance approach to hull maintenance represent an irresistible conspiracy against good safety standards in an age when societal concerns for the environment are heightened.

- Shipping companies interested in extended vessel lifetimes and reliable structural performance are likely to have heightened expectations relative to hull robustness and durability

- The transfer of risk-based safety methods from industrial and offshore applications is occurring in the marine shipping industry. While increased involvement of the IMO in ship structural standards and the wider use of risk-based techniques for the development of prescriptive class and statutory rules will undoubtedly steadily improve the performance of hull structures, there is a lack of evidence of any improved scope for the buyer's influence in the design. This major weakness in current ship design and procurement will be addressed through the further development of a risk-based structural assessment framework which is one of the main objectives of the present study.

# Chapter 4 - Articulating Product Performance Criteria and the MCDA/ER Structural Assessment Framework

***SUMMARY***

*In the previous chapter, problems with the current methods of ship procurement and quality were identified. In this chapter a unique approach to the selection between alternative ship structural designs is adopted, and a model is developed based on multiple criteria decision analysis (MCDA), evidential reasoning (ER) and the Dempster Shafer evidence combination rule. The method relies on articulation and identification of a set of key structural performance criteria or attributes developed here, some of which may be directly specified by the buyer. This method is chosen to deal with the complex array of quantitative and qualitative data, and sometimes incomplete or uncertain subjective judgements encountered in this type of problem. The model takes into account both economic and technical criteria. The method is proposed as a useful framework for the purchaser, by improving transparency in conducting fast preliminary rational techno-economic capital expenditure project evaluations, such as the purchase of new ships. The above goals for this chapter partially satisfy the sub-objective no.4 stated in section 1.2.*

## 4.1 Introduction

In chapter 2, a literature survey was conducted, revealing recurring performance problems in large tanker and bulk ship structures, posed mainly by the combined hazards of corrosion and fatigue, and the failure of the current prescriptive rule-based regulatory system to properly address these hazards. In chapter 3, the current ship production environment, characterised by optimised designs, short delivery schedules, baseline designs and underscored by the prevailing seller's market conditions were outlined. In section 3.2, flaws in the minimum prescriptive standards approach to procurement of large bulk carriers and tankers were exposed. In section 3.3, a range of new risk-based safety technologies recently introduced into shipping were described including design for safety, formal safety assessment, the safety case model and the goal-based common structural rules. In section 3.5, a risk-based method of structural categorisation using critical structural details, priority ratings and a risk-matrix was proposed.

The background to MCDA decision support methods will be briefly explained as a lead up to the reasoning for the selection of the evidential reasoning (ER) theory for this application. The ER method is based on multi attribute utility theory (MAUT) and evidence theory advanced by Dempster & Shafer. The MCDA/ER method has been extensively used for a variety of engineering and business applications in a contemporary context (Yang et al, 2002a). The ER method forms the kernel of a unique structural assessment framework indicated as the primary objective of this research work. In section 4.4 as a prelude to the use of the ER framework, a set of structural attributes is articulated in order to construct a rational framework for use in the ER algorithm and for eventual utility ranking of alternative structural design options.

## 4.2 Decision Support Methods

### *4.2.1 Multiple Criteria Decision Analysis (MCDA)*

There is a growing consensus of opinion that the principal function of engineers is to make decisions, that the heart of design is decision making, and engineering design essentially consists of identification of options and selection of the best option (Mistree and Bras, 1991; Mistree et al, 1990). To deal with selection decisions involving trade-offs between multiple conflicting attributes associated with risk or uncertainty, methods such as the utility-based selection decision support problem (DSP) for rapid prototyping of products, and the work of the Georgia Institute of Technology is noteworthy in this regard (Fernandez et al, 2001). There are a number of other decision support methods relying on identification of relevant product characteristics or attributes including quality function deployment (QFD), the house of quality (HoQ), Pughe's selection method, scoring and weighting methods, analytical hierarchy process (AHP), multi-attribute utility theory (MAUT), physical programming, the Taguchi loss function and Suh's axiomatic design (Olewnik et al, 2003).

Multiple criteria decision analysis (MCDA) refers to decision-making in the presence of complex, often conflicting criteria. MCDA methods have a relatively short history spanning approximately 35 years. Business applications of MCDA such as the European Foundation for Quality Management (EFQM) business excellence model are in common use (Xu et al, 2003). In the medical sector, the Canadian Health Utilities Index (HUI2 & HUI3) is a multiple attribute health status classification system, combined with a generic utility scoring system (HRQL) providing a comprehensive framework within which to describe health status. The HUI12 system contains 7 attributes – *sensation, mobility, emotion, cognition, self-care, pain and fertility*, each with 3-5 levels, describing 24,000 unique health states. Information for the system is provided by HUI questionnaires. According to Vassalos (2007) earlier in section 3.5.3, risk-based ship design has been referred to as a typical case of a multi-objective, multi criteria optimisation problem.

### *4.2.2 Techno-Economic Considerations*

When assessing the benefits of new capital expenditures including ships, the aggregate changes in the welfare of all stakeholders have to be evaluated. These changes are usually measured in monetary terms, but the effect on life or the environment cannot easily be calculated on the basis of cash disbursements. Investment decisions represent major commitment of corporate resources and can have significant impact on the financial stability of an organisation. Companies can easily incorporate economic, environmental and social aspects in dollar terms. This research proposes that all major capital expenditure decisions like the purchase of a new oil tanker or bulk carrier should be carried out on the basis of a full techno-economic evaluation according to a comprehensive rational and transparent procedure. Only then can the latent financial risks associated with improper tradeoffs in the list of technical options be properly anticipated.

Recurrent accident scenarios have a relation to market conjectures. So-called "blue-chip" companies should keep operational management independent from commercial management, as reported by Soma (2004), following an in-depth study of the link between freight rates and ship loss ratios, adopting the term "commercial accidents" in section 2.2.4. Possibly, commercial considerations have often taken precedence over technical concerns in the inevitable capital expenditure trade-offs which occurred during the purchase of new tonnage. In the past, where cargo owners had no interest in safety and quality, substandard ships and shipping companies could trade under all flags ands class societies and find insurance. There appeared to be little incentive for an improved techno-economic approach (OECD, 2001).

### *4.2.3 Product Characteristics and Quality*

The product attribute "quality" is often loosely defined and commonly misunderstood. Often quality is perceived as fitness for purpose or for intended use. In discussions concerning quality of ship structures, there are many varied viewpoints. There are those who consider current quality levels to be high. On the other hand, many critics contend that current quality levels are unacceptably low. Many definitions of quality can be found in the literature as discussed in section 3.2.5. This subjectiveness in interpreting the quality attribute makes a precise definition impossible. Therefore, to capture the meaning of quality in order to define it, one must look to the general product engineering field for an answer.

High product quality involves performance characteristics that are highly optimised to meet customer expectations together with robust product performance. Generally, the majority of performance characteristics are quantitative. Quality is diminished by variability in manufacturing, variability in adverse operating environments and by product deterioration (Lewis, 1994). Current markets for consumer products, high technology equipment, medical, automotive, aerospace and the defence related industries, dictate meeting customer needs and providing superior value through quality. Where there is no one monolithic voice of the customer in consumer markets, the aim is to capture multiple and diverse customer needs and convert them into better perspectives for product development.

Fig 4.1. Generic House of Quality (Olewnik & Lewis, 2003)

In a recent article, Olewnik and Lewis (2003) have described the quality function deployment (QFD) technique for translating customer requirements into product requirements, through a comprehensive matrix called the house of quality (HoQ) depicted in figure 4.1. QFD was developed by Akao and was implemented first at Mitsubishi Heavy Industries Kobe Shipyard in 1972 and later adopted by Toyota between 1977 and 1984. The HoQ represents a basic design tool which depicts the relationship between the customer attributes listed in the rows of the matrix and the product engineering or technical requirements listed in the columns of the matrix. In the relationship matrix, the effects of each engineering attribute on each customer attribute are determined. The HoQ paradigm is widely used in product development as attested by a large number of websites offering related services (e.g. http://www.sixsigma.com)

### *4.2.4 Selection of an Appropriate Method*

Unfortunately, large scale real world problems often involve a mixture of quantitative and qualitative attributes with uncertainties. Therefore, a need exists to provide a rational, transparent and repeatable procedure for dealing with MCDA problems of this nature (Xu et al, 2003). Developments in computing and information technology have made it possible to conduct systematic analysis of complex problems. Since design is essentially selection between options, and options are best compared using a set of performance attributes, the starting point in developing a risk-based approach to selection between alternative structural design options therefore, is to firstly identify the relevant performance attributes, and secondly to select an appropriate theoretical method for the selection process.

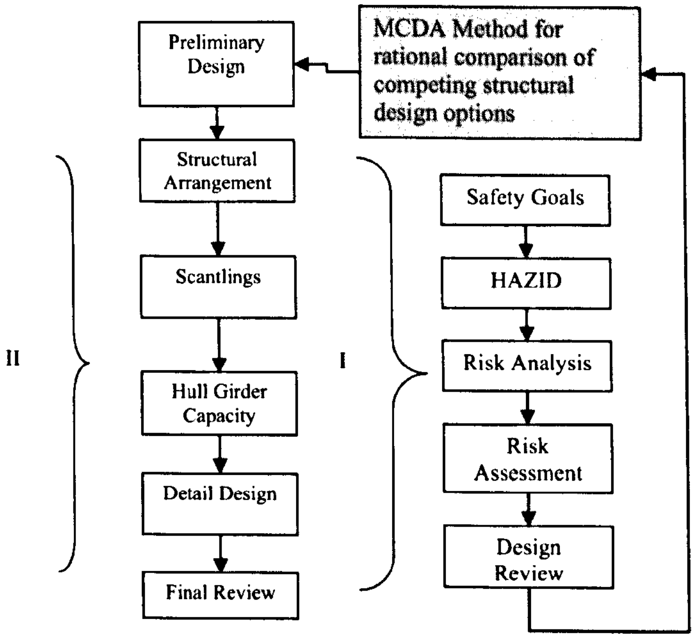


Figure 4.2. Risk-Based Ship Structural Design – Buyer's Perspective

In phase I, a formal safety assessment (FSA) is performed by the buyer, in conjunction with the preliminary structural design process. In phase II, the performance criteria and objectives arising from the results of the MCDA/ER structural assessment framework are input into the preliminary design process as shown diagrammatically in figure 4.2. The MCDA/ER method has been chosen for this particular application in view of the extensive number of published papers and research reports which have been generated including engineering safety related applications discussed in section 4.5.1 and the availability of the Intelligent Decision System (IDS) software package developed by Xu and Yang (2005).

## 4.3 Performance-Based Ship Design

### *4.3.1 Performance Based Marine Design(PBD)*

The first efforts to adopt a performance based approach to marine design came with the establishment of the EU Thematic network, SAFER EURORO in 1997, with the objective of promoting the design for safety philosophy in the maritime industry (Vassalos, 2007). This initiative led to the 1995 SAFEDOR project led by GL and funded partly by the EC and 53 consortium partners, described in detail in section 3.5.1. SAFEDOR was intended primarily for cruise vessels in Europe. Safety goals were associated with company values, policies and safety considerations. Hazards could be identified using systematic and rational hazard identification techniques. From the list of hazards, specific functional requirements and evaluation parameters could be formulated. Established optimisation tools and techniques allowed the designer to explore a wider set of possible design solutions during concept development, as described by Vassalos (2007).

The same trend has been noted in land-based industries. In recent years, an alternative to the specification-based, prescriptive approach is emerging in the civil engineering, community. This new approach is being driven by seismic engineers seeking a performance-based approach (Aktan et al, 2006; Deru and Torcellini, 2004). Generally, the design of buildings is driven by the need to satisfy a set of minimum criteria, such as budget constraints, time schedules, functionality requirements, safety regulations and energy codes. This is said to produce buildings just meeting minimum criteria. To achieve better than average or exceptional performance, the design team should include the building owner working together with a focussed effort towards performance goals to provide direction to these efforts. These performance goals need to be set during the initial stages of design, and the design team buys into the goals or establishes them (Spekkink, 2005). As a result, a clear tendency is emerging of a move away from prescriptive to performance based approaches to safety across international and industrial boundaries.

### *4.3.2 PBD of Ship Structures*

In section 3.2, the limitations of the current approach to the design and construction of large bulk ships were described and failure to properly engage the customer in the design process was indicated as a factor in the perceived quality problems associated with bulk ship designs. A spectrum of design options ranging from least cost minimum standard ship yard designs, barely complying with classification standards, through to high quality ships built to bespoke specifications, considerably in excess of classification rule requirements was identified. It was also recognized that the non blue-chip shipping interests identified by Soma and the OECD studies referred to earlier in section 2.2.4 would not be motivated beyond a minimal compliance level for ship design and this philosophy could extend to ship operation and hull maintenance. However, for shipping companies interested in extended vessel lifetimes, and maintaining good reputations with port States and other stakeholders, structural robustness and reliability of the fleet would be factors which would encourage these owners to have more influence over the way their vessels were designed and constructed.

Performance based design of ships has been envisioned as the functional requirements established by the owner and institutional requirements established by governmental and regulatory bodies concerned with safety and pollution prevention. The principal elements of the ship structure are designed in such a way that the ship will efficiently perform its function for the intended lifetime. Performance based design of ships is an exercise in philosophy, engineering and project management. The philosophy used to develop the hull structure of the 12,000 DWT Millennium Class tankers for ARCO Marine was recently described by Read et al (2000). These ships were built to operate in the Gulf of Alaska, one of the most severe ocean environments in the world. "The overall intent was not to build a ship that just met the rules of class. The intent was to construct a vessel that would meet or exceed the rules as required, to a degree that the vessel became uniquely suited to meet the owner's need for extended service in a severe environment".

### *4.3.3 The Buyer's Options*

The ship owner (customer) potentially has the opportunity to control major ship design parameters including global strength criteria, selection of materials, definition of corrosion margins etc which can profoundly influence the structural performance of the vessel. Aspects of the structural design which may be directly specified or influenced by an owner are listed below (Lee, 2000):

- Combination of cargo patterns and draught.
- Design bending moments.
- Higher cargo density for fatigue.
- Major design parameters (cargo density, scantling draught etc).
- Special full and part loading conditions.
- Ballast arrangements and unrestricted filling.
- Ballast exchange.
- Cargo Tank arrangements.
- Measures to prevent cargo sloshing.
- Structural configuration.
- Additional scantlings.
- Corrosion margins.
- Coating Specifications.
- Materials.
- % High tensile steel (HTS).
- Lightweight mass.
- Fatigue life (global + local).
- Access and ventilation arrangements.
- Detail design.
- Vibration analysis.
- Classification (+ notations).
- Construction quality (welding + fit-up).
- Coating application.

It should be noted that section 2 (5.1.9) of the new IACS Common structural rules for tankers contains a list of "owners extras" (IACS, 2006b), partially including the above listed aspects.

### *4.3.4 Structural Performance Goals*

In a performance based structural design approach, an owner should establish written performance goals or objectives. These should be compared to the stated goals developed in conjunction with the IMO goal-based structural standards described in section 3.4.1. The owner's performance objectives will reflect his own specific requirements similar to the example below:

- At least 25 years continuous and environmentally safe operation based exclusively on The Gulf to Europe and The Gulf to the Far East routes, based on normal operating conditions and reasonable duty of care obligations and an operational profile of 335 days per year at sea, in cargo mode 50% of the time, and in ballast mode 50% of the time.
- The annual probability of serious fractures or cracks leading to cargo leakage from the inner containment system into the segregated ballast tanks to be less than $1 \times 10^{-4}$ during 25 years of continuous operation based on the above specified operational profile.
- The annual probability of initial breakdown of coating systems inside the segregated ballast tanks to be less than $1 \times 10^{-4}$ during 15 years of operation, assuming the above specified operational profile.
- The hull structure to be designed for safe access and ease of maintenance
- The vessel to be designed for safe and environmentally friendly operations including cargo loading and discharge operations, including emergency conditions which may involve ballasting designated cargo holds ("gale ballast condition") and ballast transfer operations to comply with MARPOL requirements.

The above list is intended to illustrate the nature of an owner's performance objectives and therefore serves as an example only.

## 4.4 Articulation of Structural Assessment Criteria

### *4.4.1 Structural Assessment Framework*

In a recent paper dealing with the vessel selection problem, Xie et al (2008), list the main uncertainties encountered by decision makers as different types of assessment, imprecise assessment due to insufficient data, shortcomings in expertise, inadequate time for evaluation, the inability of experts to provide a fully detailed assessment and the lack of proper and robust aggregation of subjective and objective assessments made on multiple decision criteria. The basic problem is to aggregate the input data, where linguistic and numerical assessments have to be transformed into a unique plane either by transforming numerical data into qualitative forms, or by assigning numerical values to the linguistic terms. The proposed structural assessment framework therefore, represents a departure from the usual analytical approach based on calculation and comparison of stresses, because it relies upon a combination of qualitative (linguistic) and quantitative (numerical) assessment criteria, subject to the considerations outlined above.

As a means of assessing optional structural configurations, in this case large bulk ship hull structures, against the performance goals stated above, a suitable set of linguistic and numerical performance criteria must be established. The assessment criteria allow the use of standard decision support techniques such as MCDA. Due to the subjective judgments and imprecise numerical data normally available during an owners assessment of structural designs, the evidential reasoning (ER) algorithm was considered to be the most suitable technique as described by Yang et al (1997; 2002a; 2002b). This allowed a rational transparent framework to be developed for comparison of alternative but similar VLCC structural design options by ranking in order to facilitate preferences, as described in the following sections.

### *4.4.2 Top Level Criteria*

For the purpose of demonstrating the generality of the proposed structural assessment framework, the example chosen was a typical 300,000 dwt oil tanker (VLCC) similar to that shown in figure 2.1(a). In section 5.3, a description of the structural arrangements and scantlings will be presented. A five level structural assessment framework comprising a number of main criteria and sub-criteria has to be assembled in an assessment hierarchy in order to model the selection process. In this section, the selection criteria will be developed and articulated.

| Level 1 Criterion | Level 2 Sub-Criteria |
|---|---|
| ***Design Selection*** | *- Commercial*<br>*- Technical* |

Table 4.1. Top Level Criteria, Levels 1&2

At the top level (level 1), a number of alternative VLCC structural designs are to be evaluated under the main criterion, *Design Selection.* The basic hierarchical framework for structural assessment of VLCC structural options proposed in this study, comprises a combination of both *Commercial* and *Technical* (level 2) performance criteria shown in table 4.1.

| Level 2 Criteria | Level 5 Sub-Criteria |
|---|---|
| *Commercial* | *- NPV*<br>*- Warrantee*<br>*- Classification* |

Table 4.2. *Commercial* Sub-Criteria, Levels 2 & 5

As the top criterion is assessed on the basis of a combination of a set of both commercial and technical sub-criteria, the method is techno-economic. The *Commercial* criterion comprises three (level 5) sub-criteria: *NPV, Warrantee and Classification* listed in table 4.2.

### *4.4.3 Commercial Criteria*

**Net Present Value (NPV):** There are a number of established capital budgeting techniques used in conjunction with the planning of major capital outlays such as the acquisition of new ships. Erroneous forecasts of asset requirements can result in serious consequences. To satisfy boards of directors responsible for approval of major capital outlays, and to organise the necessary funding, alternative proposals have to be evaluated according to an established capital expenditure ranking procedure. Four methods for ranking mutually exclusive investment proposals are the payback method or payback period, return on assets (ROA), the net present value (NPV) method and the internal rate of return (IRR) method. Due to flaws in the payback and ROA methods, discounted cash flow (DCF) techniques were developed including the net present value method which is in widespread usage, according to Weston & Copeland (1989). The equation for the net present value is:

$$NPV = \left[ \frac{CF_1}{(1+k)^1} + \frac{CF_2}{(1+k)^2} + \ldots + \frac{CF_n}{(1+k)^n} \right] - I_0 = \sum_{t=1}^{n} \frac{CF_t}{(1+k)^t} - I_0$$

where $CF_t$ represent the net cash flow, $k$ is the firm's cost of capital, $I_0$ is the initial capital expenditure and $n$ is the project lifetime. The NPV method has been chosen as the most appropriate index of project viability (Weston & Copeland, 1989). When the discount rate is zero, the NPV of the project is simply the sum of the cash flows. As the NPV of a project is exactly the same as an increase in the shareholder's wealth, projects can be ranked on the basis of the highest NPV and this is the method adopted in the model. A zero NPV means that the debt and equity holders are compensated for risk. A positive NPV project earns more than the required rate of return. However, the IRR can also be used for ranking of projects. If the projects are mutually exclusive, any project which has an IRR greater than the cost of capital (e.g.10%) would be accepted for comparison purposes.

**Classification:** The choice of classification society is normally considered to be an owner's option, although classification is actually a commercial decision because formally, the classification society is contracted by the builder to provide classification services. The relationship with the owner does not normally commence until vessel delivery.

**Warranty:** Structural warrantees for commercial ships are usually only valid for 12 months following the delivery date, coinciding with the end of the builder's guarantee period. In some cases, an extended structural warrantee may be negotiated with the builder and therefore it is also considered to be a commercial decision in the proposed structural assessment framework.

### *4.4.4 Technical Criteria*

The literature survey carried out in chapter 2 revealed weaknesses in the current approach to the safety performance in design, construction and operation of large bulk ships. In chapter 3, the views of critics in relation to design quality were critically examined with a view to establishing a set of key performance attributes or criteria which could be used in a structural assessment framework described in the introductory remarks to this chapter. In this section, the *Technical* criteria will be articulated as part of the proposed MCDA/ER structural assessment framework.

| Level 2 Criteria | Level 3 Sub-Criteria |
|---|---|
| *Technical* | *- Strength*<br>*- Durability*<br>*- Arrangements*<br>*- Operational* |

Table 4.3. *Technical* Sub-Criteria, Levels 2&3

The main technical considerations involved in the decision-making process can be captured by four distinct sub-attributes. To achieve this, the level 2 *Technical* criterion has been sub-divided into four (level 3) sub-criteria, *Strength, Durability, Arrangements* and *Operational* listed in table 4.3. The level 3 *Strength* criterion is further sub-divided into five (level 4) sub-criteria *Global, Fatigue, Buckling, Dynamic* and *Critical Areas* listed in table 4.4 on the following page.

| Level 3 Criteria | Level 4 Sub-Criteria |
|---|---|
| *Strength* | *- Global*<br>*- Fatigue*<br>*- Buckling*<br>*- Dynamic*<br>*- Critical Areas* |

Table 4.4. *Strength* Sub-Criteria, Levels 3&4

In turn, the five (level 4) sub-criteria in table 4.4 are further sub-divided into the lowest level (level 5) *Strength* sub-criteria listed in table 4.5

| Level 4 Sub-Criteria | Level 5 Sub-Criteria |
|---|---|
| *Global* | *- Longitudinal*<br>*- Transverse* |
| *Fatigue* | *- Hull Girder*<br>*- Side Structure* |
| *Buckling* | *- Main Deck*<br>*- Member 1*<br>*- Member 2*<br>*- Member 3* |
| *Dynamic* | *- Berthing*<br>*- Sloshing* |
| *Critical Areas* | *- CA-1*<br>*- CA-2*<br>*- CA-3* |

Table 4.5. *Strength* Sub-Criteria, Levels 4&5

*Global Strength* is described by *Longitudinal Strength* and *Transverse Strength* sub-criteria. To illustrate the framework for structural evaluation, a detailed explanation of the determination of the above strength criteria is given in the following sections. In section 4.5.3 it will be demonstrated how these numerical and qualitative criteria will be used to construct the hierarchical framework for the ER model. For the purpose of illustrating the method, examples of the processing of the individual data will be given. A calculation of the ultimate strength ratio for the hull girder will be presented in section 5.4.1.2.

At an early stage in the ship design process, the hull girder global, fatigue and buckling strength can be assessed based on preliminary design information made available by the builder. If drawings are supplied by a number of competing ship yards, they could be used as a basis for evaluation of alternative structural designs. These drawings may include the General Arrangement, Midship Section, Longitudinal Profile, Transverse Sections, Structural Details and Capacity Plan. The information obtained from the builders drawings may be used as input data for the strength assessment using the criteria listed. In the following sections, a brief outline of the theory behind the chosen longitudinal strength evaluation approach is presented. In the following, the criteria will be articulated in detail.

#### *4.4.4.1 Global Strength*

**Longitudinal:** Ship structures have traditionally been designed according to the global strength and allowable stress criteria established by the international classification societies as described in section 2.2.3. However, it is now well recognized that the limit state approach to the design of steel plated structures is a much better basis for design (Frieze et al, 2007; Paik & Thayamballi, 2003a; 2003e; 2003f; Paik and Faulkner, 2003b; Sun and Wang, 2005). The simplified methods used to analyse ship structures in the past have relied upon estimates of the elastic buckling strength with a plasticity correction. The true ultimate strength is not revealed by allowable stress design (ASD) as in typical ship structures, due to the onset of buckling, where the cross section is not able to develop its full plastic moment resistance.

Under an applied vertical bending moment, the yield point is reached in deck or bottom flanges, progressing through the side shells and plastic deformation spreads over a substantial portion leading to structural failure. Failure may then occur either through fatigue cracks, spreading plasticity, instability or sudden brittle fracture. Ultimately, a fully plastic moment is reached when yield has developed at every point throughout the depth of the structure (Frieze and Lin, 1991). In double hull tankers, deck buckling is likely to occur in sagging, reducing the collapse response substantially. To obtain a safe and economic structure, it is essential to calculate the true ultimate strength. According to Paik and Thayamballi (2003a), and in the most general sense, the partial safety factor-based design criterion relating demand to capacity for a structure under multiple simultaneous load types can be expressed as follows:

Design demand = $D_d = \gamma_o \sum_i D_{ki}(F_{ki}, \gamma_{fi})$

Where $D_{ki}(F_{ki}, \gamma_{fi})$ = characteristic measure of demand for load type $i$ calculated from the characteristic measures of loads $F_k$ and magnified by the partial safety factors $\gamma_f$ and $\gamma_o$

Design capacity = $C_d = \dfrac{C_k}{\gamma_M}$ and safety measure implies that $\dfrac{C_d}{D_d} > 1$

where $F_k$ = characteristic measures of loads, $\gamma_f$ = partial safety factor related to loads, $\gamma_o$ = partial safety factor related to safety and serviceability, $C_k$ = characteristic measure of capacity, $\gamma_M = \gamma_m \gamma_c$ = capacity related safety factor, $\gamma_m$ = partial safety factor related to materials and $\gamma_c$ = partial safety factor related to quality of construction.

The practical application of the reliability approach in relation to ship structures is still in the research domain, although the incorporation of a requirement to calculate the ultimate strength of the hull has already been introduced in the common structural rules. Recently, more efficient non-linear analysis methods utilising very large-sized structural elements have been developed to analyse the progressive collapse behaviour of ships hulls. Such methods were first proposed in the mid 1970s, and have become more practicable due to the progressive development of the modern finite element method. Unlike conventional FEM, the idealized structural unit method (ISUM) utilises specially formulated ISUM unit assemblages comprising groups of plate stiffener combinations. Paik and Thayamballi (2003a) have shown that the progressive collapse behaviour of ships hulls can be predicted using an automated version of the ISUM approach, known as ALPS/ISUM. The method has been benchmarked against a physical test performed on a frigate in 1991 (Dow Frigate). The ISUM model comprised an assemblage of rectangular plate units and stiffeners between two transverse frames. Since then the ALPS/ISUM approach has been widely used and in the following, the collapse behaviour for a DH tanker will be discussed.

Figure 4.3 Collapse Behaviour of a 313k dwt DH Tanker
(Paik and Thayamballi, 2003a)

In figure 4.3, the progressive collapse behaviour of a 313,000 dwt double hull VLCC is illustrated. A series of buckling events are observed to occur in both hogging and sagging at vertical bending moment levels below the design total bending moment $M_t = 16.489$ x $10^3$ MNm (points 1,2,3,12,13 and 14). Consistent with Paik et al's findings in section 2.6.1, an allowable stress design approach may be non conservative with respect to buckling failure of the bottom structure in bulk carriers.

Critics have suggested that the minimum design vertical bending moment for a VLCC should be in the region of 1 x $10^6$ t-m. This should be compared with the standard rule vertical bending moment of around 620,000 t-m according to classification rules, This is estimated to add approximately 1000 tons of steel to a VLCC at a marginal cost of $500,000, representing an increase of 61% above the builder's recommendations. Hellespont Shipping have reported (Papachristidis, 2001) that the design bending moment for a series of four 440,000 dwt VLCC's built in Korea in 1999, was increased by 50% above the rule value to ensure the following (see section 3.2.4):

- Any transverse combination of cargo tanks across to be empty at or near design draught.
- A reasonable range of asymmetric cargo loads at full draught.
- All ballast tanks to be 100% full for a range of bunkers.
- Ship to ballast down to a reasonable draught without resorting to ballasting cargo tanks.
- Any single ballast tank to be empty with all the other ballast tanks full.
- Normal ballast exchange (not flow through) sequence without restrictions.
- Any DH tanker should withstand flooding of any single ballast tank and any single contiguous pair, trio and quartet of ballast tanks when loaded to scantling draught, without exceeding design stresses.

The increase in bending moment reportedly resulted in a 20% increase in steel weight. Others have suggested that an assumption of 40 years instead of the standard 20 years for the wave return period would result in an increase of the design wave bending moment by just 3.7%, and 60 years would mean less than 6% (Mikelis, 2001).

The above findings strongly suggest that a prudent buyer should investigate the basic longitudinal strength data offered, including the design bending moment. Adequate margins on these aspects of the design are expected to have far more impact on the long-term structural robustness and quality than any other factor. An owner can decide whether to accept the standard rule bending moment or to require additional bending moment capacity to ensure increased flexibility in operation. This decision will increase the light mass (and cost) of the vessel.

**Transverse**: The previous discussion relates only to the longitudinal strength considerations for large bulk ships. Data given in tables 5.5 and 5.6 for a typical 300,000 dwt oil tanker (VLCC_1), indicates that the ratio of the mass of the transverse structures (web frames, transverse bulkheads etc) to the total steel mass in the mid ships cargo area (26,303 tonnes) is just over 13%. This relatively small portion of the total structural weight has a vital role to play in relation to structural efficiency. Transverse bulkheads have a dual role in resisting hydrostatic and dynamic loads from tank or cargo hold contents, and together with web frames, supporting the side, bottom and strength deck plating. In bulk ore carriers, corrugated bulkheads have been problematic due to a combination of factors including corrosion together with fundamental design flaws discussed earlier in section 2.6.1. New research work by Paik and Thayamballi (1998) focussing on this problem has highlighted certain areas in which the knowledge of the structural behaviour of transverse corrugated bulkheads was demonstrated to be deficient for the reasons listed as follows:

- Variation in bulkhead buckling strength due to the influence of the corrugation angle, not properly understood.
- Lack of consideration of compressive and lateral loads acting simultaneously on the bulkhead.
- Failure to include the effects of shedder plates on the bulkhead modelling.
- Improper modelling of rotational restraints at corrugation ends.
- Lack of "Z quality" steels in the lower bulkhead stool.
- Use of partial penetration welding of corrugated bulkhead plating to stool plate instead of full penetration welding required for fatigue strength.

The above findings indicate that assessment of corrugated bulkhead designs should account for all of these factors and the quality of the FEM modelling requires careful consideration. In DH tankers, conventional transverse bulkhead arrangements are usually employed involving vertical tee stiffeners with the section modulus increasing from strength deck down to inner bottom, and bracketing top and bottom. The design of the brackets, horizontal stringers, their terminations and the penetrations of vertical stiffeners through the stringers are critical structural areas. The penetration of all longitudinal stiffeners at side shell, bottom, inner bottom, deck and longitudinal bulkhead through the water tight transverse bulkhead and web frames, give rise to thousands of critical areas (refer to section 2.2.1 and figure 2.2).

### *4.4.4.2 Fatigue Strength*

**Hull Girder:** The cyclic wave-induced hull girder bending stresses in 1970's built bulk ships constructed from normal strength steel with plate thicknesses of 30mm or more, meant that the section modulus of the hull girder was adequate to prevent fatigue fracture of the hull, and no explicit fatigue check was necessary. In current rule-based designs, the section modulus requirement is specified as a function of the principal dimensions of the vessel (see section 2.2.3). S-N curves are commonly used as explained in section 2.3.2, to specify the allowable stress range, although S-N curves are derived from constant amplitude stress cycles whereas ships experience stress ranges as random variables. Based on the operating environment and the assumed wave scatter diagram for the long-term distribution of stresses, a nominal fatigue life calculation can be performed. For ships constructed from high strength steels, with deck plate thicknesses in the region of 20mm, the increased stresses and reduced section modulus of the hull girder warrant closer attention to the hull girder fatigue problem, and this is linked to the hull girder ultimate strength capacity discussed above. The concerns raised in section 2.3.2 in relation to significant slam induced vibratory stresses and their role in overall fatigue failure need to be addressed.

**Side Structure:** In contemporary bulk ship designs, the stress range acting on the side structure located between the loaded and ballast waterlines is approximately twice that of the bottom shell due to wave action. This phenomenon is largely caused by high cycle wave action on the shell. In section 2.3.2, problems involving 1990's built VLCCs having a high percentage of HTS were recounted, where side longitudinals in way of cargo tanks were found cracked, primarily at the intersections with the transverse bulkheads. After 1990, the major classification societies introduced specific fatigue criteria for these areas. Due to the particular fatigue phenomena involved in the area between the load water line and the ballast water line, this area of the side shell has to be considered as a special area. Software supported longitudinal strength assessment tools such as MARS Rule 2000 used in section 5.4.1.2 are capable of determining the nominal fatigue strength of individual structural members.

#### *4.4.4.3 Buckling Strength*

**Main Deck Buckling**: Due to the structural configuration, the main deck in a DH VLCC typically has a section modulus approximately 70% of that for the double bottom. When the vessel is in a loaded condition with cargo tanks full, the main deck will experience high buckling stresses, making the deck structure a critical area. This is clear from figure 4.3, by the smaller margin between the onset of failure for the main deck plates in sagging (point 17) and the total bending moment (Mt). This should be compared to the collapse of the inner bottom shown by point 10 on the hogging response curve and the total bending moment. In large bulk carriers, buckling considerations may lead the focus to elements in either the strength deck or bottom structure which have been shown to be sensitive to buckling failure, as discussed in section 2.6.1.

**Buckling of Members 1-3**: The collapse response curve for the individual design can be used to determine the sequence of buckling events. This process is similar to those depicted by Paik and Thayamballi (2003a) in figure 4.3. For assessment purposes, the evaluation could be limited to several specific structural details (e.g. members 1-3).

#### *4.4.4.4 Dynamic Strength*

**Berthing**: During normal berthing operations, the side structure of bulk ships is particularly exposed to the hazard of low velocity, high energy impact. Collisions may be due to environmental influences or human error, resulting in the risk of deformation of the shell plating and buckling of associated internals. The consequences of such damage may be immediate off hire of the vessel with the associated losses. The thickness of the side shell therefore, is a major determinant in the capacity of the side structure to withstand these abnormal berthing forces.

**Sloshing**: Current double hull VLCCs and ULCCs can have centre tanks 50-60m long without swash bulkheads. The natural frequency of a half filled cargo tank may be in the region of 12-13 seconds, which roughly corresponds to the vessel's natural frequency in pitching. This can lead to high impact forces on tank boundaries. The design liquid density for sloshing calculations is sometimes assumed to be less than 1.025 (e.g. 0.9). This subtle change can lead to unforeseen restrictions on certain types of cargoes and may even mean that, for structural reasons, the "gale" ballast tank cannot be filled with seawater in an emergency in accordance with the provisions of MARPOL. An owner may influence the decision whether or not to fit swash bulkheads in long tanks. Critics have suggested that the minimum subdivision for a 300,000 dwt VLCC should be 3 x 9 cargo tanks. This it is argued would obviate the need for swash bulkheads, and the smaller tanks are required because sloshing forces "cannot be predicted" (Devanney, 2006). Since standard designs for VLCCs currently feature 3 tanks across x 5 lengthwise, it is unlikely that smaller tanks could be considered by the builder, and sloshing should therefore be carefully evaluated in relation to the potential consequences.

#### *4.4.4.5 Critical Areas*

**Critical Areas**: For evaluation purposes, critical structural details should be categorised as per the method discussed in section 3.5.4. As an example, three alternative arrangements for the lower hopper corner detail in a double hull tanker are indicated in figure 4.5. In describing ARCO Marine Inc.'s experience in building the new *Millennium Class* tankers at Avondale Industries in 1996, Read et al (2000) defined nine critical areas throughout the structure, including the lower hopper corner.

Figure 4.4. Lower Hopper Corner Arrangement Options (Kim et al, 2007)

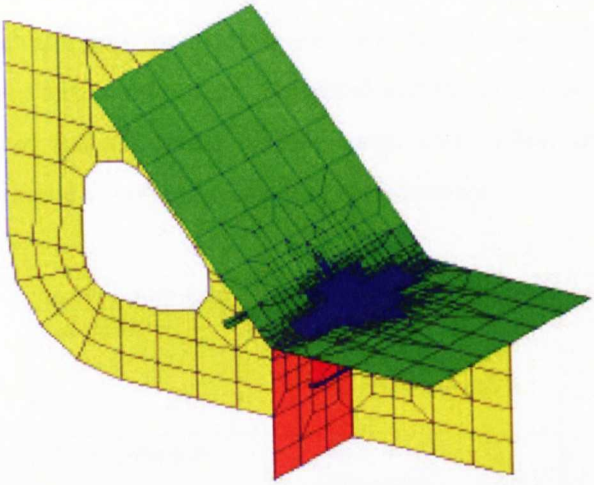


Figure 4.5. FEM Analysis of Lower Hopper Corner

These critical structural areas were analysed using FEM and detailed solid element mesh of the order of the plate thickness in the critical regions. Eight loading conditions were used to determine stresses. The improvements to the lower hopper design included re-arrangement of the hopper longitudinal, a reduction of the hopper radius and increased web frame thickness in way of the hopper. The above example illustrates a process which may include FEA strength calculations of the kind described. Alternatively, at the simplest level, an evaluation of critical areas can be done based on expert judgement and published information such as the Ship Structure Committee and other resources listed in section 2.5.6.

### *4.4.4.6 Durability*

From the top level (level 2) criteria listed in table 4.3, the second and third of the four level 3 *Technical* sub-criteria *Durability and Arrangements* are articulated in detail here. These have been further decomposed into the eight lower level (level 4) sub-criteria indicated in table 4.6. Like *Strength*, *Durability* is considered to be one of the key structural attributes and reflects softer technical considerations, many of which have to be described using linguistic terms, such as *Design* and *Quality*. Important technical aspects such as structural robustness lead to a focus on performance characteristics such as *Durability*. Durability is influenced by the quality of design and steel protection which is a function of the quality and application of the coating systems in tanks and design of structural details. Structural arrangements including distribution of ballast and access for inspections inside cargo and ballast spaces also have a profound influence on the structural design and performance.

| **Level 3 Sub-Criteria** | **Level 4 Sub-Criteria** |
|---|---|
| *Durability* | *- Design*<br>*- Protection*<br>*- Structural Details*<br>*- Quality* |
| *Arrangements* | *- Ballast*<br>*- Structural*<br>*- Access*<br>*- Peak Tanks* |

Table 4.6. Technical Sub-Criteria *Durability & Arrangements*, Levels 3&4

This categorisation of key (level 4) technical sub-criteria can be broken down into additional lower level (level 5) sub-criteria listed in table 4.7. For example, the quality of design may be strongly influenced by either the builder's reputation or the owner's experience with operation of the same type of vessel. The articulation of individual criteria follows.

| **Level 4 Sub-Criteria** | **Level 5 Sub-Criteria** |
|---|---|
| *Design* | *- Builder's Reputation*<br>*- Owner Experience* |
| *Protection* | *- Corrosion Margins*<br>*- Scantlings*<br>*- Coating Specifications*<br>*- Anodes in Tanks*<br>*- Materials in Hull* |
| *Structural* | *- Penetration Details*<br>*- Welding Design* |
| *Quality* | *- Yard QA/QC*<br>*- Owner Effort* |

Table 4.7. *Durability* Sub-Criteria, Levels 4&5

**Builder's Reputation**: Established yards with good reputations may be rated higher than new yards with less experience.

**Owner's Experience**: An owner with a history of operating a fleet of vessels will have acquired considerable experience which can be directly incorporated into a new build programme. Alternatively, consultants or other companies can also provide information which can be used to improve the quality of new construction.

**Corrosion Margins:** The level of hull durability and robustness is strongly influenced by the adequacy of corrosion margins which have been identified as a crucial factor in design. Table 6.3.1 in the CSR for tankers, contains the local corrosion additions required by the new rules. e.g. deck and side plating within 1.5m below the weather deck (4.0mm). The CSR table 6.3.2, contains the corrosion additions for structural elements outside the cargo tank region e.g. exposed upper deck plating (3.5mm). Following the introduction of the new CSR for tankers and later the JTP proposal for bulk carriers, a fierce debate took place between various industry stakeholders and IACS regarding the adequacy of the corrosion margins adopted in the new rules (IACS, 2006a). Corrosion margins currently vary between 3.0 to 7.0mm for VLCC designs. Baseline ship designs will feature minimum corrosion margins according to classification rules. Additional corrosion margins are decided by the buyer, and this is one of the most crucial decisions to be made by the purchaser. Corrosion margins were discussed in detail in section 2.3.3.

**Scantlings**: Thicknesses of 11.5mm have been permitted in previous bulk ship designs (bulkhead plating, stiffener webs etc). Generally, thin elements exposed to corrosion are at greater risk of corrosion damage since the corrosion rates are the same for thick or thin members. Therefore, a minimum thickness of 15.0mm is specified on high quality designs.

**Coating Specifications**: The specification of the corrosion protection system including the application of coatings during new construction, have a very significant impact on hull durability. For many years, the defacto standard for ballast coating systems in oil tankers was one coat of tar epoxy, and this led to short nominal coating lifetimes of between 5-10 years as discussed in section 2.3.4. DNV have for many years, proposed 3 optional performance standards for coating systems (Types I, II and III). Type I was one coat of tar epoxy at 200 microns thick, types II and III were 2 coats of tar epoxy, thickness 150-200 microns each, and paint systems II and III featured edge treatment (rounding). The target lifetimes of the different paint system options, was said to be 5, 10 and 15 years with a variance of +/- 3 years in each case (DNV, 1999).

**Anodes in Tanks**: The traditional means of ensuring ballast tank integrity is by the use of corrosion margins and an adequate coating system backed up by cathodic protection using zinc anodes. Although anodes are not a classification requirement, they are recommended as back up for the primary coating barrier.

**Materials in Hull:** Special hull materials are required according to classification rules. Normally the sheer, bilge and main deck strakes in way of the longitudinal bulkheads are of higher quality, such as IACS grades D or E. Elsewhere, either grade A or higher strength steels such as AH32 or AH36 are generally used. BP Shipping is reported to have specified D-grade steels for main decks after experiencing failures in tankers according to Melitz et al in section 2.5.2. The use of high strength steels with a yield point of 315MPa (HT-32) and 355MPa (HT-36) as an alternative to normal strength steels (yield point 235MPa) has culminated in optimised low steel weight designs with associated cost advantages. However, HTS has almost the same fatigue resistance as NS steel. Therefore, lighter scantlings accompanied by higher stresses led to spalling of coatings, as previously discussed in section 2.3.1. Accelerated corrosion followed by fatigue cracks, resulted in cargo leakage into ballast tanks or in the case of SH oil tankers, into the sea. Such controversy associated with high HTS designs meant that some owners specified a limit on the amount of HTS, typically 35% maximum. After the introduction of the CSR in 2006, at least one shipbuilder suggested a re-introduction of HTS for improved structural safety (Kim et al, 2007) an aspect which warrants careful consideration for new ship designs.

**Penetration Details:** A typical DH VLCC design features 15,000 to 16,500 main structural intersections in way of longitudinal elements (deck, bottom, side and inner bottom longitudinals) passing through the primary transverse web frames (90-100 per vessel).

Figure 4.6 Standard Penetration Details (DNV, 2005)

Each penetration represents a geometric stress concentration which is designed from the viewpoint of reducing the stresses, either by improving the shape of the cut out or by connecting the web of the longitudinal to the plating with a lug or closing plate. These generic structural details (ABS, 1995b) such as the example given in figure 4.6, can be compared using standard stress concentration factors obtained from fatigue codes such as DNV (2005), or BV (1994), or analysed using an FEM model and unit loads to determine the stress concentration factors (SCF). A simplified approach can be adopted based on SN curves of the type illustrated in figure 2.6, section 2.3.2.

**Welding Design:** Minimum welding standards are defined in classification rules. An owner may require full penetration welding or additional throat thicknesses in defined areas. Inadequate welding design has been identified as a serious weakness in contemporary ship design (Mikelis, 2001; Devanney, 2006).

**Yard QA/QC:** The build quality can be heavily influenced by a number of factors including fit-up, welding, coating systems application, the effectiveness and experience of the builder's QA/QC system, the experience of the builder and the owner's representatives, environmental conditions prevailing during the construction period (wind, rain, low temperatures, high humidity etc), or the builder's facilities and production schedule. The shipyard QA/QC performance will vary across the spectrum of ship production facilities in the established markets and in the emerging ship building nations. Interactions with the classification societies will also affect the quality of yard QA/QC systems. An owner's perception will vary according to experience or other sources of information.

**Owner Effort:** Shipyard quality can be improved through the owner inspection effort. Traditionally, an owner employed a team of representatives to monitor the progress of construction. In some cases, direct intervention in the production process may have been necessary to ensure a satisfactory level of quality. This approach may be less effective in more experienced yards producing higher quality.

#### *4.4.4.7 Arrangements*

The level 3 technical sub-criterion *Arrangements* can be further broken down into the level 4 & 5 sub-criteria listed in table 4.8. These are articulated in the following section.

| Level 4 Sub-Criteria | Level 5 Sub-Criteria |
|---|---|
| *Ballast* | *- Distribution*<br>*- % Filling* |
| *Structure* | *- Crossties*<br>*- Subjective* |
| *Access* | *- Ballast Tanks*<br>*- Cargo Tanks* |
| *Peak Tanks* | *- Forepeak*<br>*- Afterpeak* |

Table 4.8. *Arrangements* Sub-Criteria, Levels 4&5

**Ballast Distribution:** Large DH hull oil tanker designs normally feature evenly distributed segregated wing ballast tanks typically 3.0m width from the side shell and along the length of the cargo block on both sides of the vessel. This even distribution of ballast increases the design stillwater bending moment in hogging compared to designs which feature mid ships ballast tanks (Magellsen, 1996).

**% Filling:** Some VLCC designs do not allow the forepeak tank to be filled when in the normal ballast condition, without exceeding the stress limits, and critics have pointed out that this is totally unacceptable. A slack forepeak tank can result in structural damage due to sloshing (Devanney, 2006).

**Cross Ties:** Cross ties can be located either in the wing cargo tanks or in the centre cargo tanks. Figure 4.7 shows the alternative structural arrangements for a DH tanker normally specified by the builder, but subject to the buyer's approval.

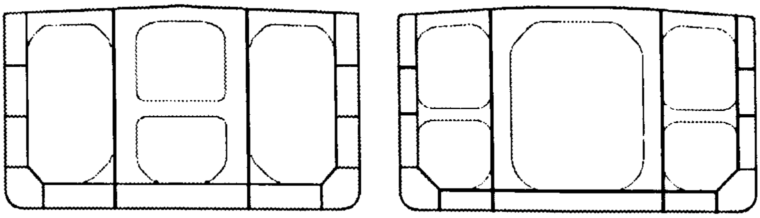


Figure 4.7 Alternatives - Cross Tie Configuration

The first SH tankers delivered in the 1960's were fitted with cross ties (struts) in the side tanks connected to web frames to support the side structure. When the first DH vessel was delivered in the early 1990s, advantage was taken of the increased rigidity of the side wing ballast tanks and the struts were placed in the centre cargo tanks.

Figure 4.8. Cracking Associated with Centre Tank Cross Ties
(Yamamoto, 2007)

Ship yards favoured the centre tank cross tie arrangement for ease of construction. Yamamoto (2007) reported damages similar to those depicted in figure 4.8 at the intersection of the transverse and longitudinal bulkheads in double hull tankers with centre tank cross ties. With the centre tank cross tie arrangement, asymmetric loading conditions cause additional forces and moments generated in the cross tie itself and especially at the ends of the longitudinal bulkhead vertical transverse girder. These concerns have to be carefully considered by the owners during the design review and may have an impact on the flexibility of operation of the vessel.

**Subjective:** A subjective assessment of the structural design based on the user's experience. This has been described by Devanney (2006) as "how the structure "flows".

**Ballast Tank Access:** Secure and practical means of access into cargo tanks and ballast spaces is mandated for new ship construction through IMO MSC/Circ.686 *Guidelines on the Means of Access to Structures for Inspection and Maintenance of Oil Tankers and Bulk Carriers* dated 2nd June 1995 (IMO, 2002a). Proper access to the structure is essential to minimise the cost of intermediate and special hull surveys. The CSR section 5 (5.1) specifies the minimum required arrangements for access into and within spaces in and forward of the cargo tank region. These requirements cross-reference the International Convention for the Safety of Life at Sea (SOLAS), 1974, as amended, Chapter II-1, Part A-1, Regulation 3-6 as required by the flag Administration. Tanks and subdivisions of tanks having L > 35m shall have at least 2 access hatchways and ladders as far apart as practicable. Further, a Ship Structures Access Manual approved by the administration is required to be kept onboard. Individual owners may choose to go beyond the minimum compliance approach and incorporate their own specifications for improved tank access.

**Cargo Tank Access:** In cargo tanks, permanent staging and walkways are provided at strategic locations below the tank top. Permanent walkways are recommended along the longitudinal and transverse bulkheads. Enlarged access openings in swash and centreline, and side girders are intended for easy access of rafts at special hull surveys (every 5 years). Owners may choose to incorporate additional measures such as hanging staging or permanent walkways at the top of the inner hull and longitudinal bulkheads.

Some 70's built ULCCs were stiffened with primary deep longitudinal girders. These structures had 5 or 6 horizontal stringers inside the periphery of the wing tanks, several metres in width. Hence they could be used as walkways right round each level in the tank. Guard rails were provided for safe access. Earlier generation VLCCs often featured horizontal stringers at cross tie level, openings through transverse web frames, access walkways under the main deck along the length of the cargo tank and walkways across the top of the cross ties. Later, the pre-MARPOL designs adopted a 3 cross tie arrangement to connect primary deep transverse web frames, stiffening up the side shell and longitudinal bulkhead structure.

**Forepeak:** The forepeak tank area is subjected to high intensity dynamic loads including bottom and bow slamming and sloshing loads due to partial filling. The forepeak structures have to be specially considered to reduce the likelihood of structural damage from these additional hazards.

**Afterpeak:** The afterpeak is sometimes subject to vibration damage from engine or propeller, and these hazards should be specially considered.

#### 4.4.4.8 Operational

The level 3 technical sub-criterion *Operational* shown in table 4.3 can again be broken down into the two level 5 sub-criteria listed in table 4.9. These are articulated in the following section.

| Level 3 Sub-Criteria | Level 5 Sub-Criteria |
|---|---|
| *Operational* | *- Hull Stress Monitoring (HSMS)*<br>*- Operability* |

Table 4.9. *Operational* Sub-Criteria, Levels 4&5

**Hull Stress Monitoring System (HSMS):** A hull stress monitoring system is usually covered by an optional class notation. Baseline designs do not usually offer an HSMS. High quality designs may be fitted with systems which can provide feedback to the ships crew to prevent structural overloading in a seaway and record data which can be used to plan structural maintenance as discussed in section 2.5.2. This is considered to be a valuable aid to the crew since a major factor in hull lifetime is the loading history of the ship, largely determined by the operators.

**Operability**: This criterion addresses how difficult it is to operate the vessel from the standpoint of the hull arrangements and structure. Maintenance can be evaluated on the basis of crew perceptions on the ease with which the structure can be accessed and maintained. Cleaning will be a function of the arrangement of internal surfaces and the tank cleaning systems. In the wing and centre cargo tanks of DH tankers, there are longitudinal sections, making cleaning much easier compared to SH vessels. However, in the event that cargo oil contamination did occur in the ballast tanks, the cleanup operation would be hazardous and hugely expensive. Cleaning of mud from ballast spaces in bulk ships is made more difficult by the necessity to adopt symmetrical tee sections in the side structure to improve fatigue performance. Ventilation of tanks for survey purposes can be improved by utilising the vessel's ballast system, and this feature would have to be incorporated into the design. Human factors can be considered based on an assessment of the human-machine interaction.

## 4.5 The Evidential Reasoning (ER) Method

### *4.5.1 Theory & Applications*

In multiple criteria decision analysis (MCDA), both numerical and qualitative data have to be dealt with including information containing uncertainty. To be successful, rational decision analysis must deal properly with this data. The evidential reasoning (ER) approach is capable of handling this type of problem. Evidence theory was developed by Dempster in 1967 and extended and refined by Shafer in 1976. Like Bayesian theory, ER deals with subjective beliefs (probabilities). The ER method relies on generating an appropriate set of evaluation criteria in the form of a hierarchical structure. The ER process is intended to rank a set of structural alternatives in order of preference arising from a risk-based techno-economic assessment procedure described in the following sections.

The evidential reasoning method provides a flexible rational approach for dealing with synthesis problems involving uncertainty, using evidence combination for multiple attributes. The ER approach is used to narrow individual evaluations and provide a combined distributive evaluation for each option (Yang and Xu, 1998). Let *S(y)* represents the assessment of criterion *y*. Then *S(E)* = $\{(H_n, \beta_n), n = 1,..., N\}$ represents that criterion $E$ is assessed to grade $H_n$ with degree of belief $\beta_n, n = 1,..., N$

$$S(e_i) = \{(H_n, \beta_{n,i}), n = 1,..., N\} \qquad i = 1,..., L$$

Let $\omega_i$ be the weight of criterion $e_i$ reflecting its relative importance to its parent criterion E and $0 \leq \omega_i \leq 1$, $\sum_{i=1}^{L} \omega_i = 1$.

Suppose $m_{n,i}$ is an individual degree to which $e_i$ supports the synthesis conclusion and $m_{H,i}$ is the unassigned probability to which $e_i$ supports the synthesized conclusion. Then such basic probability masses can be calculated as follows:

$$m_{n,i} = \omega_i \beta_{n,i} \qquad n = 1,....., N; i = 1,2,..., L$$

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

In the above, $m_{H,i} = \overline{m}_{H,i} + \tilde{m}_{H,i}$ where $\overline{m}_{H,i}$ is caused by the relative importance of $e_i$ and $\tilde{m}_{H,i}$ is due to the incompleteness of the belief degree assessment. The iterative calculation can be performed for $i$ =1,2,….,$L$-1 to obtain the coefficients:

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

where $K_{I(i+1)}$ is a normalization factor and;

$m_{n,I(i+1)} = K_{I(i+1)}\left[m_{n,I(i)}m_{n,i+1} + m_{H,I(i)}m_{n,i+1} + m_{n,I(i)}m_{H,i+1}\right]$ and $n = 1,2,\ldots\ldots,N$

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

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

$m_{H,I(i)} = \tilde{m}_{H,I(i)} + \bar{m}_{H,I(i)}$ and $i = 1,2,\ldots.,N$

The combined degrees of belief in the assessment *S(E)* can be expressed as:

$$\beta_n = \frac{m_{n,I(L)}}{1-\bar{m}_{H,I(L)}} \quad n = 1.2.....,N$$

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

Yang and Sen (1997) applied the ER method to assess options for the retro-fitting a typical short haul sea ferry. Yang and Xu (1998) compared five types of executive cars based on data collected from the media. An assessment of construction contractors based on MCDA was described by Sonmez et al (2001). Maritime security has been assessed in a study by Yang et al (2007). Recently, the ER method has also been applied to the bridge condition assessment problem (Wang et al, 2008). The ER approach has been adapted to problems in engineering and management including cargo ship design, system safety analysis and ferry design. Xie et al (2008) studied the ship selection problem using a MCDA approach. Yang and Xu (2002a; 2002b) have provided a detailed explanation of the new ER algorithm for MCDA, supported by examples.

There have been five major milestones in the development of the ER approach. Firstly the belief degree concept was introduced into the decision matrix. Secondly, the

Dempster-Shafer theory with its powerful evidence combination rules was introduced into the ER framework so that the distributive information contained in a belief decision matrix could be aggregated to produce rational and consistent results. Thirdly, rule and utility based information transformation techniques were introduced to transform sets of evaluation standards to a unified set to allow quantitative and qualitative data to be handled in a consistent manner. Fourthly, the approximate reasoning process in the original ER approach was enhanced to correct irrationalities in the original format when dealing with conflicting evidence. Finally, an implementation of the improved ER approach was developed in the form of a Windows based software package IDS. This advance greatly simplified the otherwise tedious mathematical calculations involved in MCDA calculations for the aggregation process using belief matrices (Xu and Yang, 2003). In section 5.4, the use of the IDS software will be demonstrated by selecting one alternative VLCC structural design out of 4 competing similar options.

### *4.5.2 Structural Performance Criteria*

An attribute or criterion has been defined as a property, quality or feature of an alternative. In MCDA, attributes and criteria are sometimes used interchangeably. The ER framework consists of a hierarchy of assessment criteria, the distributed assessment structure using belief degrees and the evidential reasoning approach to aggregate degrees of belief from lower to higher level attributes. Grades are assigned for assessing qualitative attributes. For example in the candidate ship selection problem described by Xie et al (2008), a set of 5 grades {*worst, poor, average, good, excellent*} was assigned. Different attributes may be assigned different grades. Belief degrees are subjective probabilities associated with assessment grades and describe the confidence level of an attribute evaluated to a grade. The ship selection problem involved evaluation of 6 tanker designs. The performance of tanker 1 in terms of *safety* was considered to be *good* to a degree of 0.6 and *excellent* to a degree of 0.2, with a degree of incompleteness equal to 0.2. The assessment was represented by the set of belief degrees (0, 0, 0, 0.6, and 0.2).

In section 4.4, a set of performance criteria suitable for evaluating alternative structural designs for VLCC's was articulated. A total of 35 bottom level (level 5) sub-criteria have been identified, and these are now presented in table 4.10 below.

| No | Lowest Level Sub-Criteria | QL. | QN. |
|---|---|---|---|
| 1 | *Net Present Value (NPV)* | | X |
| 2 | *Warrantee (Structural)* | | X |
| 3 | *Classification* | X | |
| 4 | *Longitudinal Strength* | | X |
| 5 | *Transverse strength* | X | |
| 6 | *Hull Girder fatigue* | | X |
| 7 | *Side Structure fatigue* | | X |
| 8 | *Main Deck buckling* | | X |
| 9 | *Members 1-3 buckling* | | |
| 10 | *Berthing resistance* | | X |
| 11 | *Sloshing resistance* | X | |
| 12 | *Critical area -1* | X | |
| 13 | *Critical area - 2* | X | |
| 14 | *Critical area - 3* | X | |
| 15 | *Builder's reputation* | X | |
| 16 | *Owners experience* | X | |
| 17 | *Corrosion Margins* | | X |
| 18 | *Minimum. Scantling* | | X |
| 19 | *Coating Specifications* | | X |
| 20 | *Anodes in Tanks* | X | |
| 21 | *Materials in Hull* | | X |
| 22 | *Structural Details* | X | |
| 23 | *Welding Design* | X | |
| 24 | *Yard QA/QC* | X | |
| 25 | *Owner Effort* | X | |
| 26 | *Ballast Distribution* | X | |
| 27 | *Ballast Filling %* | | X |
| 28 | *Cross Ties Location* | X | |
| 29 | *Subjective (Structural)* | X | |
| 30 | *Ballast Tanks Access* | X | |
| 31 | *Cargo Tanks Access* | X | |
| 32 | *Forepeak Tank Design* | X | |
| 33 | *Afterpeak Tank Design* | X | |
| 34 | *Hull stress monitoring system* | X | |
| 35 | *Operability* | X | |

Table 4.10. Lowest Level (Level 5) Sub-Criteria

Technical quality is measured by multiple criteria and is a combination of qualitative and quantitative attributes as indicated. Structural performance cannot be defined by a single criterion such as *Longitudinal Strength* although this characteristic can be quantified and is obviously of more importance than some of the other criteria. The table indicates quantitative (QL.) versus qualitative (QN.) criteria. The above unique set of structural assessment criteria developed in this chapter, are the basis of the proposed MCDA/ER framework, which will be demonstrated in section 5.4 using an example. In the proposed assessment scheme, some attributes will have more importance than others. For example, the *Net Present Value* will be intuitively more important than *Access* in cargo tanks. These differences will be reflected in the weights assigned to the individual attributes in the model.

In developing the structural assessment criteria in section 4.4, no suitable benchmark was found in other published work. Therefore, as part of the process, the author informally sought the opinions of a number of structures experts and naval architects involved in the field of ship structures. Articulating the main criteria and constructing the assessment hierarchy presented in the following section 4.5.3 occurred over a lengthy period of time, and was an evolutionary process. The selection of the 35 sub-criteria articulated in section 4.4 and summarised in table 4.10, forming the basic structure of the model was founded upon a wide range of information obtained from various sources in the published literature survey in chapter 2, including the Ship Structure Committee (SSC). The practical experience of the writer was used to advantage in evolving and filtering the assessment criteria and the structural assessment framework. Therefore the criteria described here were considered to be valid, reasonable, technically sound and a suitable starting point for the MCDA/ER model described in section 5.

An objective of this study was to develop and demonstrate a rational framework for comparison of alternative structural design options for large bulk ships on the basis of the cargo block, scantlings including all longitudinal and transverse structures in this zone. Restricting the area to the structural zone between the forward bulkhead of the slop tanks and the after bulkhead of the fore peak tank is considered entirely relevant, although the framework allows inclusion of the fore and after peak tanks separately.

### 4.5.3 Assessment Hierarchy

Arising from the published literature review and the hazard assessment carried out in section 3.5.3 a comprehensive hierarchical framework for assessment of alternative VLCC structural designs was constructed and is presented in figure 4.9 (p.175). The above set of criteria, articulated in detail in section 4.4, appear here in the form of a defined hierarchical structure. The overall performance of a number of VLCC design options will be evaluated in terms of the top level criterion *Design Selection* with two main sub-criteria, *Commercial* and *Technical.*

Four main level 3 technical sub-criteria *Strength, Durability, Arrangements* and *Operational* are used to make comparison between the candidate structural designs. These four criteria are decomposed into level 4 & 5 sub-criteria. A number of the criteria such as *NPV* and *Longitudinal Strength* can easily be evaluated using numerical data. Other qualitative criteria are general and have to be expressed using linguistic data which is difficult to assess directly. To facilitate cross comparison of trade-offs among different attributes, weights are assigned reflecting their relative importance. Finally belief functions are used to model the decision maker's preferences relative to the grades used to measure the attributes. A software package (IDS) is used for the ER modelling.

In table 4.10 (p.172), a total of 35 criteria have been identified as the lowest level (level 5) in the assessment hierarchy. Based on the respective criteria and the assessment grades, expert judgement and observed data/fact can be converted to belief degrees associated with the respective grades. In order to assess the performance of a candidate VLCC design, the lower level criteria have to be assessed either quantitatively or qualitatively, depending on the data sources. The evaluation can be conducted by a single individual or a team of assessors. The results can be expressed using linguistic terms or numerical grades.

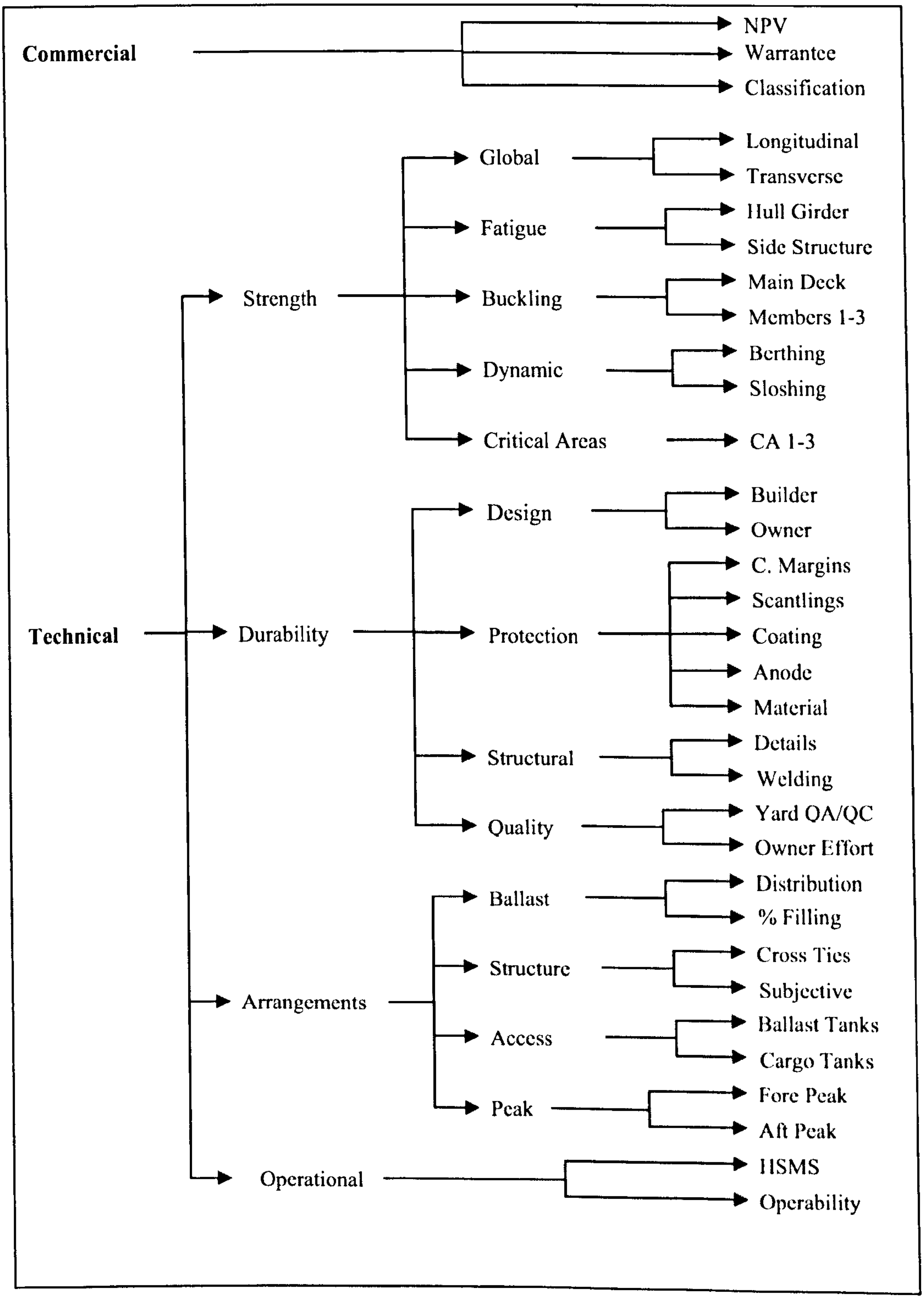


Figure 4.9. Structural Assessment Hierarchy

In the proposed MCDA/ER framework, seven grades have been adopted throughout:

$$N = 7, H_1 = \{Unacceptable\}, H_2 = \{VeryPoor\}, H_3 = \{Poor\}, H_4 = \{Fair\}, H_5 = \{Good\},$$
$$H_6 = \{VeryGood\}, H_7 = \{Excellent\}$$

### *4.5.4 General Procedure*

To enable a performance based design approach incorporating the buyer's goals and preferences, a procedure is proposed here, adapted from the methodology used in the ship selection problem referred to earlier (Xie et al, 2008). For practical reasons, the framework for the buyer's assessment should be based on a rational decision support technique, allowing all assumptions to be fully documented and transparent. Increasingly, public concerns are encouraging companies to pursue corporate social responsibility (CSR) principles in decision making. Transparency of assumptions made when purchasing major items of capital expenditure can be achieved using a techno-economic framework. The eight step procedure adopted in the model and used in the example given in chapter 5 appears below:

1. Statement of the problem and evaluation hierarchy.
2. Evaluating techno-economic quantitative criteria.
3. Setting the criteria grades and weightings
4. Transforming basic quantitative criteria.
5. Assessing qualitative criteria.
6. Pre-assessment process
7. Aggregating assessment results
8. Ranking and decision making

The assessment data may be based on expert subjective judgement, use of specialist consultants and software supported strength calculations. The collation of the assessment data must be accomplished within the strict time limit normally imposed by the builder (3-4 weeks). The ER model is used to rank the alternative structural design options on the basis of belief degrees assigned to each of the qualitative and quantitative criteria, by the buyer's team. This forms a comprehensive, rational and transparent method suitable for evaluating major capital expenditure decisions. In the structural evaluation hierarchy shown in figure 4.9 (p.175), the assessment problem is how to arrive at an aggregated assessment for a higher level attribute given the subjective judgements at the basic level. For example, qualitative assessments can be summarised using an approach where subjective judgements are captured using attributes, evaluation grades and degrees of belief. To illustrate the aggregation process, a calculation is presented below to show how the assessment for the higher attribute *quality*, is performed by aggregating the two basic attributes *Yard QA/QC* and *Owner* as shown in table 4.11. The belief functions are shown below.

S(*Yard QA/QC*) = {(indifferent, 0.1), (average, 0.7)}
S(*Owner*) = {(indifferent, 0.5), (average, 0.5)}

| **Degree of Belief ($\beta$)** | | **Evaluation Grade** | | | | |
|---|---|---|---|---|---|---|
| | | Poor | Indifferent | Average | Good | Excellent |
| *Quality* | *Yard QA/QC* | | 0.1 | 0.7 | | |
| | *Owner* | | 0.5 | 0.5 | | |

Table 4.11. Subjective Judgements for Evaluating the Criterion *Quality*

Let $y = e_1 \oplus e_2$ where the symbol $\oplus$ denotes the aggregation of two attributes. Assuming equal importance for the two attributes, then L = 2, and $\omega_1 = \omega_2 = 0.5$. The basic probability masses $m_{n,i}$ are:

$m_{11} = 0$, $m_{12} = 0.0500$, $m_{13} = 0.3500$, $m_{14} = 0$

$\bar{m}_{1H} = 0.5$, $\tilde{m}_{1H} = 0.1000$, $m_{1H} = 0.6000$

$m_{21} = 0$, $m_{22} = 0.2500$, $m_{23} = 0.2500$, $m_{24} = 0$

$\bar{m}_{2H} = 0.5000$, $\tilde{m}_{2H} = 0$, $m_{2H} = 0.5000$

Using the recursive equations to calculate the probability masses:

$$K_{I(i+1)} = \left[1 - \sum_{t=1}^{4} \sum_{\substack{j=1 \\ j \neq t}}^{4} m_{t,I(i)} m_{j,i+1}\right]^{-1}$$

$$K = \left\{ 1 - \begin{bmatrix} (m_{11}m_{22} + m_{11}m_{23} + m_{11}m_{24}) \\ + (m_{12}m_{21} + m_{12}m_{23} + m_{12}m_{24}) \\ + (m_{13}m_{21} + m_{13}m_{22} + m_{13}m_{24}) \\ + (m_{14}m_{21} + m_{14}m_{22} + m_{14}m_{23}) \end{bmatrix} \right\}^{-1}$$

$$K = \{1 - [0 + 0 + 0 + 0 + 0.0125 + 0 + 0 + 0.0875 + 0 + 0 + 0 + 0]\}^{-1} = 1.1111$$

$$m_1 = K(m_{11}m_{21} + m_{11}m_{2H} + m_{1H}m_{21}) = 1.1111\ (0+0+0) = 0$$

$$m_2 = K(m_{12}m_{22} + m_{12}m_{2H} + m_{1H}m_{22}) = 1.1111\ (0.0125+0.0250+0.1500) = 0.1875$$

$$m_3 = K(m_{13}m_{23} + m_{13}m_{2H} + m_{1H}m_{23}) = 1.1111\ (0.0875+0.1750+0.1500) = 0.4583$$

$$m_4 = K(m_{14}m_{24} + m_{14}m_{2H} + m_{1H}m_{24}) = 1.1111\ (0+0+0) = 0$$

$$\tilde{m}_H = K(\tilde{m}_{1H}\tilde{m}_{2H} + \tilde{m}_{1H}m_{2H} + m_{1H}\tilde{m}_{2H}) = 1.1111\ (0+0.0555+0) = 0.0555$$

$$\bar{m}_H = K(\bar{m}_{1H}m_{2H}) = 1.1111\ (0.5 \times 0.5) = 0.2777$$

The combined degrees of belief are;

$$\beta_1 = \frac{m_1}{1 - \bar{m}_H} = 0$$

$$\beta_2 = \frac{m_2}{1 - m_H} = 0.2884$$

$$\beta_3 = \frac{m_3}{1 - m_H} = 0.6345$$

$$\beta_4 = \frac{m_1}{1 - \bar{m}_H} = 0$$

$$\beta_H = \frac{\tilde{m}_H}{1 - \bar{m}_H} = 0.0077$$

The aggregated assessment for VLCC quality is therefore given by the following distribution:

S(*Quality*)=S(*YardQA/QC* ⊕ *Owners*) = $\{(\mathit{indifferent}, 0.2884), (\mathit{average}, 0.6345)\}$

## 4.6 Conclusions

In this chapter a set of 35 structural performance criteria has been conceptualised and articulated as the first step in developing a comprehensive structural assessment framework. In section 4.2, the MCDA method was reviewed in terms of its suitability in respect to the structural assessment problem. Each of the assessment criteria has been explained. These were assembled into a hierarchy which will allow the use of an MCDA/ER synthesis approach. The ER algorithm will be used to aggregate the assessments and rank the structural options. This fulfils objective no.4 in section 1.2, which was to articulate a set of product performance characteristics (criteria) part of an MCDA methodology incorporating the Dempster-Shafer theory of evidence as the basis for a structural evaluation framework, used to compare alternative structural design options for VLCCs and to demonstrate and validate the method using an example.

Central to the engineering discipline it is recognized that engineering design consists of compromise, identification of preferences and selection of the best option. Capital investment decisions represent major commitment of corporate resources and can have a significant impact on the financial welfare of shipping companies. Companies can easily incorporate economic, environmental and social aspects estimated in monetary terms, by adopting suitable techno-economic decision-making techniques. This research proposes therefore, that all major capital expenditure decisions like the purchase of new tonnage, should be carried out in this way, according to a comprehensive rational and transparent procedure. Only then can the latent financial risks associated with improper tradeoffs in the list of technical options be properly anticipated. In the next chapter the process will be demonstrated by an example.

# Chapter 5 - Selection Between Alternative VLCC Structural Design Options – An Example

***SUMMARY***

*In this chapter, a method is presented for selecting a preferred structural design from a number of alternative VLCC structural design options. The method is based on a multi-criteria synthesis approach which incorporates the evidential reasoning algorithm, to facilitate decision-making under conditions of uncertainty. The array of product performance criteria are assembled into a techno-economic hierarchy which can then be evaluated using the evidential reasoning algorithm, to aggregate the criteria. To demonstrate the method, the principal quantitative performance criteria including "NPV" and "ULS" are calculated by example. The method is shown to be capable of handling a large number of qualitative technical attributes involving complex, subjective and often incomplete data. The aggregation of quantitative and qualitative assessments using the ER approach is accomplished easily using the Windows based Intelligent Decision System (IDS) software. Preferred structural candidate designs are ranked in order of preference according to their utility values calculated by the programme. The results of the ER model are discussed in terms of their contribution to the evidence required for the evolving hull structures safety case explained in chapter 7.*

## 5.1 Introduction

The technical problem relating to comparison of alternative ship structural designs is usually thought of as an exercise in conventional structural analysis performed by standardised procedures. This involves determination of structural response based on a given set of loads and load combinations obtained from classification rules or by direct assessment methods. Given alternative structural designs, a direct comparison of stresses and scantlings would then be undertaken to elicit preferences. A less common approach, would involve definition of a set of structural attributes or criteria to be simultaneously measured and evaluated. These attributes may involve a combination of subjective, sometimes incomplete quantitative and qualitative data. The MCDA synthesis method using ER has been used in relation to selection of a preferred ship from a group of candidate vessels for a new design (Xie et al, 2008). In this thesis, a novel and unique framework for comparison of alternative structural designs of VLCCs is developed, based on the ER algorithm.

From the detailed historical perspective of ship structural operation and maintenance performed in chapter 2, key regulatory controls were identified and some recent high profile structural failures were forensically examined to find possible common root causes. The literature review served to highlight the primary structural hazards and risks associated with contemporary management of large ship structures and the effectiveness of these measures. From chapter 3, it is apparent that there is an increasing trend away from total reliance on prescriptive rules in favour of performance based standards for constructed systems, including civil and marine structures. In chapter 4, a set of evaluation criteria suitable for performing a rational techno-economic appraisal of competing VLCC structural designs was proposed and articulated. These criteria will be combined using the MCDA/ER approach and the Dempster-Shafer theory.

## 5.2 Statement of the Problem and Assessment Hierarchy

Within the realm of design and construction of large engineered structures, commercial ship procurement is usually thought of, as selecting the best option which represents the highest profit or lowest transportation cost, while complying with all mandatory rules and regulations. However, failure to properly address important technical considerations at the design stage may increase the risk of unexpected consequences such as pre-mature failure of tank coating systems or hull fractures leading to cargo leakage into the sea. Such undesirable outcomes can result in environmental damages which may dramatically affect the economic performance and reputation of a ship owner or manager.

Although high level bespoke specifications have been used to improve the quality of vessel structural designs (see section 3.2.5), generally there are commercial and practical difficulties limiting this approach. The opportunity for the buyer to exert influence on the quality of a given ship design is often restricted to requirements expressed in an outline specification and by performing a review of key structural design drawings. This opportunity is constrained by strict time limits imposed by the builder. Contractually, the buyer has to return his comments related to the structural design usually within 3-4 weeks of contract signing.

In section 3.2, the current ship production environment characterised by an emphasis on production considerations and moves towards a collaborative approach by the shipyards and international classification societies to develop a 3D product model for eventual concurrent engineering development and virtual prototyping were described. The view of critics, alleging that shortcomings in the ship procurement process had led to deficiencies in ship design quality was examined. The deficiencies in standard current ship structural design specifications were highlighted. The responsibility of the ship owner in relation to the consequences of structural failures was emphasised. In section 3.5, the benefits of a risk-based approach to the hull structures question were outlined.

In chapter 4, a set of structural performance criteria were developed, part of a proposed new structural assessment framework based on conventional MCDA and synthesis using the ER Algorithm, incorporating the Dempster Shafer evidence combination rule explained in section 4.5. For convenience, the structural assessment hierarchy is reproduced in figure 5.1 on the following page. At the top level, two major performance criteria *Commercial* and *Technical* are sub-divided into four principal sub-criteria *Strength*, *Durability*, *Arrangements* and *Operational*. These in turn are further decomposed down into 35 individual (level 5) sub-criteria as indicated. The hierarchical structure of the model in the format shown was modelled directly in the Intelligent Decision System (IDS) software as illustrated in figure 7.7 on page 212. In the following sections, the structural assessment framework will be demonstrated by an example.

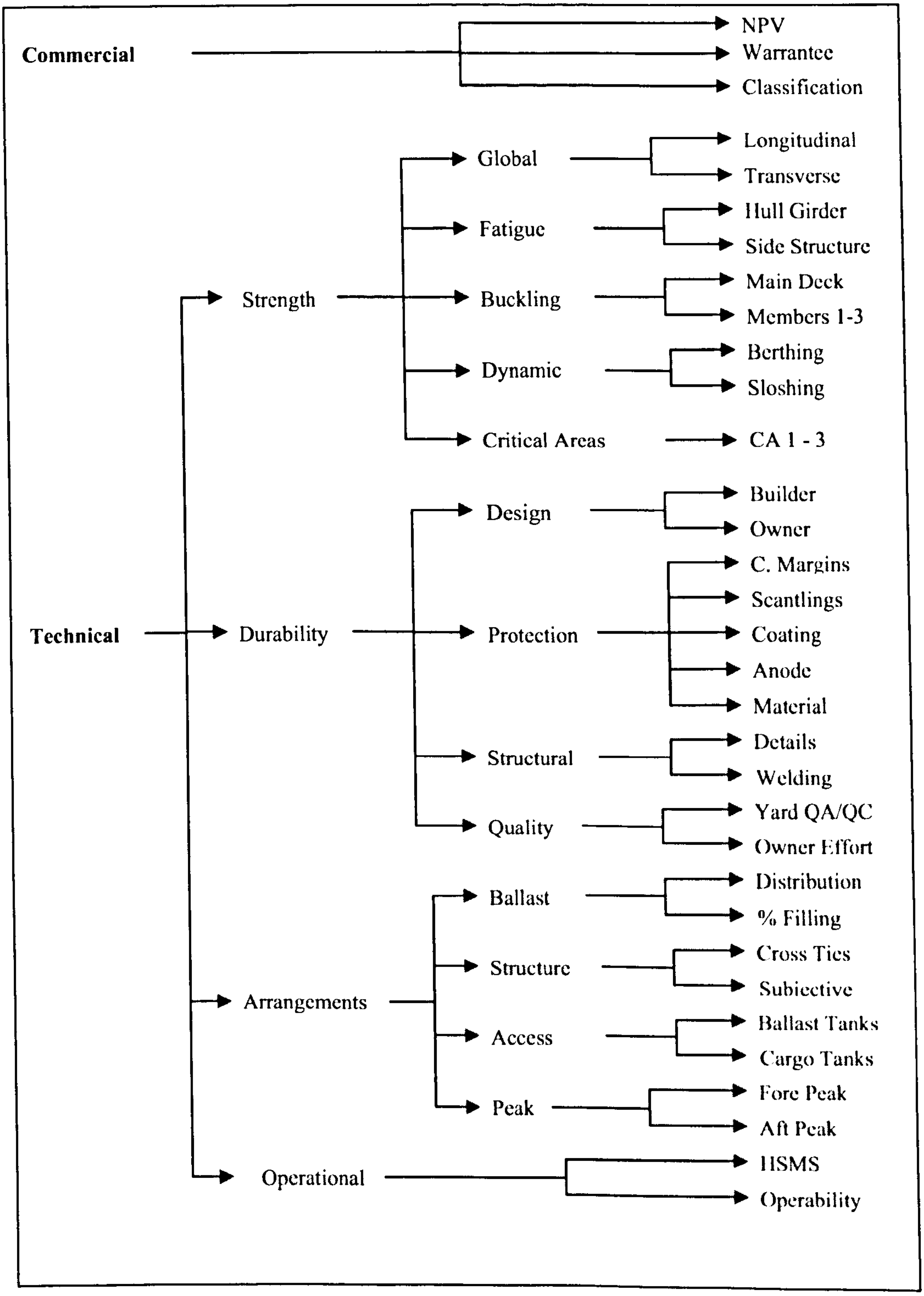


Figure 5.1. Assessment Hierarchy

## 5.3 VLCC Structural Design Options (Description).

For comparison purposes, four alternative similar double hull VLCC structural designs have been selected with the principal particulars indicated in table 5.1.

| Option | Dimensions (LxBxD) | Deadweight (mt) | Description |
|---|---|---|---|
| VLCC_1 | 316 x 58 x 30 | 299,000 | Pre-CSR Enhanced scantlings |
| VLCC_2 | 318 x 58 x 31.25 | 308,500 | Pre-CSR Fully HTS Korean design |
| VLCC_3 | 320 x 58 x 31 | 300,000 | CSR standards |
| VLCC-4 | 320 x 58 x 31 | 300,000 | High quality design CSR+ |

Table 5.1. Four Alternative VLCC Structural Designs

In a typical 300,000 dwt VLCC, each cargo tank is approximately 50m in length and the total length of the mid ships cargo tank zone from the aft bulkhead of the aft cargo tank to the forward bulkhead of the forward cargo tank is approximately 250m. The cargo tank length for VLCC_2 was 50.8m and for all the other options, was taken as 52.0m.

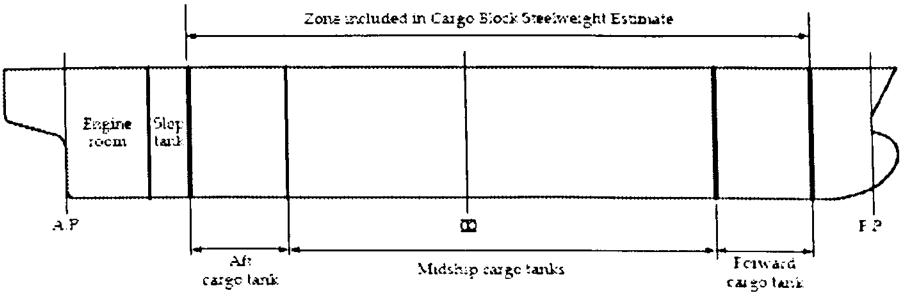


Figure 5.2. Structural Zone under Consideration

For the purposes of the structural assessment framework and to demonstrate the model developed herein, attention was directed to the structural zone under consideration, as indicated in figure 5.2 above. For simplicity, only the cross sectional area extending from the aft bulkhead of the aft cargo tank to the forward bulkhead of the forward cargo tank (*zone included in cargo block steelweight estimate* in figure 5.2) was considered. Details of the transverse structures discussed in section 4.4.4.1 (p.151) have not specifically been considered in this example but are part of the structural assessment process since they are assessed by the lower level sub-attribute *Transverse* under *Global*. However, the total steel masses include the weights of the transverse structures and these are listed in table 5.5 on page 188. In focussing on the longitudinal structures, valid comparisons can be drawn based on a systematic risk-based evaluation framework, one of the principal objectives of this study. Most of the information required for the assessment process can be obtained directly from the Midship Section drawing showing all the required data including materials, plate thicknesses and scantlings of longitudinal members.

Both VLCC_1 and VLCC_2 were designed prior to the introduction of the common structural rules (CSR). VLCC_1 has enhanced scantlings compared to VLCC_2 and this is reflected in the greater steel weight for this option. The second alternative VLCC_2, was based on a ten year old (1999) South Korean design, and it has the least steel weight of the four options. VLCC_3 was designed to comply with the CSR requirements and has a significantly higher steel weight compared to the previous two options. VLCC_4 represents the high quality option having the highest steel weight among the other alternatives. Table 5.1 on the previous page shows the deadweight for the various options. It can be seen that the deadweights are similar for each of the four options. For simplicity it was assumed that the breadth was the same in all cases, and the spacing of the longitudinal members was similar.

For the purposes of demonstrating the model and in the absence of real data due to propriety restrictions on the use of such data, realistic simulations had to be developed, based mainly on published information. With the exception of VLCC_2, the longitudinal scantlings (stiffeners sizes, plate thicknesses and materials) were taken from the examples given in the Joint Tanker Project (JTP) Consequence Assessment – 2nd draft rule values published jointly by three major class societies (ABS, DNV, LR, 2005). In the captioned study, the full details and the origin of the original designs were not revealed for confidentiality reasons. In tables 5.2, 5.3 and 5.4 on the following pages, the main mid ship longitudinal scantlings and materials are listed for the four structural design options.

|  | VLCC_1 | No. | Mat. | VLCC_2 | No. | Mat. |
|---|---|---|---|---|---|---|
| Main Deck | 400x13+100x19A | 29 | HT315 | 350x12+100x17A | 29 | HT355 |
| Bottom | 550x12+150x34T | 27 | HT315 | 580x12+180x24T | 27 | HT355 |
| Inner Bottom | 600x12.5+150x38T | 21 | HT315 | 600x12+180x28T | 21 | HT355 |
| Side | 650x13+150x38T | 5 | NS | 550x11.5+150x25 | 5 | HT355 |
|  | 550x11.5+150x34T | 3 | NS | 550x11.5+150x20T | 3 | HT355 |
|  | 500x11+150x30T | 5 | NS | 550x11.5+150x25T | 4 | NS |
|  | 500x11+150x22T | 5 | NS | 550x11.5+150x20T | 3 | NS |
|  | 500x11+150x16T | 3 | NS | 500x11.5+150x18T | 3 | NS |
|  | 450x11+150x14T | 5 | NS | 450x11.5+150x18T | 6 | HT355 |
|  | 350x12+100x15A | 3 | HT315 | 400x13+100x18A | 2 | HT355 |
|  | --- | --- | NS | 350x12+100x17A | 3 | HT355 |
| Inner Side | 500x11+150x34T | 5 | NS | 550x11.5+150x22T | 3 | HT355 |
|  | 500x11+150x28T | 4 | NS | 500x11.5+150x18T | 2 | HT355 |
|  | 500x11+150x22T | 4 | NS | 500x11.5+150x18T | 3 | HT355 |
|  | 500x11+150x19T | 6 | NS | 450x11.5+150x16T | 3 | HT355 |
|  | 450x11+150x16T | 3 | HT315 | 400x13+100x18T | 6 | HT355 |
|  | --- | --- | NS | 350x12+100x17A | 2 | HT355 |
| Long. Bhd. | 600x12.5+150x34A | 6 | NS | 500x11.5+150x22T | 10 | HT355 |
|  | 550x11.5+150x34A | 4 | NS | 500x11.5+150x20T | 4 | HT355 |
|  | 550x11+150x32A | 4 | NS | 450x11.5+150x18T | 4 | HT355 |
|  | 500x11+150x25A | 4 | NS | 450x11.5+150x16T | 6 | HT355 |
|  | 500x11+150x19A | 6 | NS | 400x13+100x18A | 3 | HT355 |
|  | 500x11+150x14A | 6 | NS | 400x11.5+100x16A | 5 | HT355 |
|  | 500x12+100x18A | 2 | HT315 | --- | --- | HT355 |
| Lower Hopper | 550x12+150x36T | 4 | HT315 | 580x11.5+150x24T | 4 | HT355 |
|  | 550x11.5+150x36T | 3 | NS | 550x11.5+150x24T | 3 | HT355 |

Table 5.2. Longitudinal Stiffeners for VLCC_1 and VLCC_2

Footnotes

1. Numbers in columns refer to the number of longitudinal stiffeners in each group.
2. Longitudinal stiffeners are either Tee section (T) or angle stiffeners (A) as indicated.
3. HT315 and HT355 refer to High Tensile Steel and NS is normal strength steel.
4. See figure 5.4 for typical mid ship section from MARS Rule 2000 output.
5. VLCC_2 inner side fitted with extended longitudinal stiffeners 1350x16+150x16T (3)

| | VLCC_3 | No. | Mat. | VLCC_4 | No. | Mat. |
|---|---|---|---|---|---|---|
| Main Deck | 400x12+150x20A | 29 | HT315 | 550x15+200x25T | 29 | HT315 |
| Bottom | 650x13+175x25T | 27 | HT315 | 650x15+200x30T | 27 | HT315 |
| Inner Bottom | 625x12.5+175x25T | 21 | HT315 | 625x15+175x30T | 21 | HT315 |
| Side | 600x12.5+175x25T | 5 | HT315 | 600x13.5+175x26T | 5 | HT315 |
| | 600x12.5+175x20T | 3 | HT315 | 600x13.5+175x21T | 3 | HT315 |
| | 600x12.5+175x25T | 4 | NS | 600x13.5+175x26T | 4 | NS |
| | 600x12.5+175x20T | 3 | NS | 600x13.5+175x21T | 3 | NS |
| | 575x12+150x20T | 3 | NS | 575x13+150x21T | 3 | NS |
| | 550x12+150x20T | 3 | NS | 550x13+150x21T | 3 | NS |
| | 525x12+150x20A | 5 | NS | 525x13+150x21T | 3 | NS |
| | 375x12+150x15 | 3 | HT315 | 550x13+150x21T | 2 | HT315 |
| | --- | --- | --- | 500x15+200x25T | 3 | --- |
| Inner Side | 625x12.5+175x20T | 4 | HT315 | 625x14+175x26.5T | 4 | HT315 |
| | 600x12+175x20T | 2 | NS | 600x13.5+175x21.5T | 2 | NS |
| | 575x12+150x20T | 4 | NS | 575x13.5+150x21.5T | 3 | NS |
| | 550x12+150x20T | 3 | NS | 550x13.5+150x21.5T | 4 | NS |
| | 525x12+150x20T | 7 | NS | 525x13.5+150x21.5T | 6 | NS |
| | 325x12+150x15 | 2 | NS | 325x14.5+150x17.5T | 1 | NS |
| | --- | --- | --- | 350x15+150x20T | 2 | --- |
| Long. Bhd. | 625x12+175x25A | 4 | NS | 625x13+175x26T | 4 | NS |
| | 575x12+175x20A | 6 | NS | 575x13+175x26T | 6 | NS |
| | 625x12.5+175x20A | 4 | NS | 625x13.5+175x21T | 4 | NS |
| | 600x12+175x20A | 4 | NS | 600x1.5+175x21T | 4 | NS |
| | 575x12+150x20A | 6 | NS | 575x13.5+150x21T | 6 | NS |
| | 550x12+150x20A | 3 | NS | 550x13.5+150x21T | 3 | NS |
| | 450x12+175x20A | 3 | HT315 | 450x15+175x23T | 3 | HT315 |
| | 375x12+150x15 | 2 | HT315 | 375x15+150x20T | 2 | HT315 |
| Lower Hopper | 600x12.5+175x25T | 4 | HT315 | 600x14+175x26.5T | 4 | HT315 |
| | 600x12.5+175x20T | 3 | HT315 | 600x14+175x21.5T | 3 | HT315 |

Table 5.3. Longitudinal Stiffeners for VLCC_3 and VLCC_4

Footnotes

1. Numbers in columns refer to the number of longitudinal stiffeners in each group.
2. Longitudinal stiffeners are either Tee section (T) or angle stiffeners (A) as indicated.
3. HT315 and HT355 refer to High Tensile Steel and NS is normal strength steel.
4. See figure 5.4 for typical mid ship section from MARS Rule 2000 output.

| Zone | VLCC_1 | VLCC_2 | VLCC_3 | VLCC_4 |
|---|---|---|---|---|
| Keel Strake | 22.5 | 19.5 | 27.5 | 27.5 |
| Bottom Shell | 18.0 | 20.0 | 19.5 | 19.5 |
| Side Shell | 17.5-19.5 | 19.0-21.0 | 18.0-24.0 | 20.0-25.0 |
| Main Deck | 19.5 | 19.5 | 18.5-19.0 | 22.0 |
| Inner Bottom | 19.5 | 21.0-22.0 | 21.0 | 22.0 |
| Lower Hopper | 23.0-30.0 | 20.0-22.0 | 23.0-25.0 | 24.5-26.5 |
| Inner Side | 15.0-20.0 | 15.0-19.5 | 16.0-21.0 | 17.5-22.5 |
| Long. Bhd | 15.0-21.5 | 15.0-19.0 | 15.5-20.0 | 16.5-21.0 |
| DB Girders | 16.5-21.0 | 16.5-23.0 | 17.0-18.0 | 18.5-19.5 |
| BT Stringer | 12.5-14.5 | 13.0 | 14.0-15.0 | 15.5-16.5 |
| Materials | Bottom & Deck HT315 | Fully HT355 | Bottom & Deck HT315 | Bottom & Deck HT315 |

Table 5.4. Plate Thickness and Materials for VLCC Options

The mass of the longitudinal material for VLCC_1 in the mid ship cargo tank region (length 3 x 52m) was 12,514 tonnes. The breakdown of the mid ship region transverse structures for VLCC_1 is shown in table 5.5. The total steel mass in the mid ships cargo area was 12,514 + 3,456 = 15,970 tonnes. The transverse material in the mid body section comprised approximately 21.6% of the total. The combined mass of the no.1 and no.5 cargo tanks was 10,333 tonnes.

| Transverse Structures | Mass (tonnes) |
|---|---|
| Transverse bulkheads | 863 |
| Swash bulkheads | 722 |
| Webframes | 1,871 |
| **Total** | 3,456 |

Table 5.5. Breakdown of Transverse Structures for VLCC_1

The total steel masses were calculated for each option per table 5.6 on the following page. Note that column 2 is the mass of the mid ships cargo tank zone (3 cargo tank lengths) and column 3 the total mass of the zone under consideration as shown in figure 5.2 (p.184). As noted previously, VLCC_2 was based on a 1999 built, pre-CSR Korean double hull design, having the least amount of steel in the design, and therefore the differences in steel weight and percentages for the other 3 options are listed in columns 4 & 5 relative to VLCC_2.

| Option | Long. Steel Mass | Total Steel Mass (mt) | Difference (mt) | % |
|---|---|---|---|---|
| VLCC_1 | 12,514 | 26,303 | 572 | 2.22 |
| VLCC_2 | 11,996 | 25,731 | --- | --- |
| VLCC_3 | 13,341 | 29,203 | 3,472 | 13.50 |
| VLCC_4 | 14,902 | 31,965 | 6,234 | 24.22 |

Table 5.6. Steel Mass and Mass Distributions VLCC_1 to VLCC_4

Given the known lightship mass of 43,000 tonnes for a 300,000 dwt VLCC, the steel mass can be roughly estimated as 70% of the lightweight. The calculated steel weights shown in table 5.6 do not include the slop tanks, the after body, the forepeak tank and the accommodation block. In the last column, the % difference in steel mass can be seen relative to VLCC_2. The high quality option (VLCC_4) is seen to have 24.2% more steel compared to the baseline option. It should be noted that the above individual breakdowns for each VLCC option were determined to provide a means of comparing all four structural options. The variation in steel mass between options has a direct relationship to corrosion margins as discussed in section 2.3.3.

## 5.4 Application of the MCDA/ER Methodology

### *5.4.1 Evaluation of Quantitative Techno-Economic Criteria*

#### *5.4.1.1 Commercial Criteria*

Using examples, the detailed techno-economic calculations which can easily be performed to derive typical numerical data for the commercial and technical assessment criteria developed in chapter 4, including the Net Present Value and the Ultimate Longitudinal Strength are presented here. The net present value (NPV) criterion was introduced in section 4.4.3 as the most appropriate commercial index for this type of project evaluation. Published DNV studies have used the building cost of an HT36/HT32 DH VLCC design as a basis for using accumulated net present value of costs associated with additional steel to compare life cycle costs (Magelssen et al, 1998). A series of net present value (NPV) calculations for each of the four optional designs have been carried out, using the following published commercial data for VLCCs.

Recent press reports indicated that PTT Pcl, Thailand's biggest energy company hired the tanker *Xin Jin Yang* for World Scale (WS) 138. WS 132 is approximately equivalent to USD 100,030 per day, and this is currently typical for a voyage from Saudi Arabia to Korea (Gulfnews, 2008). In the same article Frontline, the worlds largest VLCC operator, reported that an income of USD 31,400/day was required, just to break even. In March 2008, strong demand for steel led primarily by China, resulted in scrapping rates of USD 725 per ldt.

| No | Earnings/Costs (per annum) | USD M |
|---|---|---|
| 1 | Average gross earnings | 35.01 |
| 2 | Operating costs | 11.00 |
| 3 | Net earnings | 24.01 |
| 3 | Scrap price at 2008 levels (VLCC_2) | 19.93 |
| 4 | Construction Cost | 150.00 |

Note: assuming 350 days/year operational time.

Table 5.7 Average VLCC Earnings/Costs 2008

At the time of writing (October 2008), tanker rates had plummeted to WS 87 (USD 65,760/day). This confirms the observations made earlier when discussing rapidly changing economic circumstances in section 2.2.4. Current VLCC construction costs in Korea are in the region of USD 150 million for a standard design. Steel is estimated to cost around USD 2,000/tonne based on current unofficial data sourced from Korean and Chinese Shipyards. The differences in total steel mass between the four optional designs shown in table 5.6 reflect the additional capital costs and assumed scrap values used in the NPV spreadsheet. Using the above data, average annual earnings for VLCC_1 based on March 2008 data have been compiled in table 5.7. The data has been converted into a Microsoft *Excel* spreadsheet analysis and is reasonably representative of actual current project cash flows, but is greatly simplified for the purpose of demonstrating the method. The calculations are easily performed on spreadsheets and have the advantage that sensitivity studies can be performed with ease.

| YEAR | CF | PVIF | PV |
|---|---|---|---|
| 0 | **-151.14** | 1.0000 | -151.14 |
| 1 | 24.01 | 0.9091 | 21.83 |
| 2 | 24.01 | 0.8264 | 19.84 |
| 3 | 24.01 | 0.7513 | 18.04 |
| 4 | 24.01 | 0.6830 | 16.40 |
| 5 | 24.01 | 0.6209 | 14.91 |
| 6 | 24.01 | 0.5645 | 13.55 |
| 7 | 24.01 | 0.5132 | 12.32 |
| 8 | 24.01 | 0.4665 | 11.20 |
| 9 | 24.01 | 0.4241 | 10.18 |
| 10 | 24.01 | 0.3855 | 9.26 |
| 11 | 24.01 | 0.3505 | 8.42 |
| 12 | 24.01 | 0.3186 | 7.65 |
| 13 | 24.01 | 0.2897 | 6.95 |
| 14 | 24.01 | 0.2633 | 6.32 |
| 15 | 24.01 | 0.2394 | 5.75 |
| 16 | 24.01 | 0.2176 | 5.23 |
| 17 | 24.01 | 0.1978 | 4.75 |
| 18 | 24.01 | 0.1799 | 4.32 |
| 19 | 24.01 | 0.1635 | 3.93 |
| 20 | 24.01 | 0.1486 | 3.57 |
| 21 | 24.01 | 0.1351 | 3.24 |
| 22 | 24.01 | 0.1228 | 2.95 |
| 23 | 24.01 | 0.1117 | 2.68 |
| 24 | 24.01 | 0.1015 | 2.44 |
| 25 | **43.94** | 0.0923 | 4.06 |
|  |  | **NPV =** | **68.64** |

Table 5.8. Results of NPV Calculations for VLCC_1

Table 5.8 shows the results for VLCC_1. A vessel lifetime of 25 years has been assumed. The capital cost has been adjusted for the additional steel weight of VLCC_1 compared to the baseline cost for the least cost option, VLCC_2 (USD 150 million). The NPV is calculated based on the estimated net cash flows listed in table 5.7. The assumed capital expenditure of USD151.4 million and the scrap value of USD 19.93 million are indicated in column 2 in years 0 and 25 respectively. In column 3, the present value interest factor (PVIF) has been calculated using the method presented earlier in section 4.4.3. In column 4, the product of the PVIF and the present value (PV) for each year are summed. The results indicate an NPV of USD 68.64 million at 10% interest rate. A summary of NPV results for all four options appears in table 5.9, assuming an interest rate of 10%, which is considered a reasonably representative opportunity cost for capital project evaluation purposes (Weston and Copeland, 1989).

| Option | Additional Steel | CAPEX USD(M) | Scrap USD(M) | NPV USD(M) |
|---|---|---|---|---|
| VLCC_1 | 572 | 151.14 | 19.93 | 68.64 |
| VLCC_2 | Baseline | 150.00 | 19.50 | 69.74 |
| VLCC_3 | 3,472 | 156.94 | 22.13 | 63.01 |
| VLCC_4 | 6,234 | 162.47 | 24.22 | 57.71 |

Table 5.9. Estimated Capital Costs, Scrap Value and NPV.

For VLCC_1, a sensitivity analysis was performed by varying the discount rate, as depicted in figure 5.3. The internal rate of return (IRR) is the point where the discount rate causes the NPV to be zero (>13%).

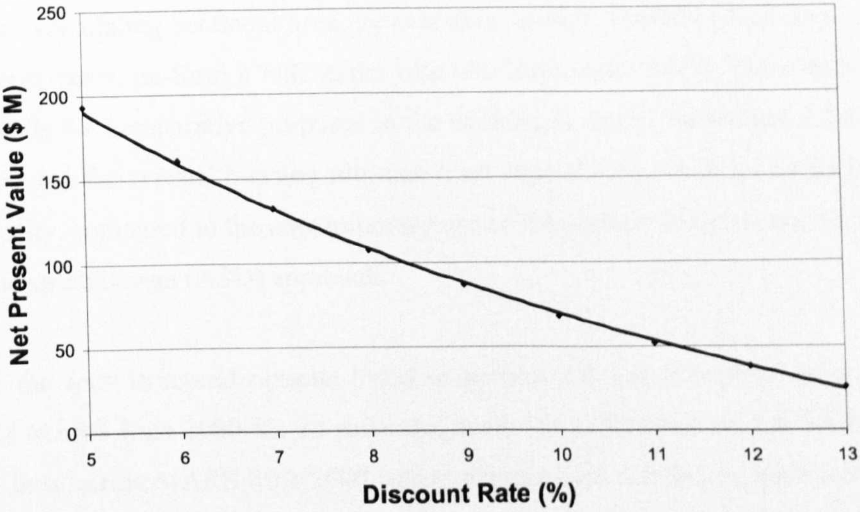


Figure 5.3. NPV of Project Options at Different Discount Rates

For the purposes of this study, the NPV has been calculated for the vessel's lifecycle of 25 years, and includes all projected costs including initial capital expenditure, all operating cash flows throughout the vessel lifetime and disposal costs.

#### *5.4.1.2 Technical Criteria*

To illustrate in detail the method for producing typical representative numerical data for the technical criteria, two important examples will be given, *Ultimate Strength and Corrosion Margins.*

**Ultimate strength**: In the early 1990's, a number of the major IACS societies introduced computerised rule formulations and software-supported structural assessment tools. Cheap computing power and ready availability through the internet, meant that some of these tools became available in the public domain. Use of such products has allowed yards, consultants and in some cases the owner's technical department, to perform rapid preliminary structural design assessment from data contained in the key structural drawings, principally the Midship Section. A brief description of a number of these products appears in the literature survey, section 2.5.5.

Software based scantling assessment tools such as *MARS2000 (BV), RULESCALC 2008 (LR), SafeHull (ABS), POSEIDON ND (GL), and Nauticus Hull (DNV)* are capable of calculating sectional area, neutral axis, section modulii (deck and bottom), and in most cases, perform a hull girder ultimate limit state check. These data can be used directly for comparative purposes in the evaluation model. In section 2.2.3, it was suggested that the vertical bending ultimate limit state (ULS) was a preferred index of hull capacity, compared to the contemporary use of the section modulus arising from an allowable stress design (ASD) approach.

Each of the four structural options listed in section 5.3 was modelled using Bureau Veritas's MARS Rule 2000 V2.2d software, available as freeware on the internet. The purpose in selecting MARS Rule 2000 was to demonstrate that these sophisticated tools are readily available in the public domain, although other products would have been equally or more suitable. MARS Rule 2000 is capable of computing scantlings of plating and ordinary stiffeners of any transverse section located along the ship length according to the April 2007 Bureau Veritas Rules for the classification of Ships and IACS common structural rules (CSR) for tankers (www.veristar.com). MARS Rule 2000 computes geometric properties, hull girder strength criteria, ultimate strength and rule scantlings. The detailed calculations are omitted from the thesis as the main purpose here was to obtain realistic comparative data using readily available and powerful tools. Figure 5.4 on the following page, shows a typical mid ship section output from the MARS Rule 2000 software program.

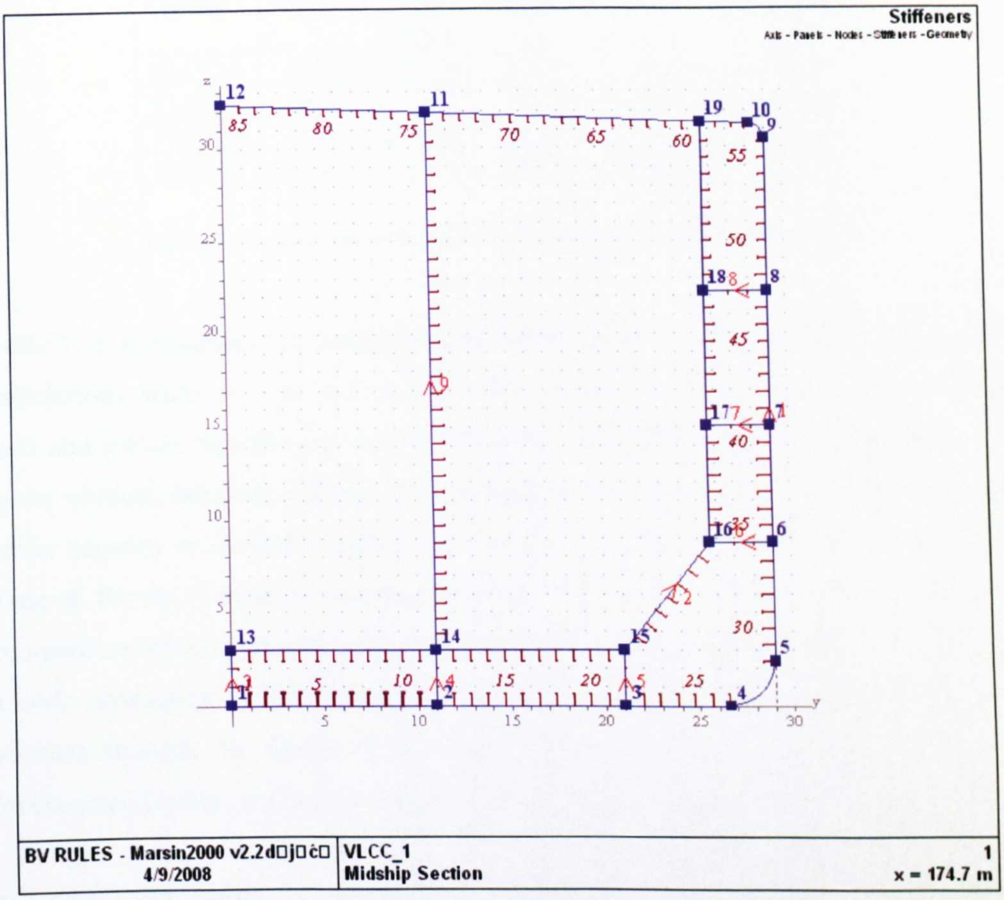


Figure 5.4. DH VLCC Mid Ship Section - Basis for Longitudinal Strength Calculations

In table 5.10 the BV Rule values of stillwater and wave bending moment are given, together with the shear force assumed in the longitudinal strength calculations for all four options.

| Design Load (kN-m) | Hogging | Sagging |
|---|---|---|
| Stillwater Bending Moment | 7,161,300 | 6,602,130 |
| Wave Bending Moment | 9,746,946 | 10,384,960 |
| Shear Force | 153,654 | |

Table 5.10. Design SWBM/WBM and Shear Force Applied

In table 5.10, the rule design stillwater and wave bending moments (hogging and sagging) assumed in the Mars Rule 2000 models are listed.

| Option | A (m^2) | Mass (t/m) | Zd (m^3) | Zb (m^3) | Mt/Mu % |
|---|---|---|---|---|---|
| VLCC-1 | 10.270 | 80.62 | 78.668 | 106.965 | 96.62 |
| VLCC_2 | 10.027 | 78.71 | 77.195 | 105.347 | 88.62 |
| VLCC_3 | 10.834 | 85.05 | 81.662 | 111.061 | 92.15 |
| VLCC-4 | 12.169 | 95.53 | 100.017 | 124.826 | 70.89 |

Table 5.11. Results From Longitudinal Strength Calculations

Table 5.11 summarises the main structural results obtained from the MARS Rule 2000 calculations, where A = cross sectional areas, *Zd* and *Zb* are the section modulii of the deck and bottom respectively, and Mt/Mu is the ratio of the total bending moment (*Mt*) to the ultimate bending moment (*Mu*) in sagging mode, which is an index of the hull girder capacity in vertical bending. All the above calculations were performed on the basis of Bureau Veritas's classification rules (2007). This was done to permit direct comparison between all options on the same basis. The MARS Rule 2000 software uses a code developed by the Technical University of Szczecin to calculate hull girder ultimate strength. No details of the code are given by BV, and this aspect was not investigated further, as it was considered to be outside the scope of this research work.

**Corrosion Margins**: In section 2.3.3, corrosion margins were discussed. For comparison purposes, corrosion margins for a range of structural elements in the four alternative structural options have to be estimated. Corrosion margins for the first two options (VLCC_1 and VLCC_2) were calculated assuming 20% maximum wastage for individual structural members, corresponding to pre-CSR practice. In VLCC_1, the main deck plating thickness was 19.5mm, and the corrosion allowance was 3.9mm. It should be emphasised that this rule of thumb may not apply to deck plating on double hull tankers due to high buckling stresses For VLCC_3 (CSR compliant). Nominal corrosion margins were taken from the data given in IACS *Background Document Section 12 – Ship in Operation Renewal Criteria* (IACS, 2006c), and these are shown in table 5.12. For VLCC_4, the corrosion margins were estimated based on 20% of the actual scantlings, and since the thicknesses are greater for option 4, the corrosion margins are correspondingly higher. Finally, an average is taken for each option, and this value represents a nominal corrosion margin for each.. This numeric data has been used directly in the ER model.

| **Structural Elements** | **VLCC_1** | **VLCC_2** | **VLCC_3** | **VLCC_4** |
|---|---|---|---|---|
| Deck plating | 3.9 | 3.9 | 4.0 | 4.4 |
| Sheer strake | 3.5 | 3.8 | 3.5 | 4.2 |
| Bilge & bottom plating | 3.6 | 4.0 | 3.0 | 3.9 |
| Upper strake of inner skin | 4.0 | 3.8 | 4.0 | 4.2 |
| Upper strake of long. bulkhead plating | 3.5 | 3.7 | 4.0 | 4.0 |
| Main deck longitudinal stiffeners (web) | 2.6 | 2.4 | 4.0 | 3.0 |
| Bottom shell longitudinal stiffeners (web) | 2.4 | 2.4 | 3.0 | 3.0 |
| Side shell plating at ½ depth | 3.9 | 4.2 | 3.5 | 5.0 |
| Inner skin and hopper plating at ½ depth | 4.6 | 4.0 | 3.0 | 5.3 |
| Longitudinal bulkhead plating | 3.0 | 3.0 | 2.5 | 3.7 |
| Inner bottom plating | 3.9 | 4.2 | 4.0 | 4.4 |
| Longitudinal girders (in double bottom) | 3.3 | 3.3 | 3.0 | 3.7 |
| Upper longitudinal stringers (in WBT) | 2.5 | 2.6 | 3.0 | 3.1 |
| **Average** | **3.4** | **3.5** | **3.4** | **4.0** |

Table 5.12. Estimation of Corrosion Margins

Reference can be made to table 5.4 (p.188) showing the thickness ranges of plate scantlings for each of the 4 options.

### 5.4.2 Setting the Criteria Grades & Weightings

In table 4.10 (p.172) of section 4.5.2, a total of 35 criteria for the structural assessment framework were presented, and for convenience, these are listed here again in table 5.13 on the following page. In structural performance evaluation, some of the quantitative criteria can easily be described by numeric data, including *NPV, Warrantee, Longitudinal Strength, Fatigue Life, Buckling* etc. The assessment of many of the other attributes including *Sloshing Resistance, Critical Areas, Builder's Reputation, Owner's Experience, Structural Details and Welding Design* etc is not straightforward, because they are qualitative in nature and require subjective judgements. Vagueness and incompleteness of the data is also characteristic of the nature of this type of assessment problem.

| No | Sub-Attribute | QL. | QN. |
|---|---|---|---|
| 1 | NPV | | X |
| 2 | Warrantee | | X |
| 3 | Classification | X | |
| 4 | Longitudinal Strength | | X |
| 5 | Transverse strength | X | |
| 6 | Hull Girder fatigue | | X |
| 7 | Side Structure fatigue | | X |
| 8 | Main Deck buckling | | X |
| 9 | Members 1-3 buckling | X | |
| 10 | Berthing resistance | | X |
| 11 | Sloshing resistance | X | |
| 12 | Critical area -1 | X | |
| 13 | Critical area - 2 | X | |
| 14 | Critical area - 3 | X | |
| 15 | Builder's reputation | X | |
| 16 | Owners experience | X | |
| 17 | Corrosion Margins | | X |
| 18 | Minimum. Scantling | | X |
| 19 | Coating Specifications | | X |
| 20 | Anodes in Tanks | X | |
| 21 | Materials in Hull | | X |
| 22 | Structural Details | X | |
| 23 | Welding Design | X | |
| 24 | Yard QA/QC | X | |
| 25 | Owner Effort | X | |
| 26 | Ballast Distribution | X | |
| 27 | Ballast Filling % | | X |
| 28 | Cross Ties Location | X | |
| 29 | Subjective (Structural) | X | |
| 30 | Ballast Tanks Access | X | |
| 31 | Cargo Tanks Access | X | |
| 32 | Forepeak Tank Design | X | |
| 33 | Afterpeak Tank Design | X | |
| 34 | Hull stress monitoring system | X | |
| 35 | Operability | X | |

Table 5.13. Lower Level (Level 5) Sub-Criteria

To limit the complexity of the model without losing relevance, a common grading system consisting of the following seven grades has been chosen throughout for both numeric and qualitative criteria:

$$N = 7, H_1 = \{Unacceptable\}, H_2 = \{VeryPoor\}, H_3 = \{Poor\}, H_4 = \{Fair\}, H_5 = \{Good\},$$
$$H_6 = \{VeryGood\}, H_7 = \{Excellent\}$$

For consistency and to reduce subjectivity (Xie et al, 2008), a clear definition of the standard of each assessment grade needs to be provided for all the numerical assessments and subjective judgements involved in the data assessment process. These definitions are intended to reflect the preferences of a single decision maker and are given below as an example:

*Unacceptable*: Clearly not satisfactory
*Very Poor*: Not satisfactory
*Poor*: Marginally unsatisfactory
*Fair*: Just acceptable and satisfactory
*Good*: Fully satisfactory
*Very Good*: Fully compliant with the performance specifications
*Excellent*: Above the performance specifications and buyer's expectations

Subjective judgement inevitably has to be used and the contribution of structural experts will be obvious to facilitate cross trade offs between different attributes, weights have to be assigned and a utility function needs to be defined for the assessment grades of each attribute. The assignment of weights represents a very important part of the ER modelling, and should be estimated with care (Yang & Xu, 1998). For the purpose of demonstrating the general framework, the importance of the individual attributes is reflected in the weights assigned in the generalised decision matrix. The weights are indicated in column 2 of table 5.14. It was assumed that the weights for *Commercial* and *Technical* were of equal importance (i.e. 0.5 in both cases).

| **Top Level Criteria** | |
|---|---|
| Technical | 0.5 |
| Commercial | 0.5 |
| **Main Technical Criteria** | |
| Strength | 0.4 |
| Durability | 0.4 |
| Arrangements | 0.1 |
| Operational | 0.1 |

Table 5.14. Assignment of Weights for Top Level Criteria

Weights of each criterion or sub criterion could have been calculated using the analytic hierarchy process (AHP) method. However, for the purposes of this study, AHP was not used.

### *5.4.3 Transforming Basic Quantitative Criteria*

In the proposed framework, 7 grades have been adopted. To avoid excessive complexity, and in view of the number of sub-criteria used in the model, the 7 grades are the same throughout for both numeric and qualitative criteria. Numeric sub-criteria can be transformed to an equivalent assessment using the method given by Xie et al (2008) as follows:

If $h_{N,i}$ and $h_{1i}$ are the largest and smallest values that an assessed option can take on the sub-criterion and a value $h_{n,i}$ is judged equivalent to a grade $H_n$, n = 1,....,N, then a value $h$ on $e_i$ can be mapped to the grade set with degree of belief.

The assessment $S(e_i(h)) = \{(h_{n,i}, \beta_{n,i}), n = 1,...,N \}$

where $\beta_{n,i} = \dfrac{h_{n+1,i} - h}{h_{n+1,i} - h_{n,i}}, \beta_{n+1,i} = 1 - \beta_{n,i}$, if $h_{n+1} \leq h \leq h_{n+1,i}$

and $n = 1,\ldots,N-1$

$\beta_{k,i} = 0$ for $k = 1,\ldots,N$ and $k \neq n, n+1$.

The assessment $S(e_i(h))$ transformed into the form of a belief structure shown above, can be used directly in the ER algorithm. In table 5.15, the range of the numeric data in the model is listed. To aggregate the information for use in the ER algorithm, the assessments performed on quantitative criteria have to be transformed into a common set of grades or belief structures. In the ER model, the worst and best values listed are used to determine the range of the numeric criteria throughout.

| Criteria | Worst | Best | Units |
|---|---|---|---|
| NPV | 57.71 | 69.74 | USD Million |
| Warrantee | 1 | 5 | Years |
| Longitudinal Strength | 96.62 | 70.89 | % |
| Hull girder fatigue | 20 | 40 | Years |
| Side structure fatigue | 20 | 40 | Years |
| Main deck buckling | 224 | 174 | MPa |
| Berthing resistance | 19 | 25 | mm |
| Corrosion margins | 3.4 | 4.0 | mm |
| Minimum scantlings | 11.5 | 15.0 | mm |
| Coating specifications | 5 | 20 | Years |
| Materials (HTS) | 80 | 30 | % |
| Peak tank filling | 62.5 | 100 | % |

Table 5.15. Ranges of Numeric Criteria Assumed in the ER Model

The net present values (NPV) shown in table 5.15 range from USD 57.71 million to USD 69.74 million. It is assumed that the extreme values are equivalent to *unacceptable* grade for the lowest NPV and *excellent* grade for the highest NPV. For each of the 5 grades (*VP, P, F, G, VG*) between *unacceptable* and *excellent*, decision makers have to establish intermediate values. For simplicity, a linear distribution ranging from 0 to 1.0 is assumed in the model, leading to the following results:

$$VP = U + \frac{(E-U)}{6} = 57.71 + \frac{(69.74-57.71)}{6} = 59.715$$

$$P = U + 2\,\frac{(E-U)}{6} = 57.71 + 2\frac{(69.74-57.71)}{6} = 61.725$$

Similarly $F = 63.725$, $G = 65.730$ and $VG = 67.735$

### *5.4.4 Assessing Qualitative Criteria*

To aggregate all the information using the ER algorithm, the above assessments have to be transformed using a common set of grades in the format of belief structures. For the qualitative criteria, each option can be evaluated using expert judgement and assigning belief degrees associated with the grades.

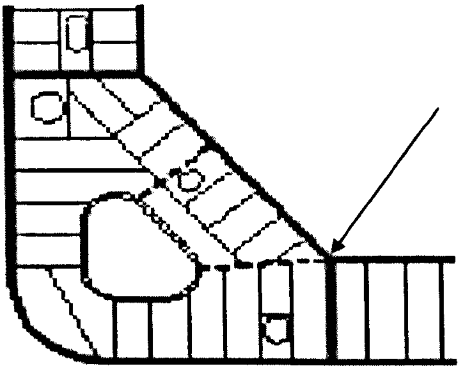


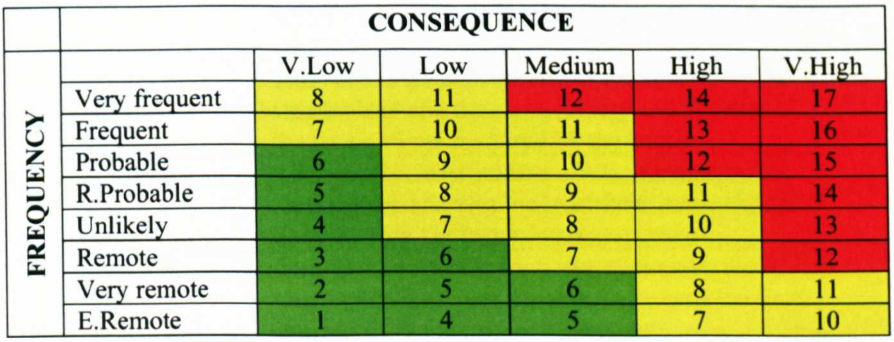
Figure 5.5. Lower Hopper Corner Arrangement

To evaluate *critical areas 1* for example, the lower hopper corner area indicated by the arrow shown in figure 5.5 has been chosen. In section 4.4.4.5 (p.158), reference was made to categorisation of critical areas by systematically ranking and prioritising hazards according to the risk-based procedures described in section 3.5.4 (p. 124) according to the method. At the simplest level, structural assessment could be conducted on the basis of subjective judgement by a team of experts using scantlings and welding details reviewed against class rule minima, illustrating the flexibility and simplicity of the structural assessment process. In a more sophisticated approach, coarse mesh finite element analysis and fatigue calculations carried out using one of the proprietary software structural analysis tools offered by the major class societies such as ABS*'s SafeHull,* DNV's *Nauticus Hull* or GL's *Poseiden ND* may be used, as described earlier in section 2.5.5 (p. 68). Detailed solid element mesh models can be generated as described by Read et al (2000) in relation to the *Millenium Class* tankers.

Figure 5.6. Detailed FEM Results for Lower Hopper Corner (Read et al, 2000)

Fatigue considerations may also be incorporated into the evaluation process by calculating stress concentration factors from fine-mesh models and comparing stresses against acceptance criteria including the industry standard "C" and "D" SN curves from the UK Department of Energy shown in figure 2.6 of section 2.3.2. Figure 5.6 shows the radius plate modification which was found necessary to overcome the design objections to the cruciform welded connection detail originally offered in the *Millenium Class* tankers described by Read et al above.

Recent Japanese built DH tanker feature radiused hopper corners of increased thickness to overcome fatigue problems associated with the welded joints normally featured in this area. The corner detail above is considered to have a high probability of failure due to high stresses and low fatigue life indicated from the FEM results. Failure consequences may involve cargo entry into the double bottom ballast spaces, with the potential to cause an explosion, loss of life and pollution. At least very high costs and most probably extended off-hire would be necessary to clean up the contaminated ballast spaces. Structural evaluation of the subject area may be accomplished using a standard risk-assessment approach developed in section 3.5.5. The risk matrix in figure 5.16 can be used to directly assess the risk by assuming that the frequency of a fatigue fracture in the area in question is reasonably probable and the consequences of this type of failure are judged to be very high. The corresponding risk category from the matrix is 14, indicating very high risk.



| | | CONSEQUENCE | | | | |
|---|---|---|---|---|---|---|
| | | V.Low | Low | Medium | High | V.High |
| FREQUENCY | Very frequent | 8 | 11 | 12 | 14 | 17 |
| | Frequent | 7 | 10 | 11 | 13 | 16 |
| | Probable | 6 | 9 | 10 | 12 | 15 |
| | R.Probable | 5 | 8 | 9 | 11 | 14 |
| | Unlikely | 4 | 7 | 8 | 10 | 13 |
| | Remote | 3 | 6 | 7 | 9 | 12 |
| | Very remote | 2 | 5 | 6 | 8 | 11 |
| | E.Remote | 1 | 4 | 5 | 7 | 10 |

Table 5.16. Risk Matrix

The outcomes from the preliminary risk-assessments described above are used to form the input data for the structural assessment model. In this way a layered risk-assessment process is evolved. The data forms part of the assessment of the major criterion *Strength* through the sub-criterion *Critical Areas*. Such critical decisions may be made by more than one decision maker. Typical subjective judgments for the lower hopper critical area might be that the structural design offered by the ship builder was considered to be *very poor* with a belief degree of 40% and *poor* with a belief degree of 60% as indicated in table 5.17. This outcome could be derived from three members of a five person team rating the critical area as *poor* and two giving a *very poor* rating.

| **Degree of Belief (β)** | **Evaluation Grade** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **U** | **VP** | **P** | **F** | **G** | **VG** | **E** |
| Critical Area 1 | | 0.4 | 0.6 | | | | |
| Critical Area 2 | | 0.5 | 0.5 | | | | |
| Critical Area 3 | | 0.8 | 0.2 | | | | |

Table 5.17. Subjective Judgments for Evaluating *Critical Areas*

A further example of the use of linguistic terms to describe the qualitative criteria used in the model will be given. In table 5.18, a detailed explanation of the assessment grades for the commercial sub-criterion *classification* appears.

| **Grades** | **Definitions and Explanation** |
|---|---|
| Unacceptable | The vessel's classification was chosen by the ship builder and was the least preferred option out of 11 societies from the owner's point of view. |
| Very Poor | The vessels classification was nominated by the ship builder and the class society was not one of the four options favoured by the owner. |
| Poor | The vessels classification was nominated by the ship builder and was the least favourable of four options from the owner's point of view. |
| Fair | The vessels classification was chosen by the ship builder and was the third best from the four options from the owner's viewpoint. |
| Good | The vessels classification was chosen by the ship builder and coincided with the second best of the four options from the owner's viewpoint. |
| Very Good | The vessels classification was chosen by the ship builder and was the best of the four options from the owner's viewpoint. |
| Excellent | The owner selected the society of choice to class the vessel because of historical associations with the nominated organisation. |

Table 5.18. The Assessment Grade *Classification*

An assessor would document other similar evaluations in order to maintain the transparency and validity of the structural assessment process.

### *5.4.5 General Pre-Assessment Process*

As a preliminary step in the proposed structural assessment framework, each of the four VLCC structural designs were generally assessed as shown in tables 5.19 and 5.20 on the following pages. This step is recommended to broadly capture and document key considerations as a prelude to more detailed assessment which follows. The identification of general considerations involved in the decision-making process is the prerequisite for constructing a generalised decision matrix containing the belief probability distributions which is the main outcome of the structural assessment framework. In table 5.19, the assessments for VLCC_1 and VLCC_2 are given.

| **SUB ATTRIBUTE** | **VLCC_1** | **VLCC_2** |
|---|---|---|
| *NPV* | USD 68.64 million | USD 69.74 million |
| *Warrantee for hull* | 1 year | 1 year |
| *Classification society* | Chosen by yard, but least preferred option | Class chosen by yard, and not one of four favoured options |
| *Longitudinal strength* | 96.62% of ultimate capacity | 88.62% of ultimate capacity |
| *Transverse strength* | To minimum rules standards | To minimum rules standards |
| *Hull Girder fatigue* | 20 years minimum standard worldwide wave data | 20 years minimum standard worldwide wave data |
| *Side Structure fatigue* | 20 years minimum standard worldwide wave data | 20 years minimum standard worldwide wave data |
| *Main Deck buckling* | Stresses in deck longitudinals | Buckling stresses in deck longitudinals |
| *Members 1-3 buckling* | Stresses in 3 nominated areas | Stresses in 3 nominated areas |
| *Berthing resistance* | Side shell thickness 19.5mm | Side shell thickness 21.0mm |
| *Sloshing resistance* | Minimum rule requirements | Minimum rule requirements |
| *Critical area -1* | Yard standard design | Yard standard design |
| *Critical area – 2* | Yard standard design | Yard standard design |
| *Critical area - 3* | Yard standard design | Yard standard design |
| *Builder reputation* | Poor reputation | Mediocre reputation |
| *Owners experience* | Very experienced | Very experienced |
| *Corrosion Margins* | 3.4mm | 3.5mm |
| *Minimum. Scantling* | 11.5mm upper ballast tanks plating | 11.5mm upper ballast tank plating |
| *Coating Specifications* | 5 year nominal lifetime | 5 year nominal lifetime |
| *Anodes in Tanks* | Minimum requirements | Minimum requirements |
| *Materials in Hull* | 32% high tensile steel | 80% high tensile steel |
| *Structural Details* | Yard standard design | Yard standard design |
| *Welding Design* | To minimum rule requirements | To minimum rule requirements |
| *Yard QA/QC* | Poor quality system | Poor quality system |
| *Owner Effort* | Substantial effort | Substantial effort |
| *Ballast Distribution* | Evenly distributed | Evenly distributed |
| *Ballast Filling %* | 62.5% in Normal Ballast condition | 62.5% in Normal Ballast condition |
| *Cross Ties Location* | Centre tanks | Wing tanks |
| *Subjective (Structural)* | Optimised design | Optimised design |
| *Ballast Tanks Access* | Standard provisions + rafting | Standard provisions + rafting |
| *Cargo Tanks Access* | Standard provisions | Standard provisions |
| *Forepeak Tank Design* | Basic design | Basic design |
| *Afterpeak Tank Design* | Basic design | Basic design |
| *HSMS* | Not fitted | Not fitted |
| *Operability* | No special consideration | No special consideration |

Table 5.19. General Considerations for VLCC_1&2

| SUB ATTRIBUTE | VLCC-3 | VLCC-4 |
|---|---|---|
| *NPV* | USD 63.04 million | USD 57.71 million |
| *Warrantee for hull* | 1 year | 5 years |
| *Classification society* | Chosen by yard, and was the 2nd best option | Owner chose class and it was the most preferred option |
| *Longitudinal strength* | 92.15% of ultimate capacity | 70.89% of ultimate capacity |
| *Transverse strength* | Design upgraded to CSR rules | Enhanced scantlings |
| *Hull Girder fatigue* | 25 years worldwide wave data | 40 years worldwide wave data |
| *Side Structure fatigue* | 25 years worldwide wave data | 40 years worldwide wave data |
| *Main Deck buckling* | Buckling stress in deck longitudinals | Buckling stress in deck longitudinals |
| *Members 1-3 buckling* | Buckling stresses in 3 nominated areas | Buckling stresses in 3 nominated areas |
| *Berthing resistance* | Side shell thickness 20.5mm | Side shell thickness 25.0mm |
| *Sloshing resistance* | Meets CSR requirements | Specially considered |
| *Critical area -1* | Yard standard design | FEM analysis, and design upgraded |
| *Critical area – 2* | Yard standard design | FEM analysis, and design upgraded |
| *Critical area - 3* | Yard standard design | FEM analysis and design upgraded |
| *Builder reputation* | Good reputation | Fair reputation |
| *Owners experience* | Very experienced | Very experienced |
| *Corrosion Margins* | 3.4mm upper ballast tanks plating | 4.0mm upper ballast tanks plating |
| *Minimum. Scantling* | 11.5mm | 15.0mm |
| *Coating Specifications* | 15 year nominal lifetime & IMO Res. A.798(19) and IACS UI SC 122 | 20 year nominal lifetime & IMO Res. A.798(19) and IACS UI SC 122 |
| *Anodes in Tanks* | CSR requirements | Owners requirements |
| *Materials in Hull* | 32% high tensile steel | 30% high tensile steel |
| *Structural Details* | Basic CSR design | Specially considered and enhanced details |
| *Welding Design* | To CSR rules minimum | Specially considered and increased |
| *Yard QA/QC* | Good quality system | Good/Fair quality system |
| *Owner Effort* | Substantial effort | Very substantial effort |
| *Ballast Distribution* | Evenly distributed | Evenly distributed |
| *Ballast Filling %* | Ballast tanks 100% full in normal ballast condition | Ballast tanks 100% full in normal ballast condition |
| *Cross Ties Location* | Centre tanks | Wing tanks |
| *Subjective (Structural)* | Basic design with enhancements | Much improved design |
| *Ballast Tanks Access* | Standard IMO provisions | Incorporating owners requirements |
| *Cargo Tanks Access* | Standard IMO provisions | Incorporating owners requirements |
| *FPT Design* | Basic design with enhancements | carefully considered, and design upgraded |
| *APT Design* | Basic design with enhancements | Improved design |
| *HSMS* | Not fitted | HSMS fitted |
| *Operability* | Some enhancements | Owners requirements |

Table 5.20. General Considerations for VLCC_3&4

In table 5.20, VLCC_3 and VLCC_4 have been assessed. Having established a procedure for compiling the general considerations outlined in tables 5.19 and 5.20, the process for determining the lower level attributes for VLCC_1 is described in detail in table 5.21. All the assumptions made as part of the evaluation process should be documented. A team approach is recommended with a mix of skills, including specialists and ship operators. It should be emphasised that the intention here is to present a broad framework for structural assessment and to demonstrate and validate the processes and the IDS model rather than to attempt to develop a commercially viable system. Therefore the decision process and data presented in the model is notional and should not be interpreted to be real data, although the numerical and qualitative criteria have been based on the published literature and the practical experience of the author.

In row one of table 5.21, the net present value calculated in section 5.4.1.1 (p. 189) has been entered. In row three, the hull girder ultimate strength ratio for VLCC_1 calculated in section 5.4.1.2 and summarised in table 5.11 on page 195 is given. Similarly, other numerical sub-attributes such as *Berthing Resistance* in row ten have been assessed based on the considerations given in section 4.4.4.4 (p.157). In table 5.21, the subjective judgements associated with the various qualitative sub-criteria have also been captured using belief degrees assigned to the seven evaluation grades. For example, in row two, the assessment of the sub-criterion *Classification* was transformed into a grading of *Unacceptable* with a belief degree U (1.0). In row eleven, *Sloshing Resistance* was evaluated by the decision maker/s in the following way:

*S (sloshing Resistance) = {(Unacceptable, 0.3), (Very Poor, 0.7)}*

The real numbers 0.3 and 0.7 denote the degrees of belief of 30% and 70% respectively. For *Builder's Reputation* in row fifteen, a grade of *Good* (0.8) was decided and the degree of incompleteness was 0.2. Similarly, the other qualitative sub-attributes have been evaluated and the corresponding belief degrees assigned.

| SUB ATTRIBUTE | EVALUATION RESULTS FOR VLCC_1 |
|---|---|
| *NPV* | The NPV was calculated = USD 68.64 million (see calculations) |
| *Hull Warrantee* | Standard ship yard warrantee offered by the ship builder was 12 months, when an extended warrantee was desired. |
| *Classification* | The Class Society was chosen by yard and was the least preferable option available to the owner, without incurring significant additional costs, and was graded U(1.0) |
| *Long. Strength* | The hull girder ultimate capacity was calculated by the MAR Rule S2000 software according to pre-CSR BV Rules and the ratio was found to be 96.62% |
| *Transv. Strength* | Offered design of main transverse structures including bulkheads and web frames was evaluated by specialists and graded VP(0.5), P(0.5) due to low thicknesses and poor details. |
| *H.G fatigue* | Scantlings calculated for standard 20 years (world wide trading) |
| *S/S fatigue* | Scantlings calculated for standard 20 years (world wide trading) |
| *M/D buckling* | Main deck buckling stress calculated = 224 Mpa |
| *M/D buckling 1-3* | Members 1-3 assessed for buckling capacity and graded as VP(0.5), P(0.5). |
| *Berth. Resistance* | Side shell thickness = 19.5mm |
| *Slosh. Resistance* | Due to the lack of a Swash Bulkhead in the cargo tanks, the risk of sloshing was evaluated and found to be high and graded U(0.3), VP(0.7) accordingly |
| *CA – 1* | The offered design of critical area no.1 (lower hopper corner) was evaluated by specialists using subjective judgement and graded as VP(0.4), P(0.6) due to anticipated elevated risk of serviceability problems including fractures. |
| *CA – 2* | The offered design of critical area no.2 (connection of transverse bulkhead to double bottom) was evaluated by specialists using subjective judgement and graded as VP(0.5), P(0.5) due anticipated elevated risk of serviceability problems including fractures. |
| *CA – 3* | The offered design of critical area no.3 (typical side shell longitudinal penetration through web frame in way of Wing Ballast Tanks) was evaluated by specialists using subjective judgement and graded as VP(0.8), P(0.2) due to anticipated elevated risk of serviceability problems including fractures. |
| *Builder reputation* | The builder was considered to be relatively inexperienced with a fair reputation, and hence graded F(0.8) |
| *Owners experience* | The owner was experienced with operation of double hull VLCC's and had access to good technical resources and therefore this attribute has been given a high grade of G(0.8), VG(0.2). |
| *Corrosion Margins* | The corrosion margins for the plating within 3.0m from the top of the Wing Ballast Tank were assessed and the additional corrosion margin was 1.75mm |
| *Min. Scantling* | The minimum thickness found in the mid ship section scantling list was 11.5mm for a longitudinal stiffener web thickness. |
| *Coat. Spec's* | The Ballast Tank coating system corresponded to DNV preparation system I with 1 x 200 microns Epoxy (5 +/- 3 years nominal lifetime) |
| *Anodes in Tanks* | The minimum number of anodes were fitted in way of Ballast Tanks. This was considered to be F(0.6), G(0.4). |
| *Materials in Hull* | The hull design featured 32% High Tensile Steel (HTS) |

| SUB ATTRIBUTE | EVALUATION RESULTS FOR VLCC_1 |
|---|---|
| *Structural Details* | A range of standard generic structural details including deck, bottom and side longitudinal frame penetrations through web frames were evaluated by experts using subjective judgement and a combined grading of U(0.5), VP(0.5) given, due to generally unsatisfactory quality of the offered details and anticipated risk of structural problems in service. |
| *Welding Design* | The welding details in selected areas were assessed by experts using subjective judgement and owing to the lack of full penetration welding in selected areas and generally deficient leg length in other areas designed according to classification society minima, a grade of U(0.5), VP(0.5) was given. |
| *Yard QA/QC* | The yard quality department and quality system was judged to be of a relatively poor standard from previous experience. A grade of VP(0.5), P(0.4) was given. |
| *Owner Effort* | Due to perceived shortcomings on the part of the yard QA/QC, The owner allocated significant team resources to focus the quality effort. Hence a grade of G(1.0) was assigned. |
| *Ball. Distribution* | The offered design featured evenly distributed ballast in side Segregated Ballast Tanks with no option for mid ships ballast to offset exceptionally high bending moments in the ballast condition. Hence this aspect of the design was graded U(0.3), VP(0.7). |
| *Ballast Filling %* | The offered design featured a partially filled Fore Peak Tank in the Normal Ballast departure condition. The filling was 62.5%. |
| *Cross Ties* | Cross Ties were fitted in the centre tanks in the offered design. This was graded P(0.6) since there was some doubt about the technical aspects involved. |
| *Subjective* | The main structural drawings for the design were examined and the judgement of experts resulted in a combined grade of U(0.2), VP(0.8) for the general subjective structural design aspects. |
| *B.T. Access* | The Ballast Tank access arrangements offered by the builder were just in compliance with the minimum statutory and class requirements, and therefore were graded P(0.5), F(0.5). |
| *C.T. Access* | The Cargo Tank access arrangements offered by the builder were just in compliance with the minimum statutory and class requirements, and therefore were graded VP(0.5), P(0.5), because the provisions for access to the main deck structures for survey purposes were considered to be lacking. |
| *FPT Design* | The structural design of the Fore Peak Tank was examined by experts and graded as VP(1.0) due to the risk of structural damage caused by sloshing (see *Ballast Filling %* above). |
| *APT Design* | The structural design of the After Peak Tank was examined by experts and graded as P(0.5), F(0.5). |
| *HSMS* | A HSMS was not offered by the builder for standard designs and this was considered unacceptable and was graded U(1.0) accordingly. |
| *Operability* | No special provisions were made by the owners and graded VP(0.4), P(0.6) |

Table 5.21. Evaluation of VLCC_1 in Relation to the Lowest Level Sub-Criteria

Similar evaluations would be carried out and documented for the other three options, The results of the data building exercise carried out in the previous sections have been compiled in the generalised decision matrix appearing in table 5.22 on the following page. For each of the 4 options, the individual degrees of belief are listed in the rows of the matrix. The evaluation results for VLCC_1 from table 5.21 have been transferred into the generalised decision matrix for subsequent input into the IDS software in order to carry out the aggregated assessment process using the ER algorithm. The chosen weightings are listed in column 2 of table 5.22. For the purposes of demonstrating the model, the detailed evaluations of the other options are omitted for clarity. However, the procedures for determining the degrees of belief data shown in table 5.22 were similar. The qualitative data was judged to be reasonably representative based on the scantlings for each option and the general considerations summarised in tables 5.19 and 5.20.

If all criteria are qualitative, the ER algorithm described in section 4.5 can be used directly to aggregate sub-criteria assessments to the upper level parent criteria. However, when the qualitative sub-criteria and parent criteria have different grades, the assessments must be transformed. For example, the sub-criterion *Builder's Reputation* could have been graded as follows:

$$N = 5, H_1 = \{Worst\}, H_2 = \{Poor\}, H_3 = \{Average\}, H_4 = \{Good\}, H_5 = \{Excellent\}$$

In such a case, fuzzy mapping techniques are available to unify linguistic terms between the different criteria, where it is desirable to adopt these into the model (Yang et al, 2007).

### *5.4.6 Aggregating Assessment Results*

In table 5.22, the results of the data building carried out in the previous sections are combined and presented in the form of a generalized decision matrix. The numeric and qualitative data resulting from the individual assessment procedures appearing in the generalised decision matrix in table 5.22 is listed in a form which can be projected to the normalised utility space.

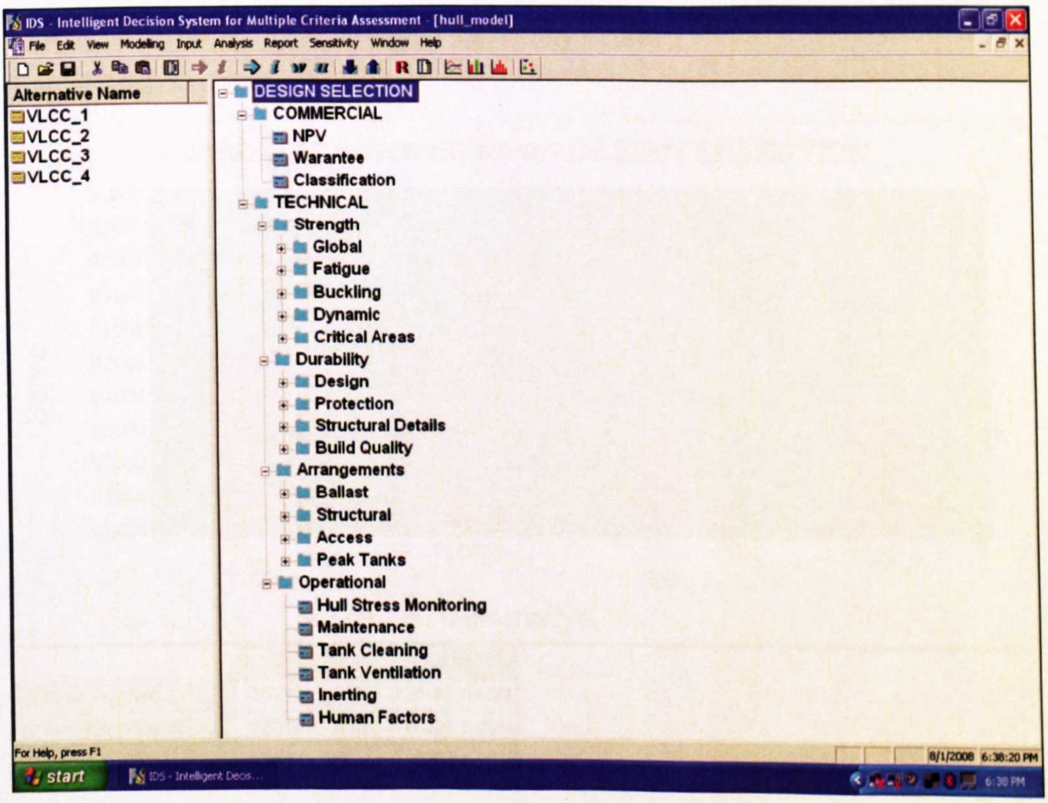
| Sub Attribute | W | VLCC_1 | VLCC_2 | VLCC_3 | VLCC_4 |
|---|---|---|---|---|---|
| NPV | 0.8 | $68.64 million | $69.74 million | $63.04 million | $57.71 million |
| Warrantee | 0.1 | 1 year | 1 year | 1 year | 5 years |
| Classification | 0.1 | U(1.0) | VP(1.0) | G(1.0) | E(1.0) |
| Longitudinal | 0.8 | 96.62% | 88.62% | 92.15% | 70.89% |
| Transverse | 0.2 | VP(0.5),P(0.5) | F(0.5), G(0.5) | F(0.5), G(0.5) | G(0.5), VG(0.5) |
| Hull Girder | 0.5 | 20 years | 20 years | 25 years | 40 years |
| Side Structure | 0.5 | 20 years | 20 years | 25 years | 40 years |
| Main Deck | 0.5 | 224MPa | 225MPa | 213MPa | 174MPa |
| Members 1-3 | 0.5 | VP(0.5), P(0.5) | VP(0.5), P(0.5) | P(0.5), F(0.5) | G(0.5), VG(0.5) |
| Berthing | 0.5 | 19.5mm | 21.0mm | 20.5mm | 25.0mm |
| Sloshing | 0.5 | U(0.3), VP(0.7) | U(0.3), VP(0.7) | F(0.85) | G(0.8), VG(0.2) |
| CA-1 | 0.5 | VP(0.4), P(0.6) | VP(0.85) | U(0.2), VP(0.8) | G(0.6), VG(0.4) |
| CA-2 | 0.25 | VP(0.85) | VP(0.5), P(0.5) | VP(0.5), P(0.5) | G(0.5), VG(0.5) |
| CA-3 | 0.25 | VP(0.8), P(0.2) | VP(0.7), P(0.3) | VP(0.7), P(0.1) | G(0.8), VG(0.2) |
| Builder's Rep. | 0.3 | F(0.8) | P(0.2), F(0.8) | P(0.2), F(0.8) | F(0.5), G(0.5) |
| Owner's Exp. | 0.7 | G(0.8), VG(0.2) | G(0.7), VG(0.1) | G(0.8), VG(0.2) | G(0.8), VG(0.2) |
| C. Margins | 0.3 | 3.4mm | 3.5mm | 3.4mm | 4.0mm |
| Min. Scant. | 0.1 | 11.5mm | 11.5mm | 11.5mm | 15.0mm |
| Coat. Spec's | 0.3 | 5 years | 5 years | 15 years | 20 years |
| Anodes | 0.2 | F(0.6), G(0.4) | F(0.5), G(0.5) | F(0.5), G(0.5) | G(1.0) |
| Materials | 0.1 | 32% HTS | 80% HTS | 30% HTS | 30% HTS |
| Details | 0.5 | U(0.5), VP(0.5) | U(0.1), VP(0.9) | U(0.1), VP(0.9) | G(0.6), VG(0.4) |
| Welding | 0.5 | U(0.5), VP(0.5) | U(0.3), VP(0.6) | U(0.2), VP(0.8) | F(0.8), G(0.2) |
| Yard QA/QC | 0.25 | VP(0.5), P(0.4) | VP(0.2), P(0.8) | VP(0.2), P(0.8) | F(1.0) |
| Owner Effort | 0.75 | G(1.0) | G(1.0) | G(1.0) | VG(0.5), E(0.5) |
| Ballast Distribution | 0.2 | U(0.3), VP(0.7) | U(0.3), VP(0.7) | U(0.3), VP(0.7) | U(0.5), VP(0.5) |
| Filling % | 0.8 | 62.5% full | 62.5% full | 100% full | 100% full |
| Cross Ties | 0.5 | P(0.6) | P(0.5), F(0.5) | P(0.6) | F(0.5), G(0.5) |
| Subjective | 0.5 | U(0.2), VP(0.8) | VP(0.2), P(0.8) | P(0.85) | F(0.6), G(0.4) |
| B/Tank Access | 0.5 | P(0.5), F(0.5) | P(0.2), F(0.6) | P(0.5), F(0.5) | F(0.5), G(0.5) |
| Cargo Tanks Access | 0.5 | VP(0.5), P(0.5) | VP(0.4), P(0.6) | VP(0.4), P(0.6) | F(0.5), G(0.5) |
| Forepeak | 0.7 | VP(1.0) | VP(1.0) | U(0.5), VP(0.5) | F(0.8), G(0.2) |
| Afterpeak | 0.3 | P(0.5), F(0.5) | F(1.0) | F(1.0) | F(0.7), G(0.3) |
| HSMS | 0.5 | U(1.0) | U(1.0) | U(1.0) | E(0.8) |
| Operability | 0.5 | VP(0.4),P(0.6) | VP(0.3), P(0.7) | VP(0.3), P(0.6) | F(0.5), G(0.5) |

Table 5.22. Generalised Decision Matrix

A Windows based software implementation of the ER algorithm known as the Intelligent Decision System (IDS), developed by the University of Manchester UK, and described by Xu & Yang (2005), has been used to process the data. The IDS package is utilised for ease of performing the otherwise complex calculations involving the multiple criteria chosen for the model. All the information contained in the matrix including weights, grades and belief degrees has also been incorporated directly into the IDS model shown in figure 5.7. The utility function adopted throughout the model is defined as a linear function ranging from 0 to 1.0 as follows;

$$U(H_1) = 0, u(H_2) = 0.1666, u(H_3) = 0.3333, u(H_4) = 0.5000, u(H_5) = 0.6666,$$
$$u(H_6) = 0.8333, u(H_7) = 1.0000$$

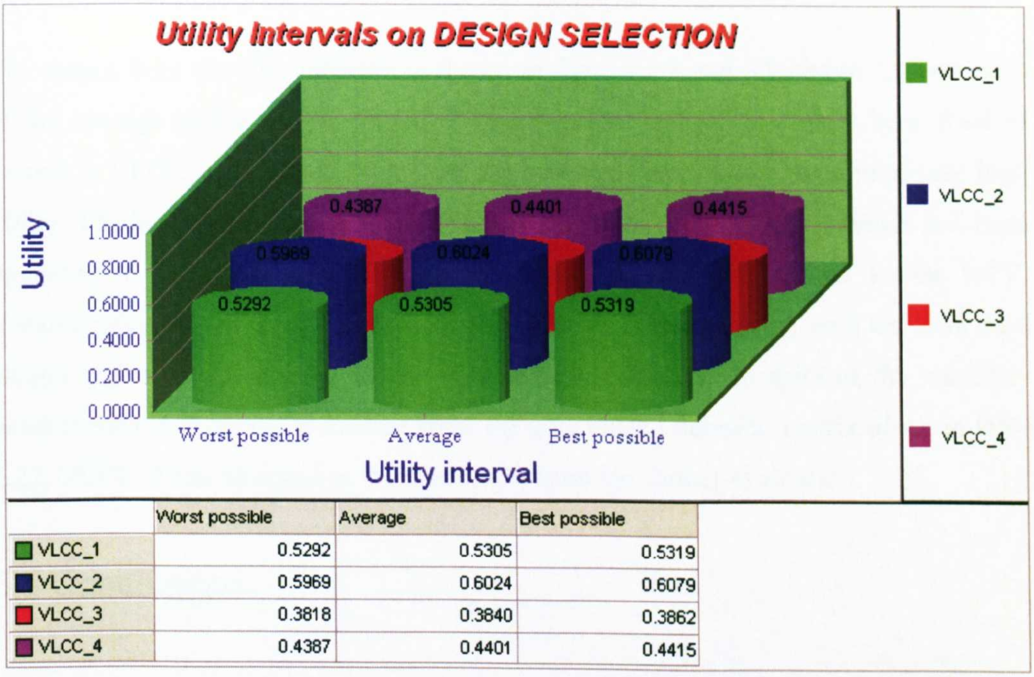
Other utility functions (distribution patterns) could be utilised in accordance with the preference of individual decision makers.



- VLCC_1
- VLCC_2
- VLCC_3
- VLCC_4

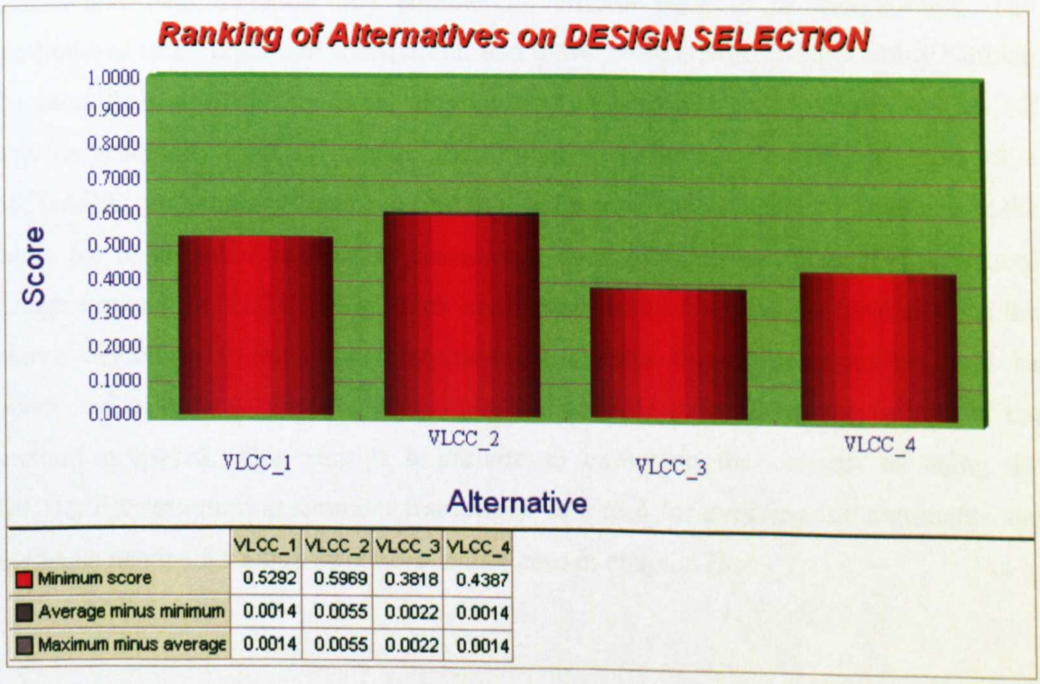
- DESIGN SELECTION
  - COMMERCIAL
    - NPV
    - Warantee
    - Classification
  - TECHNICAL
    - Strength
      - Global
      - Fatigue
      - Buckling
      - Dynamic
      - Critical Areas
    - Durability
      - Design
      - Protection
      - Structural Details
      - Build Quality
    - Arrangements
      - Ballast
      - Structural
      - Access
      - Peak Tanks
    - Operational
      - Hull Stress Monitoring
      - Maintenance
      - Tank Cleaning
      - Tank Ventilation
      - Inerting
      - Human Factors

Figure 5.7 IDS Software Model



| | Worst possible | Average | Best possible |
|---|---|---|---|
| 🟩 VLCC_1 | 0.5292 | 0.5305 | 0.5319 |
| 🟦 VLCC_2 | 0.5969 | 0.6024 | 0.6079 |
| 🟥 VLCC_3 | 0.3818 | 0.3840 | 0.3862 |
| 🟪 VLCC_4 | 0.4387 | 0.4401 | 0.4415 |

Figure 5.8. Utility Scores



| | VLCC_1 | VLCC_2 | VLCC_3 | VLCC_4 |
|---|---|---|---|---|
| 🟥 Minimum score | 0.5292 | 0.5969 | 0.3818 | 0.4387 |
| ■ Average minus minimum | 0.0014 | 0.0055 | 0.0022 | 0.0014 |
| ■ Maximum minus average | 0.0014 | 0.0055 | 0.0022 | 0.0014 |

Figure 5.9. Ranking of Alternatives

### *5.4.7 Ranking and Decision Making*

The output from the IDS software is shown in figures 5.8 and 5.9 above. On the basis of the average utility scores, VLCC_2 (the cheapest option) is ranked best. Ranked second is VLCC_1, however, VLCC_4, the best technical option has a relatively high utility. The least favourable of the four options appears to be VLCC_3 which has been upgraded to meet the new CSR requirements, but has the second lowest NPV. Recalling that VLCC_2 was a pre-CSR fully HT355 Korean design with the least steel weight and consequently the lowest cost and highest NPV. In spite of the relatively harsh technical evaluations evident from the generalised decision matrix given in table 5.22, VLCC_2 has emerged as the favoured option for further evaluation.

## 5.5 Conclusions

An objective in this study was to develop a novel and unique techno-economic framework for comparing alterative structural designs for large bulk ships. In this framework, both technical and commercial criteria were to be incorporated. The method had to be rapid and transparent, and allow comparisons using a utility ranking for identification of the preferred alternative. Sub-objective no.4 given in section 1.2 was to articulate a set of product performance characteristics (criteria), part of a MCDA/ER methodology incorporating the Dempster-Shafer Theory of Evidence as the basis for a structural evaluation framework used to compare alternative structural design options for VLCC's. The work in chapters 4 and 5 appears to have allowed the above objectives to have been realised. In chapter 6 sensitivity studies will be conducted in order to further demonstrate and to build evidence of the validity of the method proposed. This step is a prelude to exploring the concept of using the MCDA/ER structural assessment framework as a tool for evolving the arguments and evidence needed for a hull structures safety case in chapter 7.

# Chapter 6 - Sensitivity Study, Discussion & Validation

***SUMMARY***

*The MCDA/ER structural assessment framework developed in the preceding chapters was demonstrated in chapter 5 by an example involving the selection of a preferred VLCC structural design. In this chapter the model is tested and validated before describing in chapter 7 how the risk-based procedures embodied in the structural assessment framework can be used to build the evidence necessary for a hull structures safety case as a means of further improving technical management and safety of large VLCCs and VLBCs.*

## 6.1 Introduction

In chapter 5, the MCDA/ER structural assessment framework developed over the previous chapters 3 and 4 was demonstrated by an example, comprising selection between four similar competing VLCC structural designs. The structural assessment framework was presented as a process with the purpose of eliciting preferences for further evaluation. The IDS software allowed options to be simply ranked on the basis of their utility scores. The method was seen to be rational, systematic, flexible and transparent and to provide a simple means of dealing with real world problems involving quantitative and qualitative and sometimes incomplete data.

To build further confidence in the method, representative sensitivity studies are performed in this chapter, such that the outcomes can be evaluated in terms of their usefulness. In this way, the results are intended to further demonstrate the usefulness of the methodology. In view of the imprecise representations and heuristics inherent in design method synthesis of this nature, validation in terms of socially justifiable beliefs is considered appropriate and the validation square concept advanced by Pedersen et al (2000) is adopted to verify the validity of the various phases of the work packages performed.

## 6.2 Summary of Main Results from the ER Model

### *6.2.1 Distributed Assessment*

The combined distributed basic assessment results obtained from the IDS software output for the four VLCC options have been presented in figure 6.1. This type of presentation may be useful as the observer is able to gain an overview of the assessment process by reference to the spread of the individual belief degrees. In the case of the framework developed here, the patterns are quite complex due to the combination of numeric and linguistic data being simultaneously synthesised in the model and the definition of the worst and best values of the quantitative criteria.

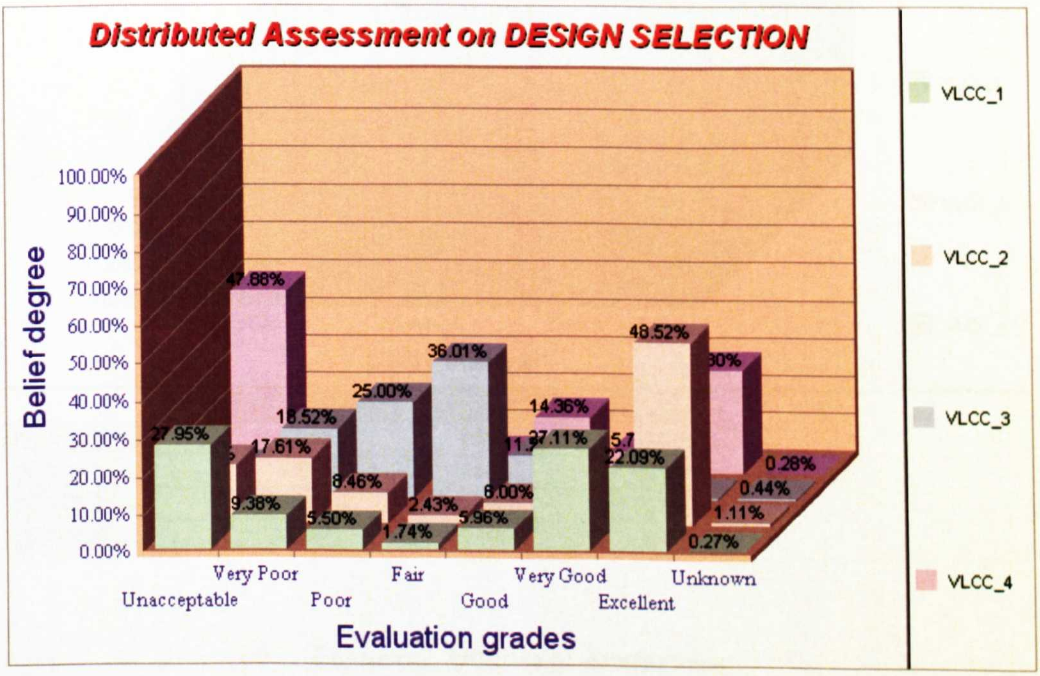
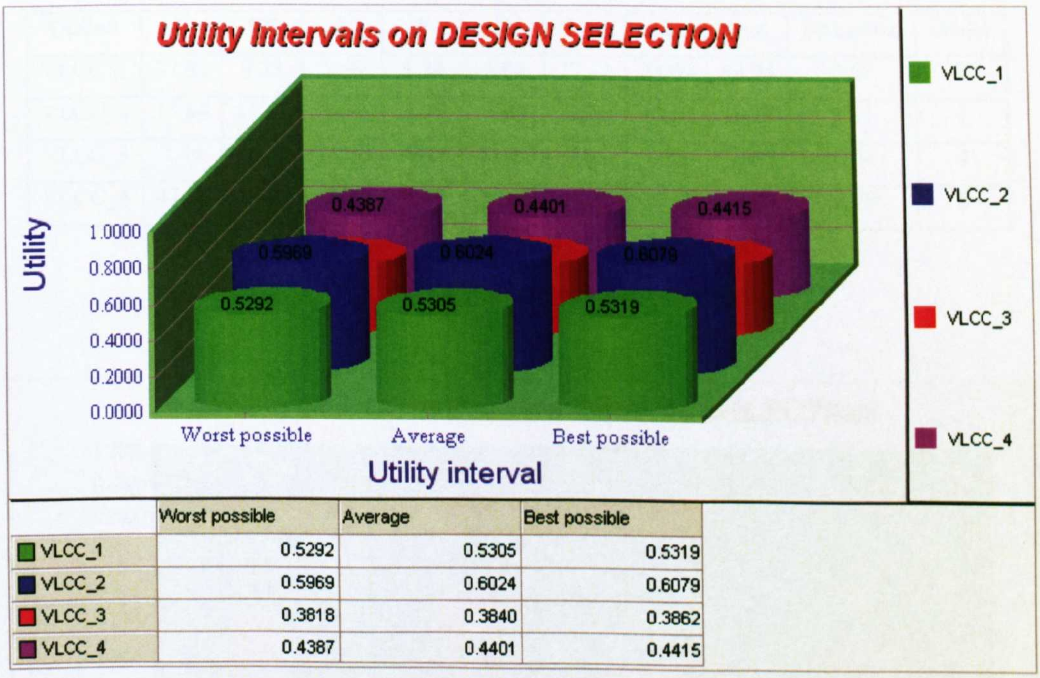


Figure 6.1. Belief Degrees from Main Results

In figure 6.1, by making reference to table 5.22 (p. 211), the differences can be seen and used to rank the alternatives but it is not a straightforward task. To precisely rank the four options, their utilities need to be estimated. Firstly, the utilities of the seven assessment grades have also to be calculated.

### *6.2.2 Utility Intervals*

The difficulty of assessing the candidate VLCC structural designs on the basis of belief degrees highlighted in the previous section may be overcome by ranking according to utility intervals. The IDS model uses the concept of utility intervals to characterise the unassigned degree of belief. The ER algorithm produces a utility interval bounded by two limits (*unacceptable* or *excellent*) in this case. As explained in section 5.4.6, the utility function adopted throughout the model is a linear function ranging from 0 to 1.0, and this has been used for both qualitative and quantitative criteria.



| | Worst possible | Average | Best possible |
|---|---|---|---|
| 🟩 VLCC_1 | 0.5292 | 0.5305 | 0.5319 |
| 🟦 VLCC_2 | 0.5969 | 0.6024 | 0.6079 |
| 🟥 VLCC_3 | 0.3818 | 0.3840 | 0.3862 |
| 🟪 VLCC_4 | 0.4387 | 0.4401 | 0.4415 |

Figure 6.2. Utilities of Alternatives

In figure 6.2, the IDS output shows the four options ranked on the basis of their respective worst, average and best possible utility values. The designs can be ranked on the utility intervals; however, for one design to be absolutely preferable to another, the minimum utility must be greater than the competing utilities. In this case the ranking is the same whether the worst possible or average utilities are used.

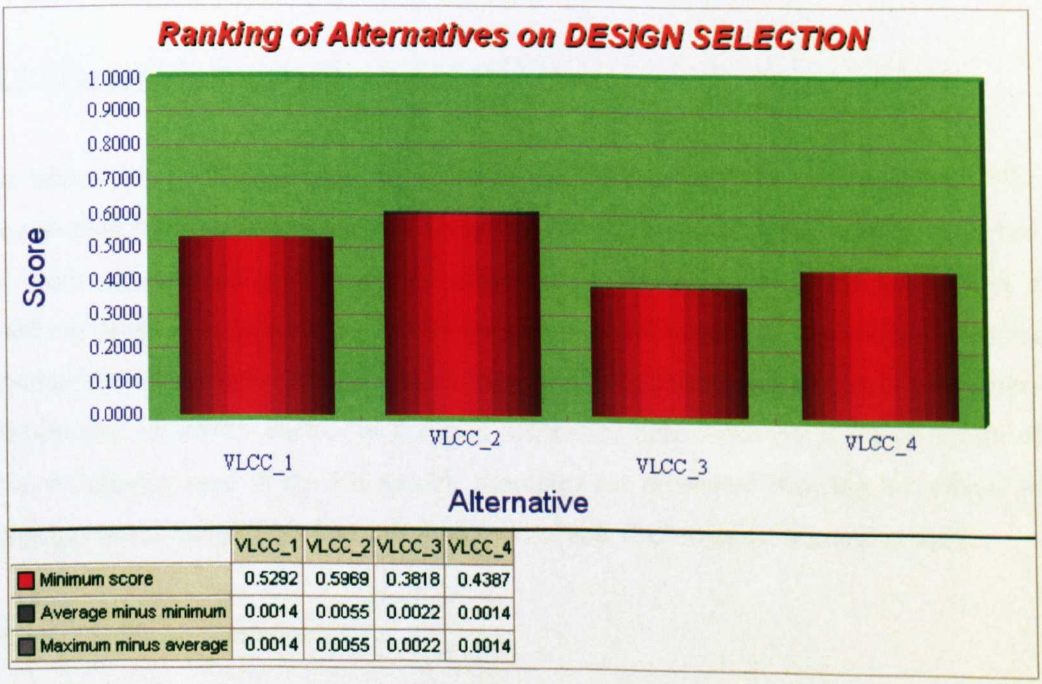
### *6.2.3 Ranking*

Theoretically the ranking of the four options can be performed on the basis of the performance distribution of the top criterion *Design Selection,* denoted by S (*design selection*) = $\{(H_n, \beta_n), n = 1,...,N\}$ .The aggregated assessments for the upper level attribute *design selection* generated for VLCC_1 are as follows;

S(*design selection*) ={(*unacceptable*, 27.95%), (*very poor*, 9.38%), (*poor*, 5.50%), (*fair*, 1.74%), (*good*, 5.96%), (*very good*, 27.11), (*excellent*, 22.09%)}.

| **Option** | **U** | **VP** | **P** | **F** | **G** | **VG** | **E** | **Ave.** | **Unknown** | **Order** |
|---|---|---|---|---|---|---|---|---|---|---|
| VLCC_1 | 27.95 | 9.38 | 5.50 | 1.74 | 5.96 | 27.11 | 22.09 | 53.05 | 0.27 | 2 |
| VLCC_2 | 15.64 | 17.61 | 8.46 | 2.43 | 8.00 | 0.24 | 48.52 | 60.24 | 1.11 | 1 |
| VLCC_3 | 7.44 | 18.52 | 25.00 | 36.01 | 11.26 | 0.51 | 0.82 | 38.40 | 0.44 | 4 |
| VLCC_4 | 47.88 | 0.01 | 0.00 | 4.47 | 14.36 | 5.72 | 27.30 | 44.01 | 0.28 | 3 |

Table 6.1. Overall Performance of Alternatives



| | VLCC_1 | VLCC_2 | VLCC_3 | VLCC_4 |
|---|---|---|---|---|
| 🟥 Minimum score | 0.5292 | 0.5969 | 0.3818 | 0.4387 |
| ⬛ Average minus minimum | 0.0014 | 0.0055 | 0.0022 | 0.0014 |
| ⬛ Maximum minus average | 0.0014 | 0.0055 | 0.0022 | 0.0014 |

Figure 6.3. Minimum Utility Rankings of Alternatives

A more convenient way of comparing the results is by ranking the options according to their utilities from the IDS results shown in figure 6.3. In this case, the average utilities confirm that VLCC_2 is the preferred option, and VLCC_1 is second as indicated in the last column of table 6.1. Reference to the generalised decision matrix, table 5.22 (p.211), section 5.4.6, reveals that the higher NPV values for VLCC_1 and VLCC_2 strongly influences the outcome of the assessment process. However, the negative influence of the ultimate strength ratio (*Longitudinal*) can also be seen for these two options. Direct comparison of the data in table 5.22 indicates that the evaluations appear to be more favourable in the case of the higher quality option 4, and the qualitative assessments for the other 3 options are relatively pessimistic and similar. However, it is very difficult to predict the outcome of the assessment process based solely on visual examination of the data in the decision matrix, and this indicates the necessity of the model. However, it needs to be stressed that the model is a tool intended to be used primarily to elicit preferences for further evaluation.

## 6.3 Sensitivity Study

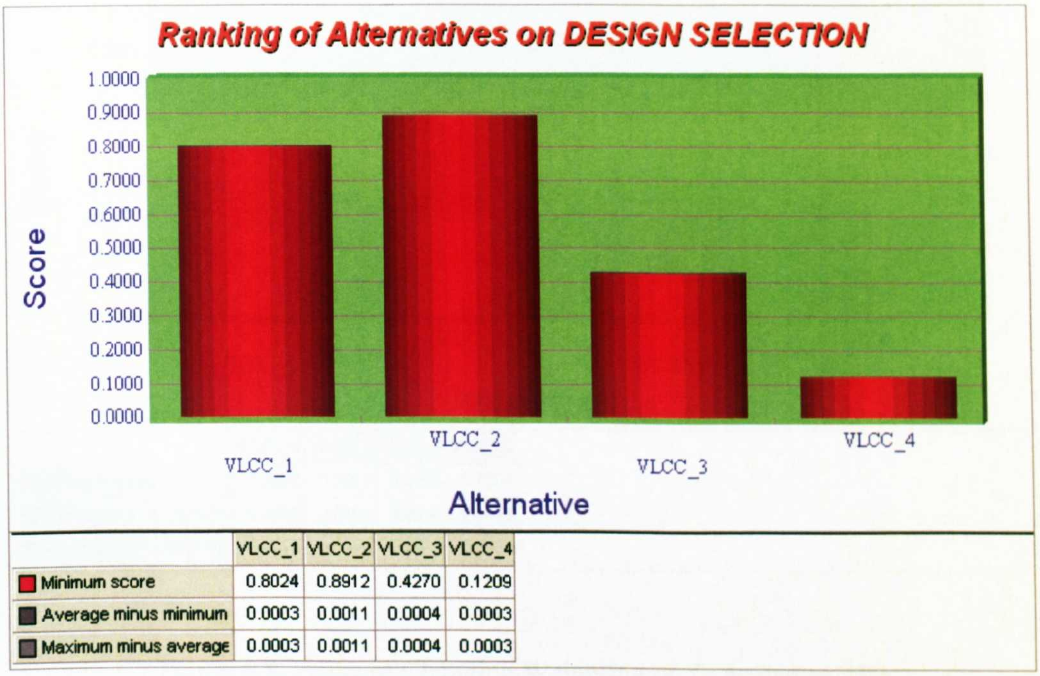
### *6.3.1 Variation in Weightings*

In table 5.14 (p.199) the weightings chosen for the main criteria were displayed. The assessment framework was initially formulated on the basis of equal weights assigned to both *Commercial* and *Technical* criteria as a starting point. This established a ranking believed to properly reflect the importance of commercial aspects in a practical evaluation framework. The ER model easily permits changes in the input parameters facilitating sensitivity studies of the kind conducted here. Because of the criticality of the weightings used in the ER model, examples are presented showing the effects of changes in the weightings for both *Commercial* and *Technical* assessment criteria.

#### *6.3.1.1 Effect on Commercial*

An increase in the weighting of the attribute *Commercial* from 0.5 to 0.75 and a corresponding reduction in the weighting of the attribute *Technical* from 0.5 to 0.25

had the expected result of distinctly increasing the preference of the lowest cost options VLCC_1 and VLCC-2 due to the relatively more favourable NPV, reflected in the increased average utility scores of 0.8026 and 0.8932 respectively. The minimum utility scores indicated in figure 6.4 show the same outcome. The utilities of the other 2 options have decreased, and the best technical option (VLCC_4) has a very low utility.

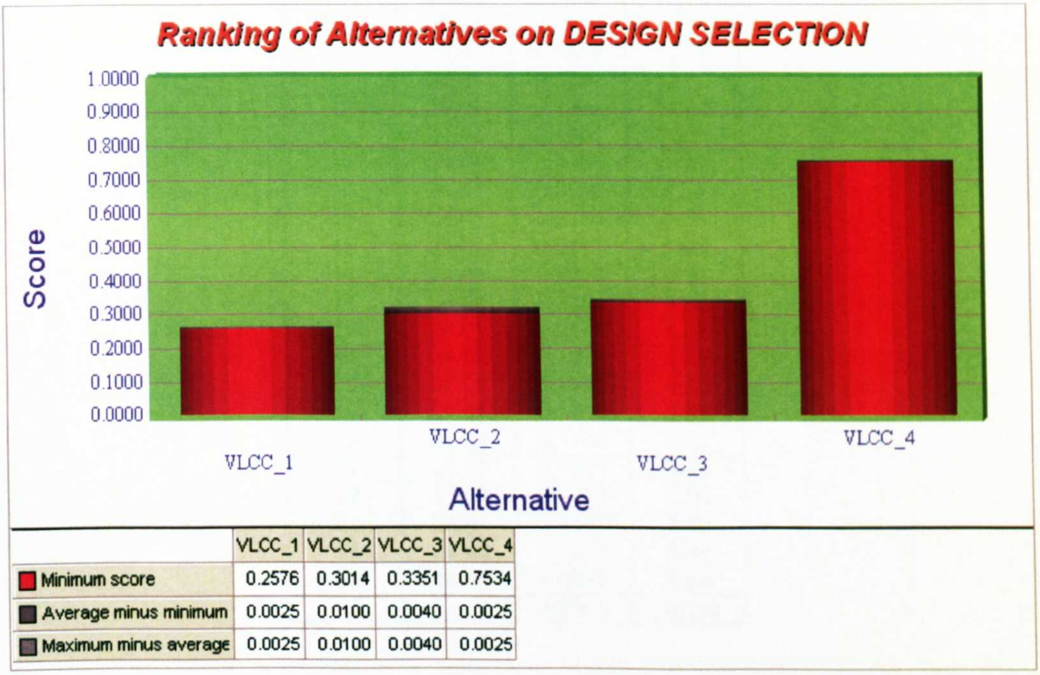


| | VLCC_1 | VLCC_2 | VLCC_3 | VLCC_4 |
|---|---|---|---|---|
| 🟥 Minimum score | 0.8024 | 0.8912 | 0.4270 | 0.1209 |
| ⬛ Average minus minimum | 0.0003 | 0.0011 | 0.0004 | 0.0003 |
| ▨ Maximum minus average | 0.0003 | 0.0011 | 0.0004 | 0.0003 |

Figure 6.4. Effect of Changing Weighting of *Commercial* to 75%

### *6.3.1.2 Effect on Technical*

By reducing the weighting of the *Commercial* criterion to from 0.5 to 0.25 and correspondingly increasing *Technical* from 0.5 to 0.75, the ranking shown in figure 6.5 was obtained. The clear superiority of the best technical option (VLCC_4) is seen. The second best technical option is VLCC_3, while VLCC_1 and VLCC_2 (least cost options) have similar but lower scores. The result is confirmed intuitively by reference to the generalised decision matrix shown in table 5.22, clearly indicting the increasingly positive trend in technical evaluations observed in the graph. Although the above comparison has merit for the purpose of evaluating the impact of these changes to the overall ranking, it is unlikely that real world commercial projects would ever be ranked on such a simplistic basis. However the model lends itself to more complex development and eventual real-world usefulness.



| | VLCC_1 | VLCC_2 | VLCC_3 | VLCC_4 |
|---|---|---|---|---|
| 🟥 Minimum score | 0.2576 | 0.3014 | 0.3351 | 0.7534 |
| ■ Average minus minimum | 0.0025 | 0.0100 | 0.0040 | 0.0025 |
| ■ Maximum minus average | 0.0025 | 0.0100 | 0.0040 | 0.0025 |

Figure 6.5. Effect of Changing Weighting of *Technical* to 75%

### *6.3.2 Variation in Commercial and Technical Criteria*

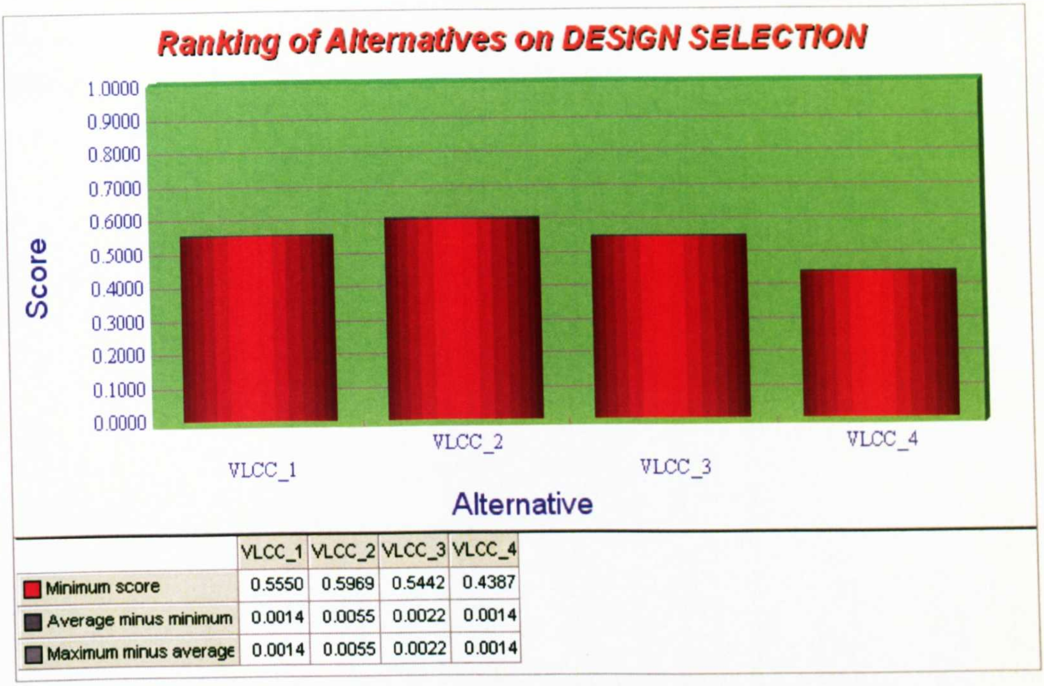
#### *6.3.2.1 High Quality Option*

In sections 3.2.5 and 4.2.3, product quality issues in relation to standard vessel procurement practice were explored. Hayer (1994) questioned whether a USD 15 million premium relating to additional options in a VLCC contract, some of them related to the hull structure, could be justified in terms of higher product quality. It was assumed that the additional cost suggested by Hayer correlates to USD 30 million in today's terms. Table 6.2 shows the effect of a 20% increase in price on the ranking of the four options. The revised NPV of USD 40.18 million calculated for VLCC_4 was used in the IDS model.

| YEAR | CF | PVIF | PV |
|---|---|---|---|
| 0 | **-180** | 1.0000 | -180.00 |
| 1 | 24.01 | 0.9091 | 21.83 |
| 2 | 24.01 | 0.8264 | 19.84 |
| 3 | 24.01 | 0.7513 | 18.04 |
| 4 | 24.01 | 0.6830 | 16.40 |
| 5 | 24.01 | 0.6209 | 14.91 |
| 6 | 24.01 | 0.5645 | 13.55 |
| 7 | 24.01 | 0.5132 | 12.32 |
| 8 | 24.01 | 0.4665 | 11.20 |
| 9 | 24.01 | 0.4241 | 10.18 |
| 10 | 24.01 | 0.3855 | 9.26 |
| 11 | 24.01 | 0.3505 | 8.42 |
| 12 | 24.01 | 0.3186 | 7.65 |
| 13 | 24.01 | 0.2897 | 6.95 |
| 14 | 24.01 | 0.2633 | 6.32 |
| 15 | 24.01 | 0.2394 | 5.75 |
| 16 | 24.01 | 0.2176 | 5.23 |
| 17 | 24.01 | 0.1978 | 4.75 |
| 18 | 24.01 | 0.1799 | 4.32 |
| 19 | 24.01 | 0.1635 | 3.93 |
| 20 | 24.01 | 0.1486 | 3.57 |
| 21 | 24.01 | 0.1351 | 3.24 |
| 22 | 24.01 | 0.1228 | 2.95 |
| 23 | 24.01 | 0.1117 | 2.68 |
| 24 | 24.01 | 0.1015 | 2.44 |
| 25 | **48.23** | 0.0923 | 4.45 |
|  |  | **NPV =** | **40.18** |

Table 6.2. NPV Calculation for High Quality Option VLCC_4

Here a capital cost of USD180m for the high quality option has been used. The technically superior solution is undoubtedly VLCC_4 as the assessment criteria in the generalised decision matrix shown in table 5.22 clearly indicate, the negative effect on the shareholder's wealth (i.e. the project NPV), and the relatively low average utility score of 0.4401 compared to the other 3 options, (0.5564, 0.6024 and 0.5464 for VLCC_1, VLCC_2 and VLCC_3 respectively) indicate that VLCC_4 is clearly not a viable option due to the relatively high capital cost. Such a finding would appear to support the commercial ship builder's prime objective to optimise the design and minimise the cost which is in accordance with the definition of product quality discussed in section 3.2.5.



| | VLCC_1 | VLCC_2 | VLCC_3 | VLCC_4 |
|---|---|---|---|---|
| 🟥 Minimum score | 0.5550 | 0.5969 | 0.5442 | 0.4387 |
| ■ Average minus minimum | 0.0014 | 0.0055 | 0.0022 | 0.0014 |
| ■ Maximum minus average | 0.0014 | 0.0055 | 0.0022 | 0.0014 |

Figure 6.6. High Quality Option

Further, the lowest cost option (VLCC_2) emerges as the likely candidate for further evaluation, while VLCC_1 and VLCC_3 are similar and merit consideration due to relatively high utility. The minimum utility values from the IDS output are shown in figure 6.6 above.

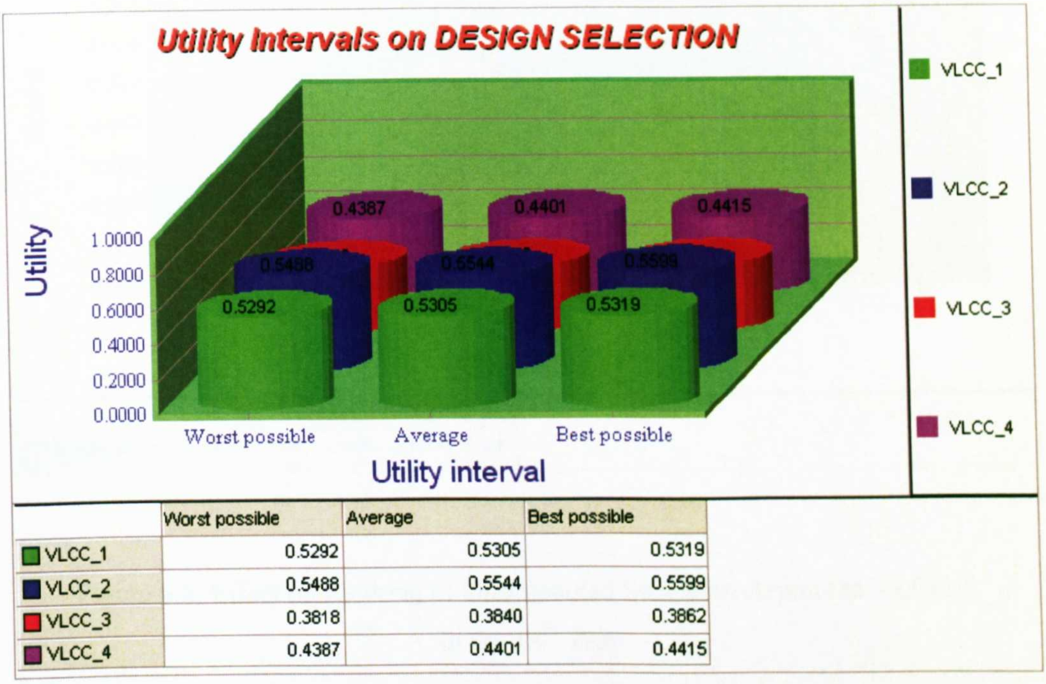
### *6.3.2.2 Unscheduled Repairs*

The structural assessment framework demonstrated, may also be used to predict the impact of future maintenance costs during the life cycle of the product. Such evaluations are considered to be potentially very useful to ship owners. The use of the NPV as the principal capital evaluation criterion permits the costs to be anticipated to assess the overall impact on the project viability in a convenient way. To investigate whether the outcome described in the previous section, could be altered if any of the other options were faced with unscheduled maintenance costs, the following hypothetical scenario will be used as an example of the effect of changes to the NPV for a specific option. It was assumed that VLCC_2 would need 1000 tonnes of steel replaced at the 3rd Special Hull Survey (year 15), at an estimated steel cost of USD 2 million.

| YEAR | CF | PVIF | PV |
|---|---|---|---|
| 0 | **-150** | 1.0000 | -150.00 |
| 1 | 24.01 | 0.9091 | 21.83 |
| 2 | 24.01 | 0.8264 | 19.84 |
| 3 | 24.01 | 0.7513 | 18.04 |
| 4 | 24.01 | 0.6830 | 16.40 |
| 5 | 24.01 | 0.6209 | 14.91 |
| 6 | 24.01 | 0.5645 | 13.55 |
| 7 | 24.01 | 0.5132 | 12.32 |
| 8 | 24.01 | 0.4665 | 11.20 |
| 9 | 24.01 | 0.4241 | 10.18 |
| 10 | 24.01 | 0.3855 | 9.26 |
| 11 | 24.01 | 0.3505 | 8.42 |
| 12 | 24.01 | 0.3186 | 7.65 |
| 13 | 24.01 | 0.2897 | 6.95 |
| 14 | 24.01 | 0.2633 | 6.32 |
| 15 | **19.01** | 0.2394 | 4.55 |
| 16 | 24.01 | 0.2176 | 5.23 |
| 17 | 24.01 | 0.1978 | 4.75 |
| 18 | 24.01 | 0.1799 | 4.32 |
| 19 | 24.01 | 0.1635 | 3.93 |
| 20 | 24.01 | 0.1486 | 3.57 |
| 21 | 24.01 | 0.1351 | 3.24 |
| 22 | 24.01 | 0.1228 | 2.95 |
| 23 | 24.01 | 0.1117 | 2.68 |
| 24 | 24.01 | 0.1015 | 2.44 |
| 25 | **43.51** | 0.0923 | 4.02 |
|  |  | **NPV =** | **68.54** |

Table 6.3. VLCC_2 - Unscheduled Repairs in the 15th Year

In this analysis the original *Commercial* and *Technical* weightings were maintained (0.5, 0.5). Purely as an illustration of the method, and in the absence of actual data, some broad but representative assumptions were made relative to the costs of repairs. The associated delays and off hire, dry docking etc costs were estimated to be USD 3 million. Here it was assumed that approximately USD 1 million was required to cover the break even costs for the vessel based on comparative data given previously in section 5.4.1.1 (i.e. in this case, USD 33,300/day for a 30 day dry docking period). USD 2 million was assumed to be the approximate lost freight revenue in this instance, taking into account the variability in freight rates, and including dry dock fees and survey fees etc. Given that the steel cost was estimated at USD 2million, the total cost of the repairs was assumed to be USD 5 million, which is reflected as a drop in net cash flow in year 15 shown in table 6.3. The NPV for VLCC_2 was seen to decrease from USD 69.74 to USD 68.54 million (i.e. a drop of around 1.72%). The scrap value was maintained due to the assumption that corroded steel had to be renewed.

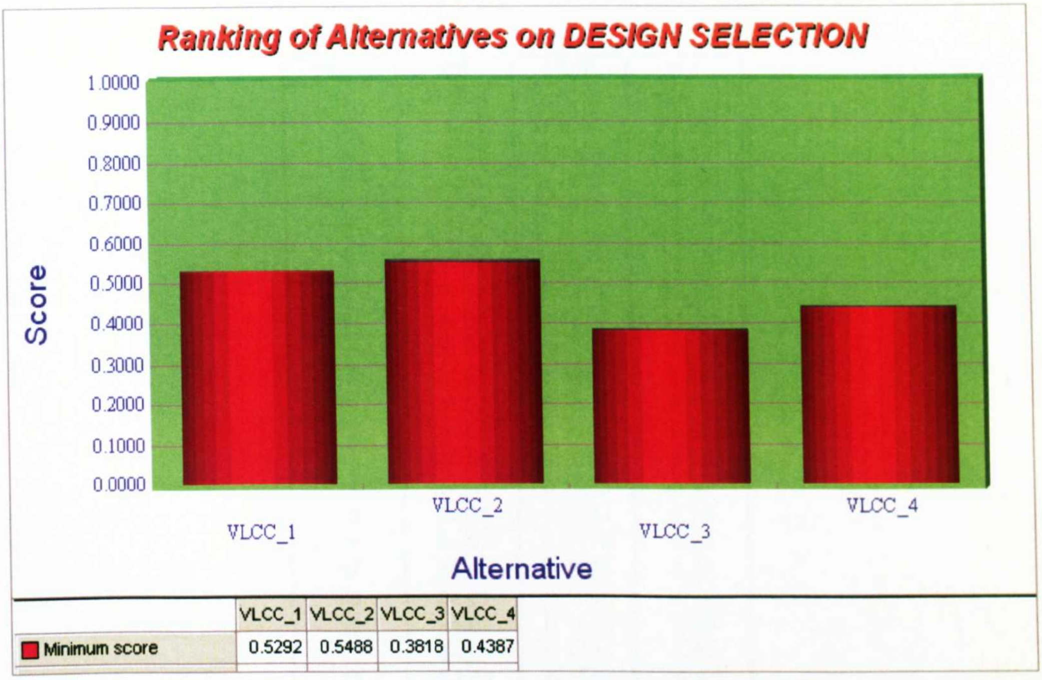


| | Worst possible | Average | Best possible |
|---|---|---|---|
| 🟩 VLCC_1 | 0.5292 | 0.5305 | 0.5319 |
| 🟦 VLCC_2 | 0.5488 | 0.5544 | 0.5599 |
| 🟥 VLCC_3 | 0.3818 | 0.3840 | 0.3862 |
| 🟪 VLCC_4 | 0.4387 | 0.4401 | 0.4415 |

Figure 6.7. Effect on Utility for Unscheduled Structural Repairs to VLCC_2 in the 15th Year

Compared to the base case shown in figure 5.9 (p.213), the average utility value for VLCC_2 decreased from 0.6024 to 0.5544 (7.9%), however the overall ranking shown in the graph figure 6.7, remained unaffected, suggesting that the high quality option continued to be uncompetitive, in spite of unscheduled and extensive steel repairs at the 3rd Special Hull Survey required by one of the lower capital cost options.

Figure 6.8 shows the ranking based on the minimum utility scores which is the same result as above. These results demonstrate the usefulness of the model for investigating hypothetical scenarios in the vessel lifecycle even at the design stage.



| | VLCC_1 | VLCC_2 | VLCC_3 | VLCC_4 |
|---|---|---|---|---|
| 🟥 Minimum score | 0.5292 | 0.5488 | 0.3818 | 0.4387 |

Figure 6.8. Effect on Ranking of Unscheduled Structural Repairs to VLCC_2 in the 15th Year

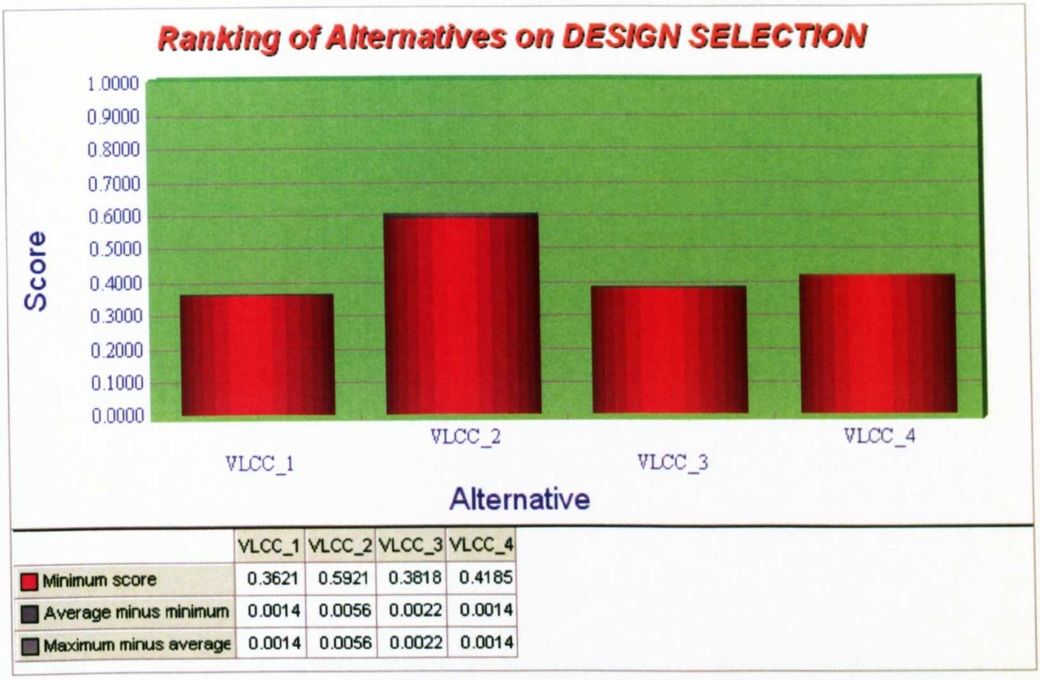
### *6.3.2.3 Corrosion Margins*

In this section, the effect of an increase in the corrosion margins for one of the options will be investigated. In tables 5.2 and 5.3 on pages 186 and 187, the structural data for the four VLCC designs was listed. For VLCC_1, the total steel mass in the 250m length mid ships cargo zone was estimated to be 26,303 tonnes, corresponding to a distributed mass of approximately 105.2 tonnes/m (refer to table 5.6 on page 189). In table 5.12 (p.196), the basis for estimation of the corrosion margins used in the ER model was presented. The average nominal corrosion margin for VLCC_1 was 3.4mm. As a broad assumption, the underlying basis for the corrosion margin assumed in the model was 20% of the longitudinal steel mass distribution, and this was the average allowable corrosion wastage model used by the IACS Societies as discussed in section 2.3.3. Assuming therefore, that the corrosion margin was increased from 3.4mm to 5.0mm, the corresponding steel weight increase was estimated as approximately 0.1 x 26,303 = 2,630 tonnes.

| YEAR | CF | PVIF | PV |
|---|---|---|---|
| 0 | **-156.4** | 1.0000 | -156.40 |
| 1 | 24.01 | 0.9091 | 21.83 |
| 2 | 24.01 | 0.8264 | 19.84 |
| 3 | 24.01 | 0.7513 | 18.04 |
| 4 | 24.01 | 0.6830 | 16.40 |
| 5 | 24.01 | 0.6209 | 14.91 |
| 6 | 24.01 | 0.5645 | 13.55 |
| 7 | 24.01 | 0.5132 | 12.32 |
| 8 | 24.01 | 0.4665 | 11.20 |
| 9 | 24.01 | 0.4241 | 10.18 |
| 10 | 24.01 | 0.3855 | 9.26 |
| 11 | 24.01 | 0.3505 | 8.42 |
| 12 | 24.01 | 0.3186 | 7.65 |
| 13 | 24.01 | 0.2897 | 6.95 |
| 14 | 24.01 | 0.2633 | 6.32 |
| 15 | 24.01 | 0.2394 | 5.75 |
| 16 | 24.01 | 0.2176 | 5.23 |
| 17 | 24.01 | 0.1978 | 4.75 |
| 18 | 24.01 | 0.1799 | 4.32 |
| 19 | 24.01 | 0.1635 | 3.93 |
| 20 | 24.01 | 0.1486 | 3.57 |
| 21 | 24.01 | 0.1351 | 3.24 |
| 22 | 24.01 | 0.1228 | 2.95 |
| 23 | 24.01 | 0.1117 | 2.68 |
| 24 | 24.01 | 0.1015 | 2.44 |
| 25 | **45.93** | 0.0923 | 4.24 |
|  |  | **NPV =** | **63.56** |

Table 6.4. NPV Calculation for Increased Corrosion Margins in VLCC_1

The capital cost increase was estimated to be 2,630 x 2,000 = USD 5.26 million. The new scrap value was assumed to be 19.93 x 1.1 = USD 21.92 million and this was used in the *Excel* spreadsheet calculation for the NPV shown in table 6.4. The NPV correspondingly decreased to USD 63.56 million compared to the original NPV of USD 68.64 million, a drop of 7.4%. In figure 6.9, the ranking indicated that VLCC_2 had emerged as the most likely candidate with a significantly higher utility. The average utility value for VLCC_1 had dropped from 0.5305 (see the base case in figure 5.9 on page 213) to 0.3635 (31.5%), making it the least favourable option, indicating that holistically, the increased corrosion margins had significantly reduced the competitiveness of this option in relation to the other alternatives. However, compared to the base case, the overall ranking order did not change.

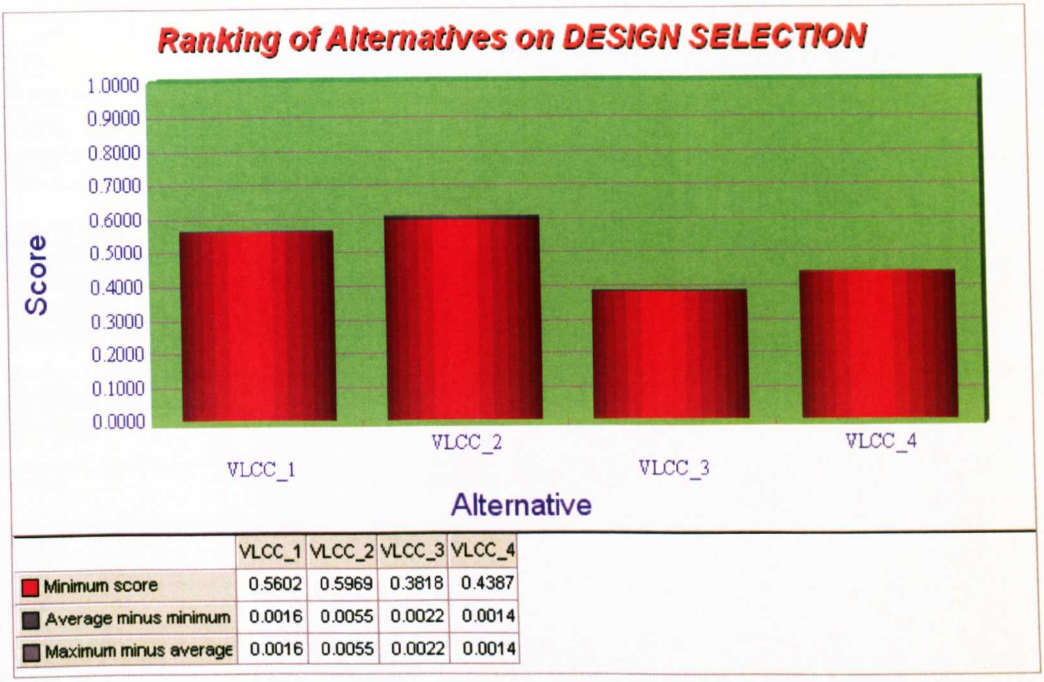


| | VLCC_1 | VLCC_2 | VLCC_3 | VLCC_4 |
|---|---|---|---|---|
| 🟥 Minimum score | 0.3621 | 0.5921 | 0.3818 | 0.4185 |
| ■ Average minus minimum | 0.0014 | 0.0056 | 0.0022 | 0.0014 |
| ■ Maximum minus average | 0.0014 | 0.0056 | 0.0022 | 0.0014 |

Figure 6.9. Effect on Ranking for Increasing Corrosion Margins for VLCC_1

#### *6.3.2.4 Technical Assessments*

To explore the impact of positive changes to technical assessments, it was assumed that the critical areas CA_1, CA_2 and CA_3 in VLCC-1 had been appraised by experts. The original assessments for the three criteria given in table 5.22 (p.211) for VLCC_1 were {0.4 VP, 0.6 P}, {0.85 VP} and {0.8 VP, 0.2 P}. These were changed to {0.5 G, 0.5 VG}, {0.7 F, 0.2 G} and {0.2 G, 0.3 VG} to reflect the higher ratings and the results are shown in figure 6.10. Compared to the base case (figure 5.9 on page 213), the average utility for VLCC_1 increased from 0.5305 to 0.5619 as expected (5.9%). If the weighting of the *Technical* criterion had increased by 5% the ranking order on the basis of maximum average utility values would have changed to VLCC_2 (0.5309), VLCC_4 (0.5182), VLCC_1 (0.5014) and VLCC_3 (0.3732). In this way, the impact of changes to the technical assessment criteria can be easily gauged.



| | VLCC_1 | VLCC_2 | VLCC_3 | VLCC_4 |
|---|---|---|---|---|
| 🟥 Minimum score | 0.5602 | 0.5969 | 0.3818 | 0.4387 |
| ■ Average minus minimum | 0.0016 | 0.0055 | 0.0022 | 0.0014 |
| ▨ Maximum minus average | 0.0016 | 0.0055 | 0.0022 | 0.0014 |

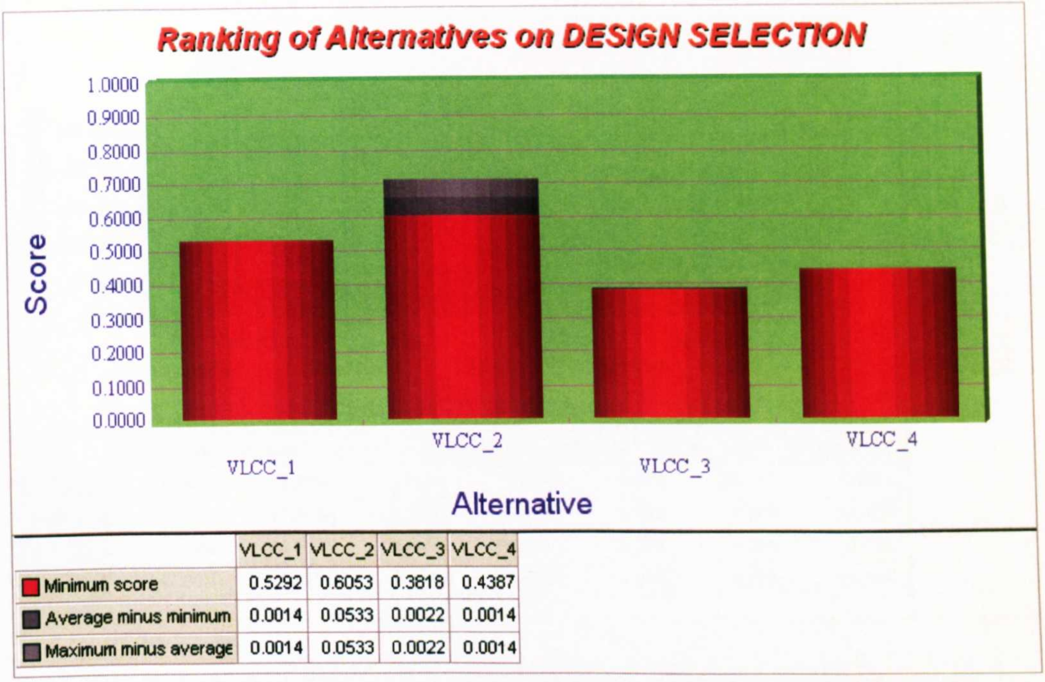
Figure 6.10. Variation in Technical Assessments for VLCC_1

### *6.3.2.5 Incomplete Assessments*

In some cases, data may be missing or incomplete. This is especially true for the nature of the assessment attempted in this research. The ER algorithm was developed to handle numeric, linguistic and sometimes incomplete information. The challenge is to find a rational, reliable, transparent and repeatable way to deal with qualitative attributes and uncertain or missing information that causes complexity in multiple attribute assessment problems (Yang et al, 2002). To investigate the effects of incompleteness on the structural assessment framework, it was assumed that information relative to VLCC_2 was missing or not available as indicated in column 4 in table 6.5 on the following page.

| **Sub Attribute** | **W** | **VLCC_1** | **VLCC_2** | **VLCC_3** | **VLCC_4** |
|---|---|---|---|---|---|
| NPV | 0.8 | $68.64 million | $69.74 million | $63.04 million | $57.71 million |
| Warrantee | 0.1 | 1 year | 1 year | 1 year | 5 years |
| Classification | 0.1 | U(1.0) | --- | G(1.0) | E(1.0) |
| Longitudinal | 0.8 | 96.62% | 88.62% | 92.15% | 70.89% |
| Transverse | 0.2 | VP(0.5),P(0.5) | --- | F(0.5), G(0.5) | G(0.5), VG(0.5) |
| Hull Girder | 0.5 | 20 years | 20 years | 25 years | 40 years |
| Side Structure | 0.5 | 20 years | 20 years | 25 years | 40 years |
| Main Deck | 0.5 | 224MPa | 225MPa | 213MPa | 174MPa |
| Members 1-3 | 0.5 | VP(0.5), P(0.5) | VP(0.5), P(0.5) | P(0.5), F(0.5) | G(0.5), VG(0.5) |
| Berthing | 0.5 | 19.5mm | 21.0mm | 20.5mm | 25.0mm |
| Sloshing | 0.5 | U(0.3), VP(0.7) | --- | F(0.85) | G(0.8), VG(0.2) |
| CA-1 | 0.5 | VP(0.4), P(0.6) | VP(0.85) | U(0.2), VP(0.8) | G(0.6), VG(0.4) |
| CA-2 | 0.25 | VP(0.85) | --- | VP(0.5), P(0.5) | G(0.5), VG(0.5) |
| CA-3 | 0.25 | VP(0.8), P(0.2) | --- | VP(0.7), P(0.1) | G(0.8), VG(0.2) |
| Builder's Rep. | 0.3 | F(0.8) | P(0.2), F(0.8) | P(0.2), F(0.8) | F(0.5), G(0.5) |
| Owner's Exp. | 0.7 | G(0.8), VG(0.2) | G(0.7), VG(0.1) | G(0.8), VG(0.2) | G(0.8), VG(0.2) |
| C. Margins | 0.3 | 3.4mm | 3.5mm | 3.4mm | 4.0mm |
| Min. Scant. | 0.1 | 11.5mm | 11.5mm | 11.5mm | 15.0mm |
| Coat. Spec's | 0.3 | 5 years | 5 years | 15 years | 20 years |
| Anodes | 0.2 | F(0.6), G(0.4) | --- | F(0.5), G(0.5) | G(1.0) |
| Materials | 0.1 | 32% HTS | 80% HTS | 30% HTS | 30% HTS |
| Details | 0.5 | U(0.5), VP(0.5) | U(0.1), VP(0.9) | U(0.1), VP(0.9) | G(0.6), VG(0.4) |
| Welding | 0.5 | U(0.5), VP(0.5) | --- | U(0.2), VP(0.8) | F(0.8), G(0.2) |
| Yard QA/QC | 0.25 | VP(0.5), P(0.4) | --- | VP(0.2), P(0.8) | F(1.0) |
| Owner Effort | 0.75 | G(1.0) | G(1.0) | G(1.0) | VG(0.5), E(0.5) |
| Ballast Dist. | 0.2 | U(0.3), VP(0.7) | U(0.3), VP(0.7) | U(0.3), VP(0.7) | U(0.5), VP(0.5) |
| Filling % | 0.8 | 62.5% full | 62.5% full | 100% full | 100% full |
| Cross Ties | 0.5 | P(0.6) | P(0.5), F(0.5) | P(0.6) | F(0.5), G(0.5) |
| Subjective | 0.5 | U(0.2), VP(0.8) | --- | P(0.85) | F(0.6), G(0.4) |
| Ballast Tank Access | 0.5 | P(0.5), F(0.5) | --- | P(0.5), F(0.5) | F(0.5), G(0.5) |
| Cargo Tanks Access | 0.5 | VP(0.5), P(0.5) | --- | VP(0.4), P(0.6) | F(0.5), G(0.5) |
| Forepeak | 0.7 | VP(1.0) | --- | U(0.5), VP(0.5) | F(0.8), G(0.2) |
| Afterpeak | 0.3 | P(0.5), F(0.5) | --- | F(1.0) | F(0.7), G(0.3) |
| HSMS | 0.5 | U(1.0) | --- | U(1.0) | E(0.8) |
| Operability | 0.5 | VP(0.4),P(0.6) | --- | VP(0.3), P(0.6) | F(0.5), G(0.5) |

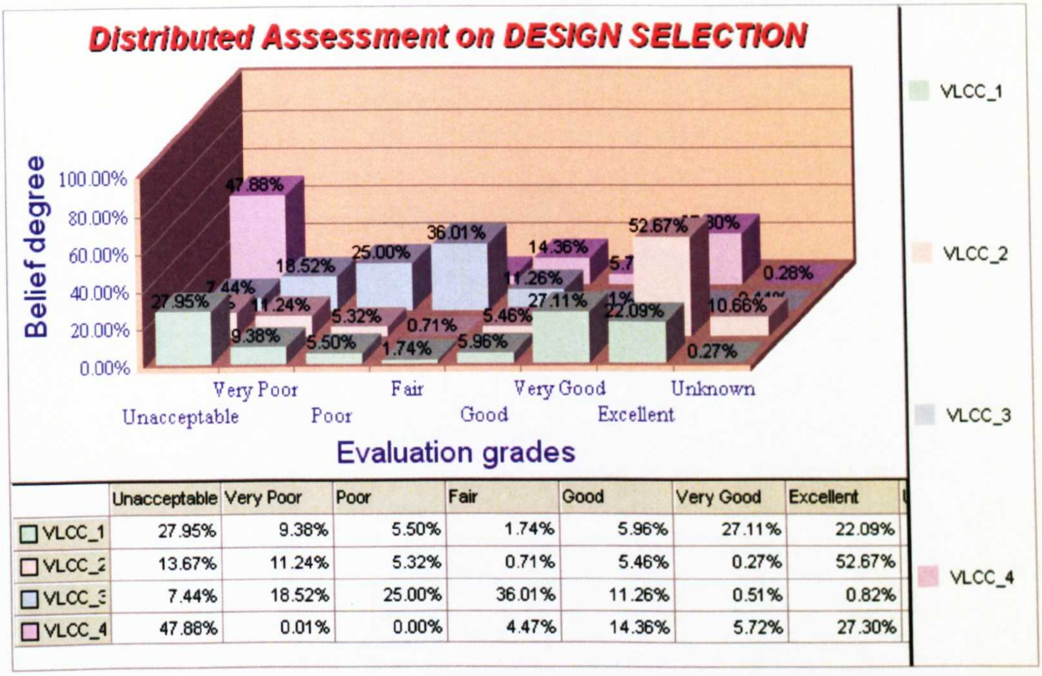
Table 6.5. Incomplete Information in the Generalised Decision Matrix



| | VLCC_1 | VLCC_2 | VLCC_3 | VLCC_4 |
|---|---|---|---|---|
| 🟥 Minimum score | 0.5292 | 0.6053 | 0.3818 | 0.4387 |
| ■ Average minus minimum | 0.0014 | 0.0533 | 0.0022 | 0.0014 |
| ■ Maximum minus average | 0.0014 | 0.0533 | 0.0022 | 0.0014 |

Figure 6.11. The Effect of Incompleteness on the Ranking for VLCC_2

The IDS output appears in figure 6.11. The grey area in the graph represents the possible utility variations in the ranges of the candidate VLCC's due to missing information. It was noted that the average utility score for VLCC_2 had increased from 0.6024 for the base case shown in figure 5.9 (p.213), to 0.6586, an increase of 9.3%. Figure 6.12 on the following page, shows the belief degrees and ranking for the four options. The degree of incompleteness for VLCC_2 was 10.8%. Despite the incompleteness in the assessment of VLCC_2, the ranking order did not change. Therefore in this case, the consequences of missing information for the criteria in question had no significant impact on the outcome. This outcome is further demonstration of the practical usefulness and flexibility offered by the MCDA/ER framework in an environment where preliminary structural assessments often involve incomplete or restricted data. The model provides the ability to perform the assessment regardless, in order to facilitate decision-making under such uncertainty.

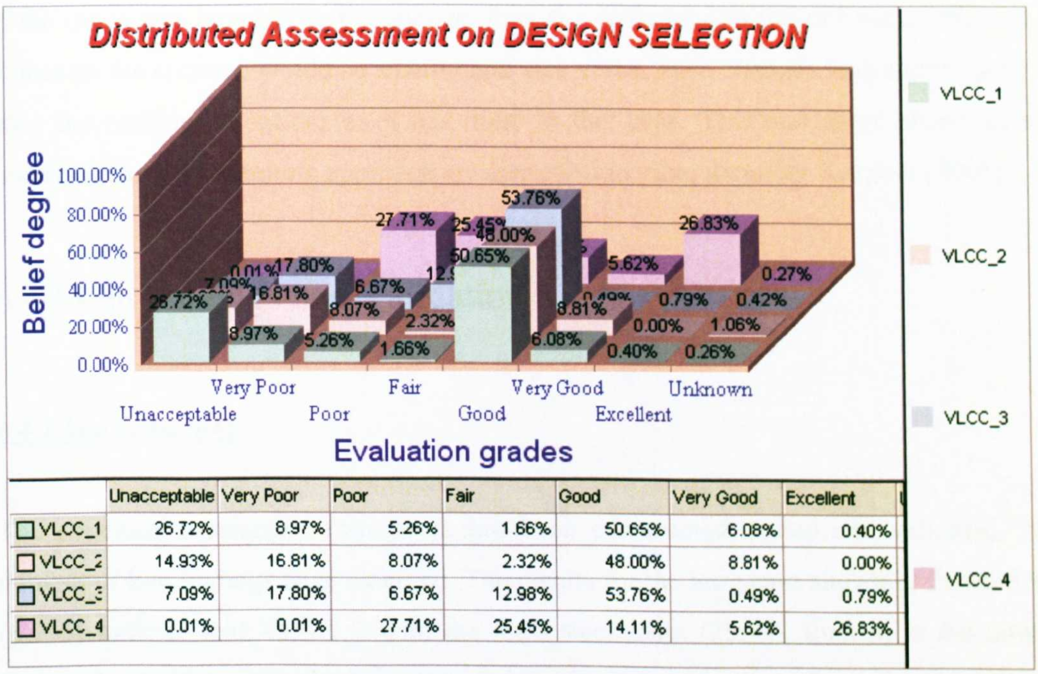


|  | Unacceptable | Very Poor | Poor | Fair | Good | Very Good | Excellent |
|---|---|---|---|---|---|---|---|
| ☐ VLCC_1 | 27.95% | 9.38% | 5.50% | 1.74% | 5.96% | 27.11% | 22.09% |
| ☐ VLCC_2 | 13.67% | 11.24% | 5.32% | 0.71% | 5.46% | 0.27% | 52.67% |
| ☐ VLCC_3 | 7.44% | 18.52% | 25.00% | 36.01% | 11.26% | 0.51% | 0.82% |
| ☐ VLCC_4 | 47.88% | 0.01% | 0.00% | 4.47% | 14.36% | 5.72% | 27.30% |

Figure 6.12. Belief Degrees for Incompleteness in Evaluation of VLCC_2

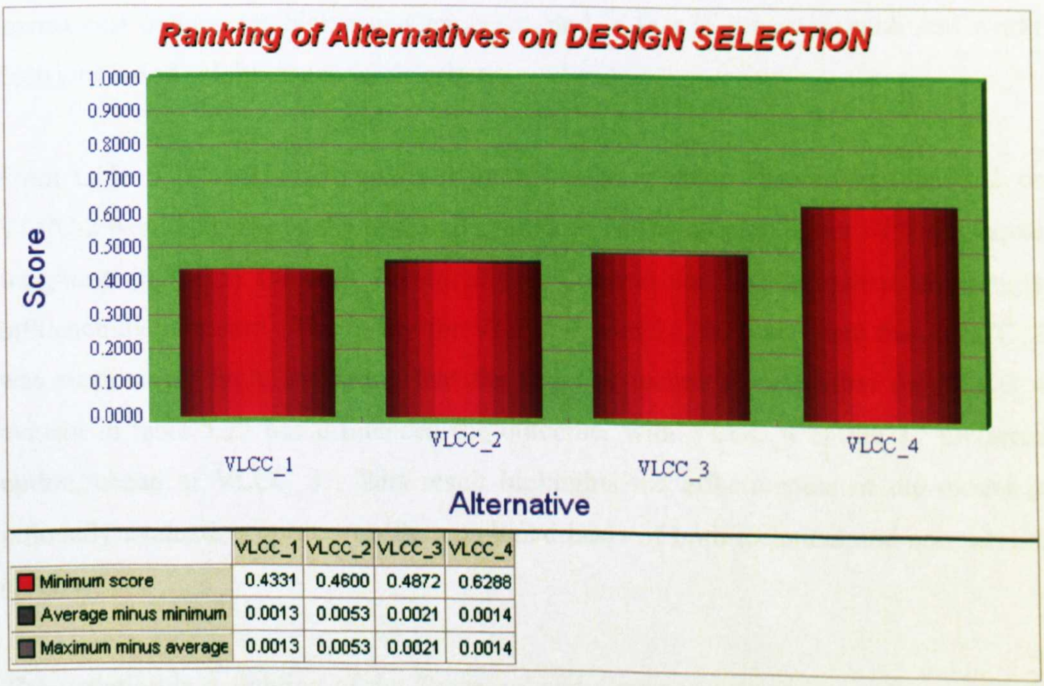
### *6.3.2.6 Range of Numeric Criteria*

One particular phenomenon requiring explanation arises due to the ranges adopted in the numeric data used in the ER model. In the high quality option discussed in section 6.3.2.1, the ranking order was established according to figure 6.6 (p.223). In this example, the worst and the best values for the NPV were USD 40.18 million and USD 69.74 million respectively. This should be compared to the range of NPV assumed elsewhere in the model, shown in table 5.15 on page 200 (USD 57.71 to USD 69.74). If the range was increased to a minimum of zero and a maximum of USD 100 million, the belief degrees in the distributed assessment appear as shown in figure 6.13. These results should be compared with those given previously in figure 6.6 in section 6.3.2.1. It is obvious that the ranking of the alternatives has changed significantly. The reason for this anomaly is that the worst and best values of a criterion are usually defined to have utilities of 0 and 1 respectively. Therefore, changes in the range of the criterion (worst and best limits) leads to changes in the linear utility function of the criterion assumed in the model.



| | Unacceptable | Very Poor | Poor | Fair | Good | Very Good | Excellent |
|---|---|---|---|---|---|---|---|
| ☐ VLCC_1 | 26.72% | 8.97% | 5.26% | 1.66% | 50.65% | 6.08% | 0.40% |
| ☐ VLCC_2 | 14.93% | 16.81% | 8.07% | 2.32% | 48.00% | 8.81% | 0.00% |
| ☐ VLCC_3 | 7.09% | 17.80% | 6.67% | 12.98% | 53.76% | 0.49% | 0.79% |
| ☐ VLCC_4 | 0.01% | 0.01% | 27.71% | 25.45% | 14.11% | 5.62% | 26.83% |

Figure 6.13. Belief Degrees for High Quality Option
with NPV Range USD 0-100 Million



| | VLCC_1 | VLCC_2 | VLCC_3 | VLCC_4 |
|---|---|---|---|---|
| 🟥 Minimum score | 0.4331 | 0.4600 | 0.4872 | 0.6288 |
| ■ Average minus minimum | 0.0013 | 0.0053 | 0.0021 | 0.0014 |
| ■ Maximum minus average | 0.0013 | 0.0053 | 0.0021 | 0.0014 |

Figure 6.14. Ranking for High Quality Option
with NPV Range USD 0-100 Million

If the range was larger after the change, then the difference in the utilities of the two values on the criterion would be smaller and vice versa. Such changes may significantly alter the ranking of options as it has done in this case. This and other phenomena involving the ER modelling approach are discussed in more detail by Xie et al (2008).

## 6.4 Main Findings and Validation

### *6.4.1 Main Findings*

The structural assessment framework has been constructed, tested and validated. A number of key findings have emerged. The results for the base case shown in figure 5.9 (p.213) indicate that VLCC_2 with the least steel mass (25,731 tonnes) is the most favoured candidate with the best potential for further evaluation. Second is VLCC_1 (26,303 tonnes). The difference in steel weight between the two options is only 2.2%. VLCC_3 and VLCC_4 have significantly lower utilities and therefore attention should be directed first at the other alternatives. The fact that the utility values of the two lowest cost options are higher was expected, and in fact is consistent with real world decisions based solely on economic criteria.

From table 5.22 (p.211), it was not immediately apparent that either VLCC_1 or VLCC-2 would emerge as the favoured candidates, although the higher NPV and equal weighting (0.5, 0.5) for both *Technical* and *Commercial* criteria appear to strongly influence the outcome. The utility for VLCC_4 with 24.2% more steel than VLCC_2 was surprisingly high, indicating that the superior technical evaluation for VLCC_4 evident in table 5.22 has influenced the outcome, with VLCC_4 as the 3rd preferred option, ahead of VLCC_3. This result highlights the effectiveness of the model in rationally evaluating options on the combined basis of both technical and commercial criteria.

The variation in weighting of the *Technical* and *Commercial* criteria performed in the sensitivity studies in sections 6.3.1.1 and 6.3.1.2, had the effect of significantly changing the utilities and rankings in the expected direction, showing the model's sensitivity to the assigned weightings. Increasing the weighting of *Commercial* from 0.5 to 0.75 and reducing *Technical* from 0.5 to 0.25 had the effect of clearly identifying VLCC_1 and VLCC_2 as the most preferred options. Increasing *Technical* from 0.5 to 0.75 and reducing *Commercial* from 0.5 to 0.25 strongly influenced the outcome for the high quality option VLCC_4 (31,965 tonnes), due to the more favourable technical scores recorded for both numerical and linguistic data shown in table 5.22.

In section 6.3, the effects of varying both the *Commercial* and *Technical* criteria in the model were explored. Firstly, in section 6.3.2.1, it was shown how a 20% increase in the capital cost for one of the alternatives (high quality option, VLCC_4) reduced the NPV to USD 40.18 million, and the ranking of the high quality option changed from third to worst, compared to the base case. Secondly in section 6.3.2.2, the effect of a USD 5 million scheduled repair occurring in year 15 for VLCC_2 showed that the utility of this option dropped slightly, but the overall ranking had not changed. Thirdly, in section 6.3.2.3, it was demonstrated that by increasing the average corrosion margin for VLCC_1 by 47% (from 3.4-5.0mm), its ranking changed from second to worst compared to the original rankings in the base case. Fourthly, in section 6.3.2.4, an increase in belief degrees for three of the technical sub-criteria was performed on one of the options (VLCC_1), and the impact on the overall ranking order assessed. Lastly, in section 6.3.2.5, the effects of incomplete information were investigated. The IDS results showed that the model allowed overall assessment to be performed even when data was missing or incomplete and the ranking was unchanged compared to the base case.

The traditional approach to procurement of new tonnage practised by many shipping companies was by using discounted cash flow (DCF) techniques as the sole criterion to determine the most commercially viable option. Historically, boards of directors generally required project proposals to be evaluated, and undoubtedly in some cases, the least cost option was selected. Increasing environmental awareness in organisations and changing corporate structures may mean that shareholders views alone or a single dollar criterion is no longer appropriate. The common challenge in design lies in the issue of how to construct design utility under uncertainty to reflect the interests of the producer, while considering the interests of the end users (Wassenaar and Chen, 2001).

The main challenge with ship procurement and design is to ensure that commercial and technical project risk assessments are adequately performed.

Although approximately 2/3$^{rd}$ of the capital expenditure for a new crude tanker is currently allocated to engines, pumps, piping, outfitting and equipment, the consequences of hull failures can be catastrophic, ranging from minor inconvenience to off-hire, explosion, and loss of life and/or environmental pollution. Commercial constraints in the design and production of large bulk ships invariably mean that these large mobile and sensitive structures have to be carefully monitored and maintained, and the risk of structural failure is significant. To mitigate these risks, a suitable risk-based techno-economic decision framework is required, to assess the impact of both commercial and technical criteria. The NPV approach used in the proposed MCDA/ER model demonstrates the importance of the assumed *Commercial* criterion in the evaluation framework and the criticality of the weightings assigned. In spite of the small range in the NPV values across the options, these differences in the NPV had a marked effect on the outcome.

The MCDA/ER structural assessment framework provides a simple effective tool with which to make better informed decisions in relation to performing trade offs between commercial and technical considerations when performing an owner's assessment of alternative structural designs. For example, increases in steel weight due to the application of common structural rules in the case of VLCC_3 resulted in a change from 17,514 tonnes to 18,353 tonnes (+ 5% in this case and typically 3%), according to ABS, DNV and LR (2005). Seen in relation to the 24.2% increase for VLCC_4 compared to VLCC_2 (refer table 5.6 on page 189), the CSR appears to represent a very modest improvement in terms of additional steel, compared to the baseline designs. The ER model clearly allows a balance to be struck in the trade-off between commercial and technical considerations. The effects of increased corrosion margins and other technical factors leading to an increase or reduction in steel weight can immediately be assessed in terms of their overall impact on the principal commercial criterion used for project evaluation.

### *6.4.2 Technical Aspects*

The subjective judgements performed and recorded in the generalised decision matrix given in table 5.22 indicate a somewhat pessimistic approach to evaluation of the various qualitative technical criteria for some of the options. For example, in the case of VLCC_1 the assessment of *CA_1* (*critical area no.1*) was VP(0.4), P(0.6) using a process described in section 5.4.4. This indicates a high expectation relative to the design of the critical area under review (e.g. lower hopper corner). Generally, it can be seen that this pattern dominates the subjective judgements for the first three options. The above arbitrary judgements intended purely to demonstrate the procedure, were assumed to reflect the views of a single decision maker or those of a small team representing the buyer. In a situation where judgements for each option are much more closely related, the ER model is still easily able to distinguish preferences, and this is one of the strengths of the method.

For project evaluation purposes, the mean corrosion margins in double hull VLCCs are typically 20% of the gross plate thickness and thus the corrosion margins determined by the new CSR rules are broadly comparable with those determined by classification rules. The calculations performed in section 6.3.2.3 allow forward projections on the effect of increasing corrosion margins at the design stage. This is one of the major determinants of ship durability and robustness controlled directly by the buyer (refer section 2.3.3). The corrosion margins may be assessed in terms of increased capital cost, increased scrap value and lower NPV, and the IDS model will allow rapid assessment of the changes in ranking of alternatives, as demonstrated in section 6.3.2.3 above. This is what Mistree et al (1990) refer to as life cycle considerations modelled in upstream design decisions.

### *6.4.3 Validity of the Framework*

The proposed MCDA/ER structural assessment framework presented and tested herein, is in fact an extension of the ship design method which allows the buyer to elicit preferences amongst competing design options. The difficulty in validating engineering research related to design methods has been discussed by Pedersen et al (2000). For design methods, they refer to a modern trend away from formal rigorous and quantitative validation anchored in the scientific tradition. More appropriately, they suggest that validation of design methods should be a process of "demonstrating usefulness with respect to a purpose". In figure 6.15 on the following page, the "validation square", the heart of their comprehensive, systematic and prescriptive approach to validation is depicted. The six step procedure is outlined in the following, where the numbers indicate the phases in the validation square:

- **Method consistency**: Using the literature and flowcharts to build confidence in the validity of individual constructs (1&2).
- **Accepting example problems**: Documenting the validity of example problems for verifying the method performance (3).
- **Accepting usefulness:** Demonstrate the usefulness of the method by some representative examples (4&5).
- **Accepting usefulness beyond examples**: Building confidence in generality of the method (6).

According to Pedersen et al (2000), the process of working through the validation square is to present circumstantial evidence to facilitate a "leap of faith", by increasing the belief in the usefulness of the method relative to the articulated purpose. Research validation is said to be a process of building confidence with respect to a purpose where scientific knowledge is defined as socially justifiable belief. In chapter 2, a comprehensive published literature review was conducted as a basis of and to build confidence in the constructs drawn out of the preceding chapters. These references have been used as benchmarks.

In figure 1.1, a conceptual flow chart representation focusing on information flow was presented. This device was used to anticipate outputs based on inputs. In chapter 3 and 4, documented viewpoints were articulated to build structural soundness in the method. In chapter 5, a representative example problem was solved in order to boost confidence in the method. In chapter 6, the method was further demonstrated to build confidence in the individual constructs through limited applications. In chapter 7, generality beyond tested example problems was sought. Hence it is believed that the circumstantial evidence needed to facilitate the “leap of faith”, that is to produce belief in the general usefulness of the method with respect to an articulated purpose has been achieved.

Figure 6.15. Design Validation Process (Pedersen et al, 2000)

## 6.5 Conclusions

A framework has been developed, presented and tested, which would allow the buyer of new VLCC/VLBC tonnage to make a rapid assessment of alternative designs, based on preliminary structural information provided by the builder. The MCDA/ER procedure is a well proven technique which lends itself to this type of problem involving a large number of criteria and subjective, sometimes incomplete information. The ER method overcomes some of the limitations displayed by MCDA methods in general, involving incompleteness and uncertainty in the data, a characteristic of the structural assessment problem described here. The IDS software is powerful, easy to use, and the assessment framework easily permits sensitivity studies to be conducted, examining the trade-offs between technical and economic criteria.

The framework is seen to provide rational and intuitive results. The model has been systematically tested to ensure that the results are reasonably consistent. It represents the first step towards formulating a design safety case for the hull structure, because it embodies all the principles of formal safety assessment, including hazard identification, risk assessment and risk reduction, cost benefit analysis and rational decision making. In the next chapter, based on the results from the evidential reasoning assessment process, an outline of the evolving hull structures safety case will be presented, leading to a proposed safety case for the operational phase.

# Chapter 7 - Evolving Arguments for a Hull Structures Safety Case from the MCDA/ER Structural Assessment Framework

***SUMMARY***

*In section 1.2, objective no.5 was to examine the applicability of the offshore safety case in the context of large bulk ship structures using a structural selection framework to evolve the arguments for a hull safety case. In the preceding chapters, a techno-economic framework was developed for selecting the best VLCC structural design option, taking into account the buyer's preferences. In this chapter, the structural assessment framework is used for evolving the arguments and evidence required to support a planned maintenance system (PMS) for the hull, following safety case principles. The proposed safety philosophy allows design, construction and operational phases to be integrated according to performance based structural goals established by the buyer. The benefits of this approach are outlined. Societal concerns with the structural integrity of bulk ships, wise use of scarce resources, and protection of the environment are addressed.*

## 7.1 Introduction

In the preceding chapters, a novel framework for selecting the best VLCC structural design from a number of options was developed, demonstrated by example, and validated. The proposed method is both goal-based and risk-based. Performance targets (goals) established by the buyer add value to the design process. Each of the 35 commercial and technical sub-criteria involved in the MCDA synthesis approach were evaluated by identifying specific related hazards and performing risk assessments. These procedures elicit the preferences needed for further evaluation and eventual selection of the best available option, reflecting the highest quality in terms of the buyer's performance objectives. The process is transparent and the assumptions made (evidence) can be utilised in the evolution of a computerised structural maintenance system for hull, based on safety case principles.

In essence, the basic elements of a hull safety case pre-exist independently in the form of the mandatory International Safety Management (ISM) Code, together with the formal safety assessment (FSA) process. A management system should be used in conjunction with the FSA methodology as suggested by Kuo (2002). The ISM Code is a safety management system which can be combined with FSA elements to create what is essentially a safety case.

## 7.2 Evolution of the Safety Case Approach

### *7.2.1 NOPSA Model*

The perceived impediments to the application of the safety case concept to ships in international trade have already been discussed in section 3.3.5. However, it is believed that the goal-setting approach adopted by the IMO and already implemented through FSA studies involving bulk carriers covered in section 3.3.2 and in the Joint Tanker and Joint Bulker projects for the development of common structural rules in section 3.4.3, has paved the way for the wider application of risk-based approaches including the safety case for ships. The safety case model adopted by the Australian offshore regulator NOPSA is regarded as a suitable paradigm. It can be used for developing a safety case for hull structures, a subset of the overall ship safety case that so far has not been trialled for oil tankers or bulk carriers due to the impediments referred to above.

The proposed safety case for hull structures would integrate the existing prescriptive regime of hull surveys defined in IACS Unified Rules for oil tankers and bulk carriers and has to be subservient to the ISM Code safety management system, as depicted in figure 7.1 on page 245. The proposed safety case for hull structures based on the NOPSA model comprises three parts, namely a description of the facility, a formal safety assessment (FSA) and a safety management system (SMS).

### *7.2.2 FSA and the Structural Assessment Framework*

The proposed structural assessment framework utilising a unique set of assessment criteria in combination with the new MCDA/ER synthesis method and evidential reasoning, is believed to offer a suitable decision framework for preliminary design assessment decisions from the point of view of the buyer. The method is flexible, practical and is based on a design for safety and formal safety assessment approach, comprising:

- A set of performance objectives developed by the buyer.
- A comprehensive hazard identification process conducted by the user focussing on the known principal generic hazards (corrosion and fatigue).
- Risk estimation associated with the critical structural area classification (safety critical elements).
- Risk evaluation of the critical structural details using established formal safety assessment risk assessment techniques.
- Cost-benefit analysis using the ER techno-economic structural assessment framework developed under this research effort.
- Transparency of assumptions made in the design.
- Maintenance philosophy tailored to suit the robustness of the design.
- Integration of design, operation and disposal phases.

### *7.2.3 SMS and the ISM Code*

In the period after 1990, safety regulation of offshore and marine structures moved towards goal-setting and quality assurance rather than the prescriptive approach leading to certification. The purpose of a safety management system (SMS) was to ensure that the goals were achieved safely, efficiently and without damaging the environment. The ISM Code indirectly addressed hazards and risks but lacked an explicit process for risk assessment/reduction and weakly addressed safety critical elements (Kuo, 1998). The weaknesses apparent in section 2.2.2 of the ISM Code in relation to establishing safeguards against identified risks, suggested that this important requirement appeared vague and imprecise (Wang and Trbojevic, 2007). The ISM Code's target of compliance with mandatory rules and regulations provided little incentive to go beyond minimum compliance. The ISM Code contained the elements of an integrated safety management system but did not go far enough.

Only by incorporating additional elements required by the safety case approach (goal setting, hazard identification and mitigation), could a fully integrated approach to safety and quality be achieved. The safety case methodology adapted to suit the hull structures safety question for bulk ships is recommended. The safety case has to be subservient to the SMS and the pre-existing ISM Code appears to be the industry's formative step towards this solution, and may eventually lead to a ship specific safety case being implemented for certain types of vessels, especially crude oil tankers and very large bulk ships, as proposed here.

### *7.2.4 Proposed Safety Case Concept*

In figure 7.1, the philosophical outline of the proposed safety case for hull structures is presented, with the ISM Code Safety management system (SMS) at the top and linked into the hull safety case. The proposed system addresses the vagueness and imprecision previously observed in relation to systematic hazard identification and risk assessment and the oblique reference to safety critical elements under the existing ISM Code, as pointed out by Wang and Tjbojevic (2007). These weaknesses can be addressed by integrating the MCDA/ER structural assessment framework proposed in this study, into the proactive measures adopted by the ship owner or manager. It is important to emphasize that the procedures suggested here are related specifically to the technical management of the hull structure which is only a part of the overall ISM Code safety management system. The safety case therefore needs to be integrated into the overall vessel safety management system under the ISM Code. The various layers of the safety system can be seen with classification rules, optional class notations and the IMO convention requirements described in section 2.4 as the baseline minimum standards and foundational elements.

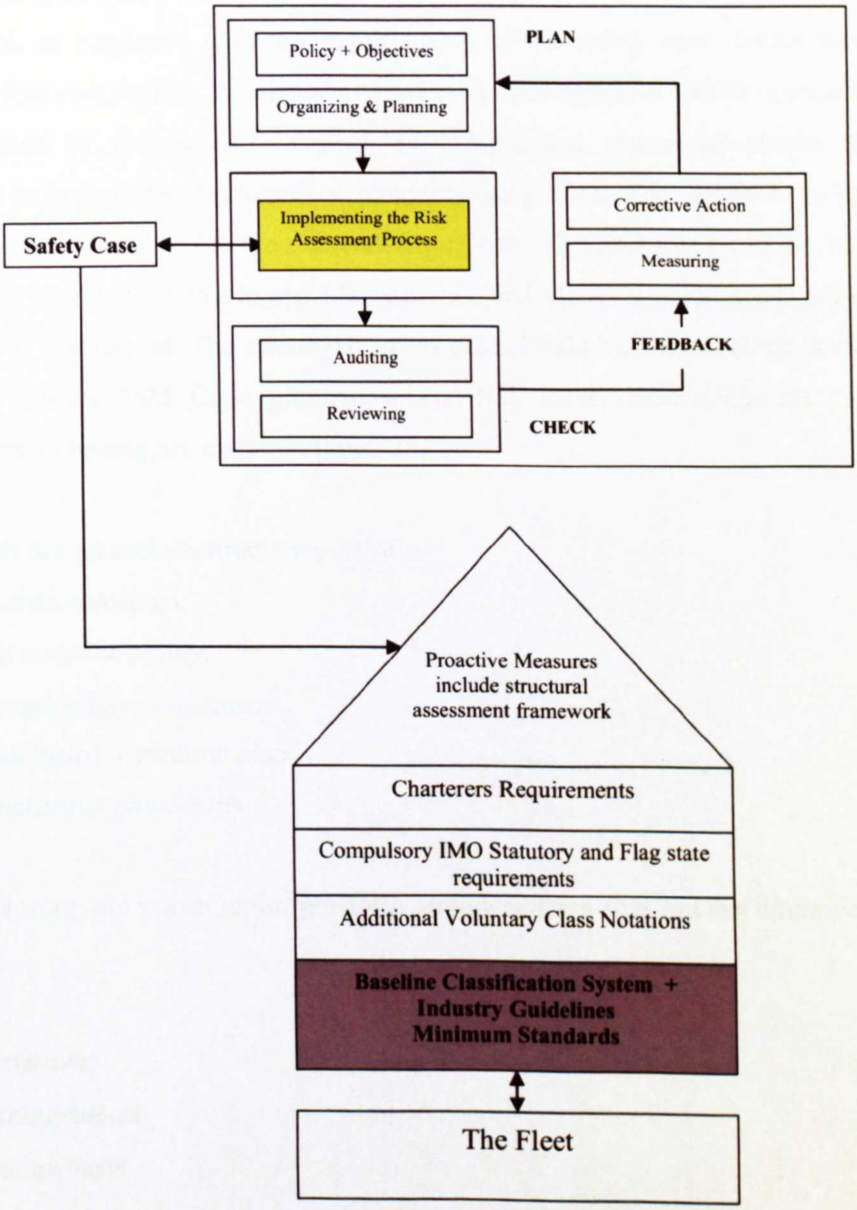


Figure 7.1.The Proposed Safety Case Concept

At the next level are the charterer's and insurance company requirements which have been covered in section 2.4.4. Finally, the risk-based procedures embodied in the

MCDA/ER structural assessment framework comprise the drivers for design and operational risk assessment for the structural design and operation phases of the vessel. The MCDA/ER framework relies on identification of critical structural details (CSDs), and a set of performance standards which can relate the CSDs to the assessment criteria. This is consistent with the requirements of the safety case. Under the UK offshore safety case regime, verification of safety critical elements (SCE) is required to be undertaken by the operator through an independent competent person (IPC). Qualitative or quantitative performance standards are generated for all SCEs to ensure that they remain suitable for their intended purpose. The SCEs have to be verified according to a written scheme to provide assurance that the level of safety set out in the safety case is maintained. The envisaged safety case should be a stand alone document under the existing ISM Code provisions. The hull safety case document would comprise the following six major sections:

1. Hull design and construction portfolio.
2. Operation manual.
3. Maintenance policy.
4. Formal safety assessment.
5. Risk-based inspection plan.
6. Emergency procedures.

The hull design and construction portfolio would address (but not be limited to) the following:

- Particulars.
- Arrangements.
- Design basis.
- Routes.
- Global bending moments.
- Loading conditions & restrictions.
- Structural loading.
- Hull Materials & welding.

- Corrosion margins.
- Coating specifications.
- Basis for fatigue design.
- Sloshing risk.
- Vibration risk.

The safety case document would be placed onboard the vessel and have the purpose of defining the hull maintenance policy and procedures required by the ISM Code. Most of the evidence for the hazard identification and risk assessment may be derived from the MCDA/ER framework described in chapters 4 & 5 as part of the preliminary ship design process. The safety case could incorporate one of the computer based maintenance systems provided by the major IACS Societies described in the following section.

## 7.3 Planned Maintenance System (PMS)

### *7.3.1 PMS for Hull and Machinery*

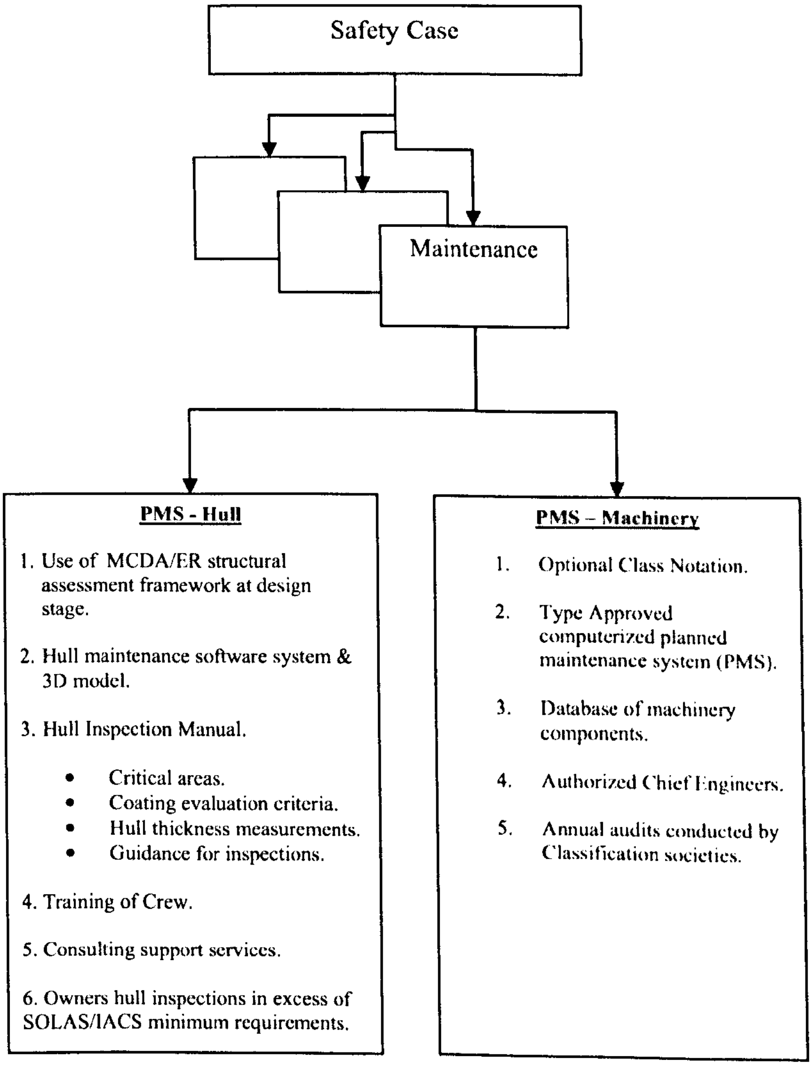
In section 2.5, the background to some early efforts to develop ship structural integrity management (SIM) systems was described. In particular, the comprehensive efforts of Bea et al from 1990-1995 were recognised. Very recently, a number of major classification societies through their consulting groups, have released new products and services which are essentially computerised hull planned maintenance systems. Examples are DNV's *Nauticus Hull Integrity*, ABS Consulting's *Hull Integrity Management Program*, Lloyds Register's *Hull Integrity System*, Germanischer Lloyds *Hull Lifecycle Program (HLP)* and Bureau Veritas's *Asset Integrity Management System (AIMS)*. Some of these products are extensions of the structural software programmes described earlier in section 2.5.5. For bulk carriers and oil tankers, they are intended to be used in conjunction with the IACS required ESP survey regime under resolution A.744 (18), and are voluntary. Effectively, the classification societies are offering comprehensive SIM management systems.

Due to potential conflict of interest with classification services performed by the same organisations, these products are being marketed by consulting groups allied to the particular class societies. For example, ABS consulting offers their *Hull Integrity Management Program.* HIMP as an optional class notation intended for ship owners and managers. The product consists of an *ABS Hull Maintenance Software Tool* supported by an *ABS Guide for Hull Inspection Management.* The ship specific manuals are intended to be used to identify "areas of concern" for inspection purposes, and provide criteria for ranking condition of these areas. The software database is said to be a platform for storage of inspection data. ABS services provide additional support in the form of anomaly review, analysis of critical areas and 3D inspection reports for dry docking (http://www.absconsulting.com). ABS Consulting suggest that the hull maintenance software tool allows for development of the inspection plan, provides a platform for the storage of the inspection results, allows for vessel specific or fleet wide monitoring, and allows access to the inspection data both onboard and ashore (http://www.absconsulting.com, 4th August, 2008).

Other developments include the release of LR's *Hull Integrity Service*, said to be guidance and tools to manage structural integrity of a fleet, using a *Hull Integrity Software Package.* DNV has developed *Nauticus Hull Integrity*, based on *Hull Life Cycle Manager* from DNV Software. The kernel of the system is a 3D model of the hull structure which utilizes colour coding, digital photos and inspection data comprising the accumulated hull history. BV released VerisSTAR Hull Life Cycle (HLC) comprising a similar 3D model comprising the inspection database. All of the above organisations offer software and analytical support for these products.The goals are stated to be to optimise inspections, analyse hull condition, organise management functions and to structure work orders and repair specifications. Bea et al's vision for an industry wide computerised marine structural integrity programme (MSIP) based on a common platform, now appears to have been achieved, albeit through the development of a multiple of software platforms provided by the leading classification societies. The driver for these developments has been largely commercial, responding to the need to provide such a service to the industry. However, the current range and complexity of these products and the short development time from concept to fruition has been remarkable.

### *7.3.2 ISM and Maintenance*

In section 10 of the ISM Code, the requirements for maintenance of the ship in accordance with the "relevant rules and regulations" are stated. In relation to the hull structure for large bulk ships, this is usually interpreted to mean compliance with classification rules, IACS procedures and IMO resolution A.744 (18).



**PMS - Hull**

1. Use of MCDA/ER structural assessment framework at design stage.
2. Hull maintenance software system & 3D model.
3. Hull Inspection Manual.
   - Critical areas.
   - Coating evaluation criteria.
   - Hull thickness measurements.
   - Guidance for inspections.
4. Training of Crew.
5. Consulting support services.
6. Owners hull inspections in excess of SOLAS/IACS minimum requirements.

**PMS – Machinery**

1. Optional Class Notation.
2. Type Approved computerized planned maintenance system (PMS).
3. Database of machinery components.
4. Authorized Chief Engineers.
5. Annual audits conducted by Classification societies.

Figure 7.2. Hull & Machinery PMS under the Safety Case

Classification was made compulsory in SOLAS Chapter II-1, by Resolution MSC194 (80), in 2007. Paragraph 10.3 in the ISM Code refers to a requirement for "companies to establish procedures in their safety management systems to identify equipment and technical systems, the sudden operational failure of which may result in a hazardous situation". Traditionally, hull maintenance planning has been carried out on the basis of calendar based rules prescribed by the IACS classification societies.

The safety case model integrates the PMS systems for both hull and machinery as shown in figure 7.2, satisfying the maintenance requirements set out in the ISM Code. Planned maintenance systems are not new. Computerised planned maintenance systems (PMS) for marine machinery systems have been available for many years and are in common use onboard ship. Computerised planned maintenance systems for ship structures are less common, and only recently are being introduced on a wider scale, as discussed earlier.

### *7.3.3 Data Management*

Traditionally, data management in most shipping companies was done on an ad hoc basis. Detailed structural information was usually found in drawings and documents stored in the chief engineer's office onboard the ship. Less than a decade ago, survey planning for entire fleets may have been conducted in-house by superintendents using spreadsheets and other simplified methods. With the advent and availability of powerful on-line database systems now provided by the major competing classification societies, real time survey planning and on-line data management for the entire fleet is currently available and implemented in many shipping companies. This trend is increasing, but may have some unanticipated consequences.

Effectively, the keepers of the hull maintenance database and the product model described in section 3.2.1 are, by default, the international classification societies. Certain owners may expect classification societies to progressively offer "turn key services" in relation to planning, execution and data entry in relation to maintenance activities for the fleet. This is especially relevant as the complexity of the maritime regulatory system increases exponentially as environmental requirements are progressively integrated with existing procedures. The danger inherent in this assumption is that it is contrary to the intent of the ISM Code which fundamentally identifies the owner as having the responsibility for the maintenance and safety of the vessel. However, for large, technically competent and responsible ship owners intent on best practises, and who clearly view maintenance as their own responsibility, the proposed hull safety case is a device which will best facilitate these goals.

### *7.3.4 Integrating Prescriptive Controls*

In figure 7.3, the envisioned safety case model is presented. The safety case is central to the hull maintenance activity. The shared hull database forms the main repository for information.

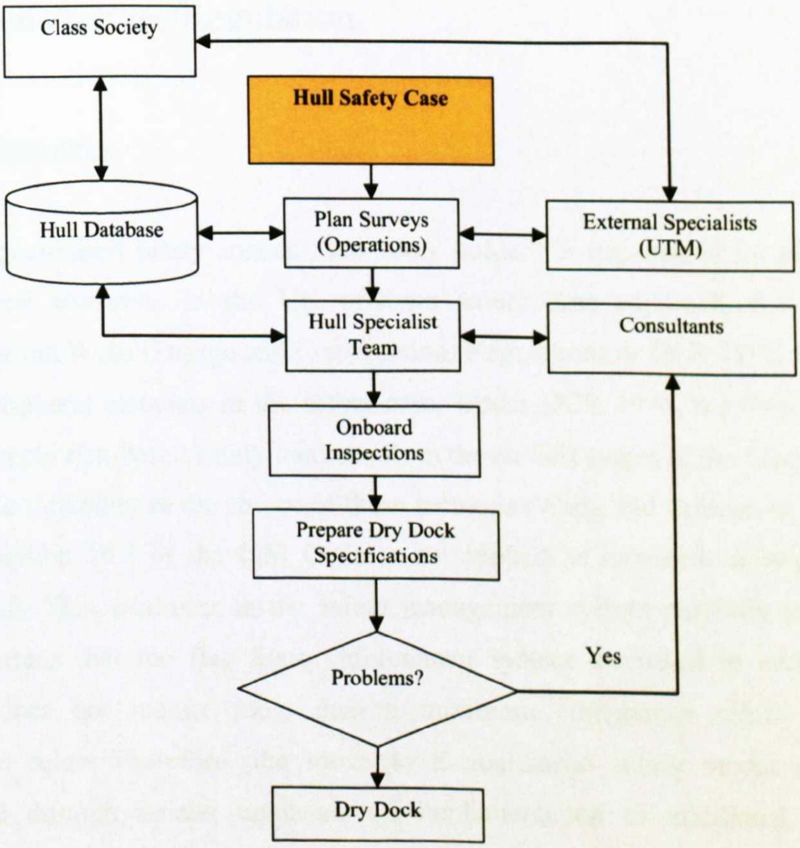


Figure 7.3. Safety Case Model

In the envisioned approach, the hull maintenance activity is intended to be driven primarily by the owner (duty holder) supported by specialists and consultants. The owner's team is managed by a structural specialist at technical manager level in the organisation. He/she is supported a team responsible for onboard inspections carried out in accordance with the documented hull safety case inspection requirements. The owner's team closely co-ordinates with external consultants and the classification societies. All data is entered into the PMS by the hull specialist team. The class societies audit the safety case as discussed in section 7.4.2. The existing regulatory controls on the operational performance of ship structures are implemented through the IACS enhanced survey programme (ESP), forming the basic requirements and minimum extent of physical surveys and reporting, as administered by the international classification societies, and overseen by the regulators (flag States).

## 7.4 Responsibilities/Regulation

### *7.4.1 Responsibilities*

Under the goal-based safety concept, the "duty holder" is responsible for identifying safety critical elements. In the UK offshore safety case approach, the Offshore Installations and Wells (Design and Construction) Regulations or DCR 1996, are one of the four peripheral elements in the safety case. Under DCR 1996, the duty holder is obliged to apply risk-based safety methods from the earliest stages in the lifecycle, with considerable flexibility in the choice of these methods (Wang and Trjbojevic, 2007). In shipping, section 10.3 of the ISM Code is not applied as intended, as suggested in section 7.2.3. This weakness in the safety management system currently in place in shipping means that the flag State enforcement system discussed in section 2.4.2 presently does not require more than a minimum compliance effort based on prescriptive rules. Therefore, the move to a goal-based safety model should be encouraged through stricter emphasis on implementation of additional layers of proactive risk-based safety measures of the kind proposed in this study and indicated in figure 7.1.

### *7.4.2 Regulatory Implications*

The problems talked about in chapter 2 in relation to the effectiveness of the present regulatory system bear repeating here. The twin threats of corrosion and fatigue and the severity of the consequences of even minor structural failures in large tank ships, demand more than a minimum compliance approach. Failure of some flag States to act effectively as a regulator, compounds the problem. In the case of the *Erika*, the accident occurred in spite of a number of port State control and vetting interventions carried out prior to the loss. In shipping, the changing role of the international classification societies as the defacto regulators to the industry and the incorporation of IACS ESP into SOLAS in 2007 means that classification is now widely viewed as the principal system for enforcement of the minimum operational requirements for hull structures for large bulk ships. This situation is at odds with the principal role of the classification societies as knowledge brokers and service providers. Classification societies make relatively poor regulators (Boisson, 1999).

In the Australian offshore regime, only the regulator (NOPSA) can assess the safety case as this activity is not delegated to other organisations. In the offshore industry world-wide, there is a transition from prescriptive rules once delegated by governments to class societies as recognised bodies, to one in which goals are established, and safety cases may be validated by any competent entity. In Australia, NOPSA assess the validator against criteria specified in MoSOF Regulation 44(5). The status of some of the international classification societies depends on distinguishing between services which are carried our purely for profit and services which have an altruistic benefit to the community. Protection of life, property and the environment continues to be the primary goal and mission statement of many classification societies for the common good of the international community. The major international classification societies have largely replaced owners' technical departments and are currently the main repositories of technical and statutory procedural knowledge in the maritime industry. In shipping therefore, the responsibility for validation of ship specific safety cases on behalf of flag States is thought to fall naturally to the international classification societies.

### *7.4.3 Verification/Validation*

Validation means assurance by an expert that design, construction and installation has been reviewed and assessed against appropriate standards. Verification is confirmation (by inspection) that a component or system has been properly manufactured and installed. In offshore terminology, verification is usually accompanied by a written verification scheme or verification plan as embodied in the written safety scheme described in section 7.2.4 (DNV, 2004). To achieve this goal, various levels of verification could be conducted (high or low). It should be noted that the methodology is entirely consistent with alternative methods already offered by major classification societies. DNV has proposed classification based on performance criteria determined from risk-assessment methodology with various levels of risk assessment according to figure 7.4. Clearly, the principles are readily transferable to the ship structures problem. Large bulk ship structures represent a considerable hazard.

Figure 7.4. Levels of Risk-Based Verification (DNV, 2004)

Such structures may be zoned or categorized into areas of elevated risk, such as the lower hopper corner example for a double hull tanker discussed in section 4.4.4.5. Using the methodology recommended by Ma et al (1997) explained previously in section 3.5.3, critical structural details (CSDs) can be identified and the qualitative or quantitative performance standards described in the MCDA/ER framework linked to the CSDs through the model.

### *7.4.4 Competence Issues*

Recognising the change from a prescriptive regime to goal setting in the UK offshore industry, a recent study by Billington and Caruana (2002) remarked on the tendency for financial managers to outsource SIM competence, claiming that the emphasis was often on minimum standards, and the question was raised as to whether competence was assessed at all. The authors pointed out the lack of SIM standards at the professional institution level, often putting professional qualifications of managers appointed to oversee SIM activities in doubt. They referred to a lack of recognition of the effect of changing business models on the ability to manage structural integrity under the goal setting regime, with more emphasis on short term financial planning and man-hour rates. The literature survey conducted in chapter 2 revealed similar patterns in the shipping industry, particularly involving the failure to embrace risk-based technology earlier, and a history of issues regarding unsatisfactory structural performance in a number of oil tankers and bulk carriers.

In section 7.3.1, computerised hull planned maintenance systems and associated services offered by consultancy groups affiliated with the class societies were described. These are marketed together with training courses and aids for the crew, such as ship specific hull maintenance manuals, containing elementary descriptors and graphics of the hull structure. Training courses for owner/manager teams is provided, and the systems rely on hull inspections performed by ship staff and superintendents. Although such initiatives are regarded as a positive development, it is considered highly unlikely that a comprehensive fleet-wide SIM system for a major bulk ship operator could be managed on the basis of data obtained from onboard inspections by ship staff alone.

In section 7.5.4 a compelling argument will be presented for reinforcing competence even in those shipping companies which have strategically decided to adopt a minimum standards approach. To properly maintain vessels which are at risk of corrosion and fatigue damage and to mitigate the potential consequences of structural failure requires substantial organisational competence, commitment and resources. Although the measures described above go some way towards generally improving the understanding of the importance of large bulk ship hull structures, the complexity of the hull structures problem and the scope of effort involved in maintaining a large fleet of vessels warrant the use of much greater resources. In this regard, it is envisioned that under the safety case paradigm, hull maintenance should be regarded as a core activity by fleet managers, involving a dedicated manager and a team with the appropriate level of responsibility, competence and skills, as suggested in section 7.3.4.

## 7.5 Improved Approach

### *7.5.1 Real-Time Hull Condition Monitoring*

In section 2.5.5 and in section 7.3.1, a number of new software supported hull maintenance products developed by the leading classification bodies were described. In parallel, a three year € 3.2M, EU funded research project entitled *Condition Assessment System (CAS)*, was initiated in February 2005, in the backcloth of the IMO's *Condition Assessment Scheme (CAS)* described earlier in section 2.4.4. Ten co-partners led by BV, and including GL and the Russian Register, co-funded the project which has 6 work packages. The overall remit of the CAS project was to transform the workflow of the thickness measurement (TM) process into an electronic process. GL have described their efforts to develop the *Pegasus* software in co-operation with their CAS consortium partners. *Pegasus* is described as a software tool intended to support the thickness measurement process. The Hull Condition Monitoring (HCM) file is based on XML technology. Measurement data can be imported into GL's FEM software, *Poseidon* from the HCM file, in order to perform longitudinal strength calculations. It should be noted that GL envision that *Pegasus* will be used primarily by their staff and the thickness measurement technicians (Jaramillo & Cabos, 2005).

In the very near future when the technology for direct integration of the UT data into the 3D model by the gauging companies matures further, real-time monitoring of structural condition of large bulk ships including coating condition will be a reality. Impenetrable and unwieldy UT gauging data and processes currently in use will be rendered obsolete, and interested parties will be able to view an executive summary of hull condition in graphical format onboard the ship. This technology will provide the opportunity for port State and charterers inspectors to gain a rapid and accurate overview of structural condition during routine audits onboard. The above tools are an essential part of the envisioned hull safety case concept.

### 7.5.2 Improved Procedures

Following the *Erika* disaster in 1999 and 3 years prior to the loss of the *Prestige*, the classification society DNV introduced a raft of measures in relation to surveys of hull structures for bulk ships and other vessels including special surveillance schemes with a focus on quality and special conditions for those vessels identified as possibly substandard. Risk factors such as age of the vessel, repeated change of ownership, multiple commencement of surveys, excessive number or overdue conditions of class, lack of co-operation with class, port State detentions etc were regarded as triggers for risk profiling and subsequent action. Owners were informed of substantial corrosion/suspect areas in tanks or that annual surveys in ballast tanks would be required on account of poor coating condition. More detailed categorisation of conditions of class or conditions of authority were introduced, with special emphasis on procedures for dealing with structural deficiencies.

All the above improved procedures implemented during the five years after 2000, included the use of flying squads to carry out unscheduled surveys on high risk vessels. At the same time, the IMO made classification requirements mandatory through the SOLAS Convention in 2007, discussed in section 2.4.1.1. Progressive tightening of the IACS Unified Rules, Resolution A.744(18) for survey of tankers and bulk carriers, now in SOLAS chapter II-1/3-1, has meant that the classification societies post *Erika* and *Prestige,* effectively function as the defacto regulator in controlling the quality of hull structures of vessels in service, although the flag States ultimately bear the burden of responsibility.

### *7.5.3 Minimum Standards and the Turnkey Approach*

Prior to the implementation of IACS CSR Rules in 2006, and as a "rule of thumb", the minimum allowable thicknesses in tanker structures were based on 75% of the gross "as built" thickness. Generally therefore, the thickness reduction allowed was a maximum of 20-25% of the original plating thickness, although under IMO requirements, the hull girder section modulus was only allowed to deteriorate down to 90% of the rule value. After IACS UR Z10.1 came into effect in 1993, the concept of "substantial corrosion" was introduced to monitor the progress of corrosion between major hull surveys conducted at five yearly intervals. Substantial corrosion was defined as 75% of the wastage allowance. Therefore, when UT gauging revealed wastage in excess of 18.75% of the gross plating thickness, substantial corrosion was recorded. After the *Erika* disaster in 1999, IACS procedures were changed to require "substantial corrosion" to be dealt with as a condition of class (CC).

In crude tankers and bulk carriers where ballast tank coatings had failed pre-maturely, sometimes only after 5-10 years in service as revealed in section 2.3.1 and 2.3.3, the required ultrasonic thickness (UT) readings obtained during rafting of tanks may not have been reliable. Corroded tank surfaces require grit blasting to remove corrosion products including scale. The time and costs involved for erecting staging and properly cleaning and de-gassing tanks prior to UT measurement and detailing of the repair specification are prohibitive. Lack of reliable UT data as a baseline for planning structural repairs may have been a factor in subsequent failures, perhaps incorrectly attributed to other causes. Cropping and renewing of corroded areas was difficult to control and made quality repair outcomes questionable. It is reasonable to assume that such structural repairs may have been carried out involving a wide spectrum of solutions with sometimes doubtful quality.

Where unprotected renewed areas were exposed to seawater, rapid and uncontrolled corrosion would ensue with disastrous results as testified by the structural failures of *Erika* and *Betelguese* and possibly many bulk carriers lost in suspicious circumstances (see sections 2.6.1 and 2.6.2).

Concerned at failures in ship structures including total losses in spite of efforts to prevent them, Paik et al (2003g) studied the effects of corrosion on hull girder strength for a range of ship types including tankers and bulk carriers.

Figure 7.5. Time Dependent ULS (Paik et al, 2003g)

Joint research was undertaken by Pusan National University and the classification society ABS. The focus of the study was to assess time-dependent ultimate hull girder strength, reliability index and probability of failure against hull girder collapse. Paik's corrosion model outlined in section 2.3.3 was incorporated in the study. Corrosion measurement data for 230 ageing single hull tankers and 109 bulk carriers were collated and analyzed. The progressive collapse behaviour of a 170,000dwt Capesize bulk carrier was calculated using the ALPS/HULL software. Figure 7.5 illustrates the trend of the resulting time dependent strength of the vessel in hogging with the effect of multiple repairs shown. The safety measure was the ratio of the ultimate hull girder strength to the IACS requirement shown on the vertical axis.

Paik et al's research revealed two important findings relevant to the central objectives in this study. Firstly, the margins on the structural design were seen to be surprisingly small. With uncontrolled corrosion and no repairs, the IACS section modulus limits were reached in less than 10 years of service. Secondly, it was evident that safety and reliability of these structures can only be controlled by proper repair and maintenance strategies as remarked by Paik et al in the above study. Alternatively, and as a strategic plan, an owner may elect to build a "maintenance free" vessel with ample corrosion margins, and high coating specifications. This has been explored by the high quality option tested and discussed in section 6.3.2. The higher capital cost would be offset by lower maintenance and off-hire costs. At the other end of the scale, an owner who chooses a least cost design, barely complying with classification rules, may be faced with significant survey and maintenance costs in the future. The trend is shown by the dotted line in figure 7.5. Failure to properly anticipate future costs caused by serious structural problems leading to cargo offloading, unscheduled dry docking, or environmental pollution has potentially huge commercial consequences.

| **Element** | **VLCC** | **CSR** | **Gratsos** |
|---|---|---|---|
| Deck plating | 0.20 | 0.12 | 0.22 |
| Deck longitudinal web | 0.25 | 0.12 | 0.28 |
| Bottom plating | 0.25 | 0.07 | 0.19 |
| Longitudinal bulkhead long. web upper 2.0m | 0.16 | 0.16 | 0.28 |
| Deck and side transverse web plating upper 2.0m | --- | --- | 0.30 |
| Transverse bulkhead plating | 0.22 | 0.22 | 0.25 |

Table 7.1. Comparison Between Corrosion Margins (Gratsos et al,2005)

Corrosion allowances were recently the subject of fierce debate in IACS. The concept of designing ship structures based on steel renewals after ten years was challenged. It was argued that corrosion margins in the new common structural rules were based on theoretical corrosion rates of 0.1mm per year. Further, the new CSR rules assume a design lifetime of 25 years compared to 20 years in the previous rules. In table 7.1, a comparison has been made between annual average corrosion margins defined by current classification rules requirements for a VLCC in column 2, and the corrosion margins proposed by Gratsos & Zachariadis (2005) in the last column. They put forward the view that the new CSR corrosion margins in column 3 were totally inadequate, a position which was strongly rebutted by IACS (IACS, 2006a). Such debate is indicative of the emotionalism and deep divisions which are sometimes encountered between the various stakeholders in the maritime community on the subject of hull structures.

One of the findings of this study has been that buyer preferences are often not exercised in ship procurement, and there is a wide variance between the discerning buyer with high bespoke specifications and the off-spec buyer prepared to accept a baseline structural design offered by the builder. Owners interested in preserving their reputations by lowering risk, may seek extended lifetimes and high structural reliability. Buyers tend to rely on classification standards which are not design codes as noted in section 2.4.3, to underwrite ship quality and reliability. However, it has been stated earlier that classification rules are inherently minimum standards.

Ship builders offer least cost solutions optimised for productivity. Devanney & Kennedy (2003) and other strident critics of the present approach whose views were presented in section 3.2.5, believe that hull warrantees of 1 year are totally inadequate. They have stated that the failure of ship builders to properly underwrite their products is unacceptable. The new CSR rules result in modest increases of between 3-10% of the total steel weight for VLCCs, and undoubtedly offer an improvement in relation to the previous structural standards. However, they are still minimum standards. The importance of the structural design in terms of the buyer's preferences and engineering effort and commitment necessary to ensure safe and reliable operation of the hull structure is believed to be a point worth emphasising.

### 7.5.4 Societal Concerns and Environmental Aspects

We live in an era of unprecedented change. Near meltdown of the global financial system in late 2008, wildly fluctuating oil prices, and the international community's deep concerns for the environment are all part of the urgent problems of our era. In these times of financial turmoil, ship owners may take heed of the increasing intolerance of the international community to environmental damages caused to innocent third parties. The recent verdict of the French courts in relation to the *Erika* trial (see section 2.6.3) indicates a sea change in public and societal attitudes towards incidents involving marine pollution by ships and the possible consequences for the owners and operators of vessels crossing international boundaries.

The published literature review carried out in chapter 2 identified key challenges facing those responsible for adequately maintaining hull integrity of large tank ships. Most structural failures have involved corrosion and/or structural fatigue phenomena. There is a great deal of evidence to suggest that the structural integrity of large tank ships involves a wider obligation to the international community on the part of the ship owner. The hazards involved in the transportation of bulk cargoes in large bulk vessels represent a serious environmental threat. The public expect ship owners and classification societies to carefully manage the risks inherent with this type of transport. The widely held minimum compliance approach is no longer deemed to be sufficient due diligence. Increasing societal concerns led by political interests and the media suggest that a minimum compliance stance in relation to damages to the marine environment will be harder to defend in the future. The trend towards performance based safety standards suggests that bulk transport by sea should not continue to depend solely on a framework of prescriptive rules and minimum standards set by the international classification societies.

### *7.5.5 Timeline of Ship Structures Events*

A brief list of some of the key developments affecting large bulk ship structures since 1989 is given below in table 7.2.

| Year | Event |
|---|---|
| 1989 | *Condition Assessment Programme(CAP)* introduced by DNV. |
| 1989 | *IACS S11 Longitudinal Strength Standard* published. |
| 1990 | US Flagged 81,283 dwt tanker *Surf City* explodes and sinks off Dubai UAE. |
| 1990 | Major international classification societies introduce explicit fatigue criteria into their ship rules as a result of early failures in tankers. |
| 1990<br>1995 | *Structural Maintenance for New and Existing Ships* Project at the University of California at Berkeley, supervised by Professor R. Bea. |
| 1992 | *Ship Structural Management for Improved Safety,* by Brooking and Barltrop. |
| 1992 | *Structural Performance Management of VLCC's - An Owner's Approach,* by Melitz, Robertson and Davison. |
| 1993 | ABS Introduces SAFEHULL Software System for the design and evaluation of ship structures. |
| 1993 | IMO Resolution A.744(18) *Enhanced Surveys of Oil Tankers & Bulk Carriers.* |
| 1993 | UK Offshore installations adopted the safety case approach in May/November 1993. |
| 1993 | UK MCA responds to Lord Carver's Report into ship safety following the *Herald of Free Enterprise* disaster, recommending to IMO that formal safety assessment (safety case) should be applied to ships. |
| 1995 | Arco Marine conducts HSMS studies, discovering that the combined effects of springing and whipping significantly affect the hull girder fatigue life (Lacey et al, 1995). |
| 1998 | At 70th session of MSC, UK proposes to IMO to carry out FSA study on bulk carrier safety. |
| 1999 | 37,283 dwt oil tanker *Erika* sinks off Brittany spilling 30,884 tonnes of heavy oil due to structural failure. |
| 2002 | 81,564 dwt oil tanker *Prestige* sinks off Spain with 76,972 tonnes of heavy oil possibly due to structural failure. |
| 2007 | Classification made mandatory for ships in SOLAS chapter II-1, regulation 3-1. |
| 2008 | French court finds the charterer and the classification society involved in the oil tanker *Erika* disaster guilty, and they are both fined. |

Table 7.2. A Short Timeline of Some Recent Key Developments in Ship Structures

## 7.6 Conclusions

A weakness in current ship design practise appeared to be the lack of a means of incorporating an owner's preferences into the design process. A number of findings were made:

- The transportation of bulk cargoes including crude oil and products in large bulk vessels represents a serious environmental hazard. Industry stakeholders including financial institutions, insurers, flag administrations, national maritime administrations and cargo owners expect ship owners and classification societies to carefully manage the risks inherent with this type of transport. In the past, it was widely held that a minimum compliance approach was deemed sufficient due diligence. However, increasing societal concerns led by political interests and the media suggest that a minimum compliance stance in relation to damages to the marine environment will be harder to defend in the future.

- The comprehensive literature review carried out in chapter 2 clearly identified the principal threats and challenges facing those responsible for adequately maintaining hull integrity of large tank ships. Most past accidents related to structural failures not directly caused by navigational error, have involved corrosion and/or structural fatigue phenomena. There is a great deal of evidence to suggest that business interests alone should not be the prevailing consideration, and that the structural integrity of large tank ships involves a wider obligation to the international community on the part of the ship owner.

- The trend towards performance based safety standards away from the certification model suggests that bulk transport by sea (a high risk industry), should not continue to depend solely on a framework of prescriptive rules and minimum standards set by the international classification societies. The hull safety case for large oil tankers would seem to be a paradigm worthy of further investigation and a logical step forward in the transition from a fully prescriptive methodology to a combined system integrating the existing rules, placing the risk creators in the leading role. Structural failures account for only 12% of the total; however, it is believed that the hull structures question is disproportionately important in the safety equation.

- In section 1.2, objective no.5 was to examine the applicability of the offshore safety case approach in the context of large bulk ship structures using a structural selection framework to evolve the arguments for a hull safety case. The work conducted in this chapter completes this objective. The safety case approach to hull maintenance subservient to the existing International Safety Management (ISM) Code and evolving from the recommended performance based ship structural design method is an improved paradigm, which addresses many of the shortcomings identified in the present systems.

# Chapter 8: Conclusions and Implications

***SUMMARY***

*This chapter summarises the main findings and conclusions from the study and how the objectives and sub-objectives are satisfied in the research. The limitations are discussed and an outline of suggestions for future research is presented.*

## 8.1 Introduction

The wide-ranging literature search conducted in chapter 2 was intended to holistically examine the current safety systems governing the design, construction and operation of large bulk vessels including VLCCs and VLBCs, with a focus on the hull structural design. The history of recent bulk carrier and oil tanker casualties was the principal motivation and driver for the research effort. Concerns expressed by industry insiders at the perceived low quality of current structural designs was also considered to be worthy of investigation.

In chapter 3, section 1.2, the third research sub-objective was dealt with i.e. to analyse the current approach to ship procurement and structural design quality, and the existing knowledge of the use of risk-based approaches to hull structures integrity. This formed the second phase of the evidence building needed to support the principal research objective, hypothesising that the buyer can effectively enhance the quality, safety and performance of VLCC/VLBC hull structures by managing risks at the design stage. This led to research objective no.4 which was to formulate examples of numerical and qualitative input data to test the novel structural selection framework proposed, developed and validated in chapters 4, 5 & 6. Arising from the foregoing studies, objective no.5 which was to examine the applicability of the offshore safety case model to the hull structures question was subsequently fully developed in chapter 7.

## 8.2 Main Findings

- Large bulk ships including VLCCs and VLBCs of around 300,000dwt capacity are the largest mobile man-made structures in existence. Their structural components have a multiplicity of function and they are sensitive, complex and highly utilised in terms of their load carrying ability relative to their structural mass. These structures rely heavily on the substantial plastic reserve characteristics of plated grillages in order to create a significant strength reserve.

- The residual stresses inherent in modern welded construction and the geometrical complexity of the internal structural arrangements, complicate attempts to accurately determine dynamic stresses at the localised level experienced by individual structural elements.

- Compared to offshore structures, large bulk ships are designed with markedly reduced safety factors and levels of reliability than their offshore counterparts. The requirement for a design check for the accident limit state (ALS) or threshold-type loading for ships is waived, based on the assumption that the operator can take avoidance action in severe weather.

- It is often stated that ship structures are highly redundant with multiple failure paths such that a high level of safety is ensured. However, in double hull tankers in the sagging mode, the onset of buckling of the deck structure occurring in some cases below the allowable total bending moment limit set by the authorities, can significantly reduce the overall collapse response. Allowable stress design (ASD) may be non-conservative for buckling failure of the deck structure in double hull tankers, or the bottom structure in bulk carriers as highlighted in recent research.

- The option of designing *safe-life* structures has proven to be inefficient and uneconomical for contemporary ship designs due to the excessive steel weight required. For maximum structural efficiency and optimisation of economy in the design, the higher strength to weight ratio of HTS steels are utilised, although recent problems associated with fully HTS designs have limited the HTS content to around 35% in DH tankers.

- The *fail-safe/damage tolerant* approach is the basis for contemporary large bulk ship structural designs, wherein it is assumed that undetected flaws of small size will not lead to significant structural consequences. The underlying assumption in this approach is that cracks of detectable length (critical flaw size) will be found during regular calendar based surveys in tanks (every 2.5 years). Because the crack initiation period in as-welded steel joints is insignificant due to the existence of welding defects, crack growth is initiated in the very early stages of the structural lifetime. The underlying weakness in the *fail-safe/damage tolerant* approach lies in the practical difficulties involved in the effective internal inspection of large vessel structures (tanks and cargo holds), and this problem has been borne out by the number of incidents involving undiscovered structural failures reported in the literature survey conducted in chapter 2. Because the majority of ship structures are fabricated from material without guaranteed fracture toughness values (A-grade normal and higher strength steels), the critical defect size is much reduced, highlighting the importance of and over reliance on structural inspections to find flaws before they propagate in a brittle manner.

- Despite limitations on the effectiveness of inspections to detect flaws, and to guarantee safe structures, the maritime industry has only explicitly addressed the fatigue problem in the design of large bulk ships after 1990. There are concerns that the standard minimum compliance approach to current fatigue design may not be sufficient to ensure reliable and robust structures.

- Current structural standards including the recent CSR for tankers fail to account for the combined effects of springing and whipping in fatigue design. These phenomena contribute towards up to 50% of the total fatigue damage for large bulk ships, and many warnings have been given in the past. The failure to address these effects in current structural design rules including the CSR has been a long standing complaint from sectors of the industry, most recently by the Greek bulk shipping community (IACS, 2006a).

- Large ships are exposed to random loads of probabilistic nature, making the prediction of the response to the loads complex. The controlling load forms are the result of operating in waves. Current design criteria for vessels with length of 300m consider significant wave heights of less than 11.0m, when significant wave heights in excess of 11.0m may be encountered thousands of times during the vessel's lifetime. Critics have suggested that there is prima facie evidence for an in-depth examination of the adequacy of the IACS unified probabilistic wave bending moment standard UR S11 for large tankers and bulk carriers.

- The principal structural hazards affecting large bulk ships are corrosion and fatigue. Water ballast tanks in oil tankers and bulk carriers represent the highest risk areas, and the integrity of coating systems is of paramount importance in ensuring structural integrity. Prior to the introduction of the PSPC convention, ballast tank coating systems commonly failed between 5-10 years after the vessels were delivered. Steel wastage in ballast tanks was, until recently, permitted up to a maximum of 18% of the gross scantling thickness. Accelerated wastage of steel surfaces in uncoated tanks due to early failure of protective coatings, coupled with reduced scantlings, higher stresses, and rapidly increasing corrosion-induced fatigue failure was the latent and underlying root cause of many accidents, and undoubtedly many bulk carriers were lost in mysterious circumstances, possibly due to a similar chain of events.

- The use of high tensile steel as an alternative to normal strength steels in hull structures has culminated in optimised designs with associated cost advantages. However, reduced thicknesses, higher stresses, spalling of coatings and accelerated corrosion and fatigue fractures have made HTS rich designs controversial. These options are particularly sensitive and require more intensive maintenance effort to avoid the domino effect.

- During the 1980s, some ship owning interests took advantage of high freight rates and low operating costs to maximise profits. Their reputation and safety standards were regarded to be of secondary importance, giving huge benefits for least costs. Speculators driving the market were not interested in ship condition. These circumstances led to the sub-standard ship syndrome. Leading shipping companies maintaining good technical condition and well qualified crews were not able to compete on this basis.

- The loss of the oil tanker *Erika* in December 1999 raised the alarm on clean ballast tank (CBT) oil tankers converted to hydrostatically balanced loading (HBL) or segregated ballast tank (SBT) mode, and the dangers inherent in uncoated sea water ballast tanks adjacent to heated crude oil cargo tanks. The *Erika* disaster was the trigger for world-wide efforts within the maritime community to improve the performance of tanker and bulk carrier hull structures. The subsequent loss of the *Prestige* 3 years later in similar circumstances re-doubled the efforts of the international maritime regulators to further tighten regulatory controls on the operation of hull structures.

- In 1993, the IMO adopted Resolution A.744 (18) and in 1995, the IMO requirements for maintenance of ship structures were shifted from MARPOL 13G into the SOLAS Convention Chapter II-1/3-1. Currently therefore, it is a statutory obligation to maintain the ship structure to classification standards, as discussed in section 2.4.3. Classification societies have become by default, keepers of the hull maintenance database.

- Commercial ship design has unquestionably been an exercise in design optimisation and profitability. Empirical methods based on accumulated experience were traditionally relied upon, and structural failures drove the development of prescriptive codes. Ship yards designing and building the product were focussed on minimisation of capital cost.

- Quality is associated with the ability to design products that incorporate characteristics and features which are optimised to meet the customer's specifications. Current commercial ships are highly optimised and this represents wise use of scarce resources. Large bulk ships represent unique made-to-order products. New tonnage is ordered across a spectrum of owners' requirements ranging from standard designs to full bespoke designs of high quality. Industry perceptions of quality are widely different, and the definition has to be linked to the buyer's expectations. In the current economic environment, productivity considerations and least cost constraints are the primary drivers for ship builders to optimise designs and lower costs. Buyers may either take a passive role in these developments and accept a baseline product as designed or exercise their options in the design process to improve the quality based on their own stated performance expectations.

- A prudent ship buyer should scrutinise the basic structural design data offered by the builder. Adequate margins on the design are expected to have far more benefit to the long-term structural robustness and quality than any other factor. Buyers of large vessels who fail to exercise their preferences through developing comprehensive performance standards and risk-based maintenance measures risk early structural failures and their consequences.

- Numerous industry critics have expressed serious concerns over the current quality of new oil tankers and bulk carriers. In an engineering sense, quality also implies performance optimisation and cost minimisation. This optimisation is not necessarily at odds with the customer's objectives provided that the specifications for design and construction are robust enough to ensure that the target safety levels are met. A balance has to be struck between structural designs optimised to the extent that the reliability, robustness and safety have been seriously compromised and designs which are grossly wasteful in terms of additional steel and cost required. In reality, the minimum standard can be used as a reference and baseline from which to work from in the structural selection problem.

- Emphasis should be directed at exercising the buyer's input into the design using a layered risk-based approach, founded upon the minimum classification and statutory standards including the goal-based CSR. This is the essential philosophy behind the proposed multi criteria decision analysis (MCDA) and evidential reasoning (ER) structural assessment framework. Capital investment decisions represent major commitment of corporate resources and can have a significant impact on the financial welfare of shipping companies. Companies can easily incorporate economic, environmental and social aspects estimated in monetary terms, by adopting suitable techno-economic decision-making techniques

- The problem with the rationally-based, computer-aided approach to ship structural design has been the underestimation of the impact of the actual stochastic loads acting on large bulk ship structures and the severity of the degradation mechanisms in relation to highly optimised ship structures, combined with improper maintenance procedures.

- Current bulk ship designs are sensitive structures which rely on increased levels of maintenance effort over the lifetime of the asset in order to compensate for the reduced safety levels incorporated in the design. This connection between quality and maintenance effort appears to be poorly understood.

- The recent introduction of common structural rules (CSR) for tankers and bulk carriers has been criticised because the allowable stresses have been increased by almost 12%, leading to safety factors that are even less favourable compared to offshore structures. Post CSR oil tanker and bulk carrier designs may not be any more robust than the previous ones. As the net increase in steel weight is marginal in most cases. However, it is reasonable to accept that incremental improvements in hull structures will arise from the adoption of risk-based principles, goal based standards and a holistic approach to safety management adopted by the IMO, although the CSR should continue to be regarded as a minimum standard. Tankers and bulk carriers designed to the new CSR rules and in compliance with the PSPC convention and corrosion margins according to CSR minimum requirements, still require careful maintenance to ensure that the protective coating systems remain intact. Failure to ensure the integrity of the coating systems will lead to pre-mature commencement of the corrosion process which is very difficult to monitor and control.

- A balance of views is always necessary between the position of the strident critic and the vested interests. However, the sensitive nature of large bulk ship structures, combined with the threats of a poorly specified and executed structural details, rapid hull degradation due to unmitigated corrosion and fatigue, and a minimum compliance approach to hull maintenance represent an irresistible conspiracy against good safety standards in an age when societal concerns for the environment are heightened.

- Quality and environmentally conscious shipping companies interested in extended vessel lifetimes and reliable structural performance are likely to have heightened expectations relative to hull robustness and durability

- While increased involvement of the IMO in ship structural standards and the wider use of risk-based techniques for the development of prescriptive class and statutory rules will undoubtedly steadily improve the performance of hull structures, there is a lack of evidence of any improved scope for the buyer's influence in the design. This major weakness in current ship design and procurement was addressed through the development of a risk-based structural assessment framework which was one of the main objectives of the present study.

- Major capital expenditure decisions like the purchase of new tonnage should be carried out on the basis of a full techno-economic evaluation, according to a comprehensive, rational and transparent procedure. Only then can the latent financial risks associated with improper tradeoffs in the list of technical options be properly anticipated.

- The transportation of crude oil and products in large bulk vessels represents a serious environmental hazard. Industry stakeholders including financial institutions, insurers, flag administrations, national maritime administrations and cargo owners expect ship owners and classification societies to carefully manage the risks inherent with this type of transport. In the past, it was widely held that a minimum compliance approach was deemed sufficient due diligence. However, increasing societal concerns led by political interests and the media suggest that a minimum compliance stance in relation to damages to the marine environment will be harder to defend in the future.

- Most past accidents related to structural failures not directly caused by navigational error, have involved corrosion and/or structural fatigue phenomena. There is a great deal of evidence to suggest that business interests alone should not be the prevailing consideration, and that the structural integrity of large tank ships involves a wider obligation to the international community on the part of the ship owner.

- The trend towards performance based safety standards away from the certification model suggests that the transport of bulk cargoes by sea (a high risk industry), should not continue to depend solely on a framework of prescriptive rules and minimum standards set by the international classification societies. The hull safety case for large oil tankers would seem to be a paradigm worthy of urgent further investigation and a logical step forward in the transition from a fully prescriptive methodology to a combined system integrating the existing rules, placing the risk creators in the leading role. It is believed that the hull structures question is disproportionately important in the safety equation.

- The present ISM Code contains vague and imprecise references to establishing safeguards against all identified hazards. Further weaknesses include lack of specificity within the safety management system, in relation to requirements for the identification of safety critical elements.

- The safety case approach to hull maintenance subservient to the existing International Safety Management (ISM) Code, and evolving from the recommended performance based ship structural design method, is believed to be an improved paradigm, which addresses the shortcomings identified in the present systems.

## 8.3 Main Conclusions

The principal research objective stated in section 1.2, was to build evidence confirming that the customer could effectively enhance the quality, safety and performance of large bulk ship structures by managing risks at the design stage using a novel structural selection framework, evolving the arguments for a hull structures safety case as an outcome from the selection process, and to demonstrate how the safety case can be successfully applied to the technical management of these types of ship structures.

The 1st research sub-objective was to review the safety management systems affecting VLCC/VLBC hull structures, and to identify the need for an improved management of ship safety. The 2nd research sub-objective was to analyse selected casualties in order to reveal possible root causes associated with inadequate quality in structural design or maintenance procedures. In meeting sub-objective no's 1 & 2, it was hypothesised that the current levels of safety and performance of hull structures in oil tankers and bulk carriers can, and should be improved by identifying weaknesses in the contemporary ship design process and the existing regulatory systems through a comprehensive review and analysis of the hull structures question, including recent structural failures. The findings from the published literature search performed in chapter 2, and listed in section 8.2 validated the above hypothesis.

The 3rd research sub-objective was to analyse the current approach to ship procurement and structural design quality and existing knowledge of the use of risk-based approaches to hull structures integrity. In chapter 3, it was revealed that modern commercial ship design is fundamentally an exercise in design optimisation and profitability. Ship yards designing and building the product are focused on minimisation of capital cost. Current commercial ships are highly optimised and this represents wise use of scarce resources. New tonnage is ordered across a spectrum of owners' requirements ranging from standard designs to full bespoke designs of high quality. Industry perceptions of quality are widely different, and the definition has to be linked to the buyer's expectations. Buyers may either take a passive role and accept a baseline product, or exercise their options in the design process to improve the quality based on their own stated performance objectives. A prudent ship buyer should scrutinise the basic structural design data offered by the builder. Adequate margins on the design are expected to have far more benefit to the long-term structural robustness and quality than any other factor. Buyers who fail to exercise their preferences through implementing performance standards and risk-based maintenance measures risk, early structural failures and their consequences.

The 4th research sub-objective was to articulate a set of structural performance criteria based on the MCDA approach, which could be used to compare alternative VLCC/VLBC structural design options. To solve the MCDA problem, an established methodology involving the evidential reasoning (ER) algorithm together with the evidence combination rule of the Dempster-Shafer (D-S) theory, was selected as the basis for the framework. The method was demonstrated and validated using an example involving selection between 4 similar VLCC structural designs. In meeting research sub-objective no 4, thereby, the MCDA/ER framework provided the means to incorporate the customer's preferences directly into the design process.

The 5th research sub-objective was to examine the applicability of the offshore safety case in the context of hull structures using the above selection framework to evolve the arguments and evidence needed for the safety case. The findings listed in section 8.2 arising from the published literature search and critical review carried out in chapters 2 & 3, provided a body of evidence suggesting that the quality, safety and performance of large bulk ship structures, can be influenced by the buyer at the design stage, by systematically managing risks. The mechanism for achieving this goal is the MCDA/ER structural assessment framework developed in sections 4, 5 and 6 of the study. The procedures incorporated into the framework, comprise the elements of a formal safety assessment, including hazard identification, risk assessment and cost benefit analysis.

The main conclusions from the research effort can be summarised and are listed as follows:

- The specific findings listed in section 8.2 arising from the wide-ranging published literature survey performed in chapter 2 and conducted as the basis for this research, address a number of systemic problems identified in the adequacy of the current safety systems governing the design, construction and operation of hull structures for large bulk ships. Numerous industry critics have expressed concerns over the current structural quality of new oil tankers and bulk carriers. Some of these concerns have been critically examined and validated and these findings have contributed to the objectives in this research.

- Current commercial ships are highly optimised although this is believed to represent wise use of scarce resources. New tonnage is ordered across a spectrum of owners' requirements. Industry perceptions of quality are widely different, and the definition has to be linked to the buyer's expectations. Productivity considerations and least cost constraints are the primary drivers for ship builders to optimise designs.

- In an engineering sense, quality also implies performance optimisation and cost minimisation. This is not necessarily at odds with the customer's objectives provided that the specifications for design and construction are robust enough to ensure that the target safety levels are met. A balance has to be struck between structural designs optimised to the extent that the reliability, robustness and safety have been seriously compromised, and designs which are grossly wasteful in terms of additional steel and cost required. In reality, the minimum standard can be used as a reference and benchmark to work from in the structural selection problem.

- The MCDA/ER structural assessment framework described, developed and validated in this research, is a process which provides a logical method for the buyer to exercise preferences to ensure that a simple and effective risk-based design for safety approach is adopted to ensure that sufficient safety margins are incorporated into the design.

- The MCDA/ER model is a means for the buyer of new tonnage to perform layers of risk assessment founded upon the pre-existing classification and regulatory prescriptive framework. Conducting proactive risk-assessment described in this research as part of the evolving design review process will empower an owner's team with the knowledge required to properly manage the decisions required to effectively maintain the asset during its lifetime.

- The use of multiple criteria decision analysis (MCDA) for evaluation of ship structures is rare in the literature, and this is associated with the difficulty in applying such methods. MCDA relies on articulation of an appropriate set of techno-economic evaluation criteria capable of dealing with both qualitative and quantitative criteria, and incomplete information. A set of 35 such criteria were identified and used to construct an appropriate assessment hierarchy. This research therefore represents a novel approach to the structures problem.

- The MCDA/ER framework is part of a holistic risk-based proactive approach to safety management of large VLCC/VLBC hull structures. The IDS model provides a simple and effective means of ranking options in order of preference on the basis of utility. The IDS model easily allows rapid assessments and trade offs to be made based on the set of qualitative and quantitative criteria articulated in this study, and is capable of dealing with sometimes incomplete or partial data. Capital investment decisions represent major commitment of corporate resources and can have a significant impact on the financial welfare of shipping companies. Companies can easily incorporate economic, environmental and social aspects estimated in monetary terms, by adopting suitable techno-economic decision-making techniques. The IDS model represents a flexible, transparent methodology for preference seeking amongst alternatives which should be prioritised for further assessment, making it suitable for presentation to shareholders, boards and other interested parties.

- Validity of the MCDA/ER framework was tested according to the principles of the validation square in section 6.4.3, by building confidence with respect to a purpose and socially justifiable belief in the usefulness of the method.

- The natural evolution of the hull structures safety case as an outcome of the MCDA/ER structural design assessment framework is the basis for an improved systematic approach to technical management of VLCC/VLBC structures in the operational phase. The procedures described in the research fulfil the requirements for a proactive risk-based approach to maintenance implicit in the ISM Code. The safety case paradigm selected was the Australian offshore (NOPSA) safety case described in chapter 7, due to its relevance and simplicity. A computerised hull planned maintenance system was considered an essential element in the proposed safety case, founded upon pre-existing class and statutory rules.

In closing, this research effort identified a need to develop a simple and effective attention directing tool which would allow a buyer of new VLCC/VLBC tonnage to make rapid preliminary assessments of structural design options prior to signing of the new building contract. This is a problem characterised by multiple and often conflicting criteria, incomplete data and subjective judgements. The problem involves consideration of both technical and economic criteria. An established methodology involving multiple criteria decision analysis (MCDA) and the evidential reasoning (ER) algorithm was chosen because of its flexibility and capability of modelling numerical data and subjective assessments under uncertainty, often involving incomplete information. The MCDA/ER structural assessment framework incorporates a set of evaluation and belief degrees which are well suited to deal with the subjective judgements involved.

## 8.4 Research Contribution

The published literature survey and the critical review conducted in chapter 2 with the findings listed in section 8.2, represent a broad outcome of the attempt to critically examine specific criticisms directed at the current safety management system pertaining to the safety of large bulk ships structures. An independent objective approach was undertaken to carefully examine these claims, and a number of findings emerged to indicate that a weakness exists in the current system. There appeared to be an over reliance on a prescriptive minimalist approach. This was confirmation for the hypothesis that the current safety systems could be improved by focusing on the buyer's input into the design process.

The research work attempted herein, represents a new and novel application of the evidential reasoning method to the hull structures problem. There has traditionally been a lack of a suitable framework allowing the buyer of new VLCC/VLBC tonnage to conduct rapid preliminary risk-based structural appraisals. The method proposed would allow the buyer's team to systematically engage in the design review process as a basis for forward planning of hull maintenance through the life of the asset. Thereby, the owner is encouraged to take ownership of safety which is consistent with the proposed safety case philosophy. The proposed MCDA/ER framework is believed to address this need by providing a significant and original contribution towards the solution of this problem.

## 8.5 Limitations

The MCDA/ER structural assessment framework developed and validated in this study is not intended as a commercial tool in its present form. Usefulness will depend upon further review and development. It must be made clear that for the purpose of building and testing the model, notional data was used, although based on numerical and qualitative data and information obtained as part of the published literature survey. Therefore the utility values obtained in chapters 5 & 6 should not be construed as real-world data. The purpose of this research was to develop a framework for comparing alternative structural designs, build the model and demonstrate it.

In developing the model, no suitable benchmark was found in other published work. Therefore, the author informally sought the opinions of a number of experts and naval architects involved in the field of ship structures. However, articulating the main criteria and constructing the assessment hierarchy occurred over a lengthy period of time, and was an evolutionary process, based on a limited expert input. However, the selection of the 35 sub-criteria and the basic structure of the model were founded upon information identified from various sources in the published literature including the

Ship Structure Committee (SSC), and the practical experience of the writer. Therefore the model is considered to be valid, reasonable representative and technically sound.

## 8.6 Future Research

A number of areas have been identified where future research can be conducted based on the results of this research effort. In relation to the IDS model, future research may involve formally inviting expert opinion from a number of industry practitioners as a basis for modifying and improving the evaluation criteria and the hierarchy in the IDS model. The criteria developed in this research are considered to be a suitable benchmark and starting point. One aspect of the MCDA/ER framework presented here requiring further investigation, is the current complexity of the model. A total of 35 sub-criteria were chosen to adequately capture the key considerations articulated in chapter 4. For commercial applications, the number of criteria may have to be reduced for simplicity.

Arising from the findings conducted in part of this study, namely the criticisms raised by the Greek shipping industry commentators highlighted in section 2.3.3 bear further investigation. Their concerns were related to the adequacy of the corrosion margins adopted in the new CSR rules. Opinions were expressed claiming that these margins should be doubled in Panamax bulk carriers. The MCDA/ER framework provides a suitable opportunity and a convenient platform to test these claims, based on the relevant input data. It is recommended that an independent research project investigating this aspect of structural design should be undertaken. This should involve complete lifecycle aspects and environmental considerations.

In the present study, 7 common grades were used throughout, and the utility function used in the IDS model was assumed to be linear, ranging from 0 to 1.0. In the IDS model other non-linear utility functions may be used, and this is an area requiring further investigation. More appropriate grading systems can also be adopted to deal with individual assessment criteria described in a number of the referenced studies related to the ER method.

Ranking reversal phenomena common to MCDA applications, encountered and discussed as part of the sensitivity studies conducted in chapter 6, should be further investigated. This is considered to be a key aspect of future research as the rankings are greatly affected by a change in the range of attributes. Attribute independence should also be investigated as some of the criteria chose for the model are not truly independent. Four subject areas have been preliminarily identified arising directly from this work as future research paper topics:

1. A literature review of conventional hull structural safety management systems affecting large bulk ships.
2. Ship procurement, structural design quality, and a risk-based approach to hull structural integrity.
3. A novel decision-making framework for selecting a VLCC structural design based on multiple criteria.
4. Arguments for a hull structures safety case.

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