Apostolos D. Papanikolaou
Editor

Risk-Based Ship Design

Methods, Tools and Applications

Springer

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Preface

Risk-based ship design is a new scientific and engineering field of growing interest to researchers, engineers and professionals from various disciplines related to ship design, construction, operation and regulation. Applications of risk-based approaches in the maritime industry started in the early 1960s with the introduction of the concept of probabilistic ship's damage stability. In the following, they were widely applied within the offshore sector and are now being adapted and utilized within the ship technology and shipping sector.

The main motivation to use risk-based approaches is twofold: implement a novel ship design which is considered safe but – for some formal reason – cannot be approved today and/or rationally optimise an existing design with respect to safety, without compromising on efficiency and performance.

The present book derives from the knowledge gained in the course of the project SAFEDOR (Design, Operation and Regulation for Safety), an Integrated Project under the 6th framework programme of the European Commission (IP 516278). The topic of SAFEDOR is risk-based ship design, operation and regulation. The project started in February 2005 and will be completed in April 2009. Under the coordination of Germanischer Lloyd, 52 European organizations – representing all stakeholders of the maritime industry – took part in this important R&D project.

The present book does not aim to be a textbook for postgraduate studies, as contributions to the subject topic are still evolving and some time will be necessary until maturity. However, as the topic of risk-based design, operation and regulation is almost absent from today's universities' curricula, the book aims to contribute to the necessary enhancement of academic curricula to address this important subject to the maritime industry. Therefore, the aim of the book is to provide the readers with an understanding of the fundamentals and details of the integration of risk-based approaches into the ship design process. The book facilitates the transfer of knowledge from the research conducted within the SAFEDOR project to the wider maritime community and nurtures inculcation upon scientific approaches dealing with risk-based design and ship safety.

The book is introduced by an overview of risk-based approaches to the maritime industry in Chap. 1 by Dr. Pierre C. Sames (Germanischer Lloyd). The risk-based ship design, related concepts and a passenger ship case study, presented by Professor Dracos Vassalos (Universities of Glasgow and Strathclyde), are following in Chap. 2. The risk-based maritime regulatory framework and developments of Formal Safety Assessment are presented by Dr. Rolf Skjong (Det Norske Veritas) in Chap. 3. The risk-based approval process is outlined in Chap. 4 by Mr. Jeppe Juhl (Danish Maritime Authority). In Chap. 5, a variety of methods and tools to address critical design and operation scenarios are elaborated by Professors Jørgen Jensen (Technical University of Denmark), Carlos Guedes Soares (Instituto Superior Tecnico, Lisbon) and Apostolos Papanikolaou (National Technical University of Athens). Finally, in Chap. 6, three risk-based ship design case studies are elaborated, namely the first on the design of a lightweight composite sandwich superstructure of a RoPax ship by Mr. Dag McGeorge (Det Norske Veritas), the second on the design of an AFRAMAX oil tanker by Professor Apostolos Papanikolaou (National Technical University of Athens) and the third on the design of a fast RoPax vessel by Dr. Andrzej Jasionowski (Safety at Sea, Glasgow) and Mr. Esa Pöyliö (Deltamarin, Finland).

The target readership of this book is engineers and professionals in the maritime industry, researchers and post-graduate students of naval architecture, marine engineering and maritime transport university programs. The book closes a gap in the international literature, as no other books are known in the subject field covering comprehensively today the complex subject of risk-based ship design.

The complexity and the evolving character of the subject required the contribution from many experts active in the field. As editor of this book, I am indebted to the authors of the various book chapters reflecting their long time research in the field. Also, the contributions of the whole SAFEDOR partnership to the presented work and the funding by the European Commission (DG Research) are acknowledged. Finally, the support of Dr. Eleftheria Eliopoulou (National Technical University of Athens) in the edition of the book is acknowledged.

Athens, Greece *Apostolos Papanikolaou*

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Chapter 1
Introduction to Risk-Based Approaches in the Maritime Industry

Pierre C. Sames

Abstract Methods of risk and reliability analysis gain more and more acceptance as decision support tools in engineering applications. Integration of these methods into the design process leads to risk-based design. Ship safety is well regulated at United Nations' level by the International Maritime Organization (IMO) and a tendency to move from prescriptive to goal-based regulations is seen today. In parallel, advances in technology and the need to develop ever more economic maritime solutions drives innovation and risk analysis is becoming a central element for the development of novel ships. Therefore, an enhanced ship design process integrating risk analysis was conceived over the last decade and appropriate additions to the regulatory framework were recently developed. Today, all main elements of risk-based ship design and approval are being developed and early applications demonstrate their feasibility in practice.

1.1 The Need for Risk-Based Design

1.1.1 Societal Expectations and Economic Attractions

Sustainable development related to the welfare and safety of people and to conservation of the environment have been the subject of increasing concern to society during the last decades. At the same time, optimal allocations of available natural and financial resources are considered very important. Therefore, methods of risk and reliability analysis in various engineering disciplines, developed during the last decades, are becoming more and more important as decision support tools in engineering applications. Integration of risk and reliability analysis methods into the

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design process leads to “risk-based design”. As applied to the design of ships, risk-based design and approval was introduced by Bainbridge et al. (2004) and is the focus of this book.

Innovation in the transportation industry (aerospace, automotive and rail industry) has to a large extent been driven by safety. As an example of the automotive industry, crash-performance tests of independent authorities have shown to customers that large vehicles with integrated crash energy dissipating elements, airbags for side or frontal impact protection etc. provide increased safety in accidents. On the other hand, ship safety is well regulated at United Nations’ level by the International Maritime Organization (IMO) instead of relying on individual manufacturers’ or national administrations’ responsibility for safety. However, the development of maritime safety regulations has until recently been driven mainly by individual events instead of a pro-active and holistic approach. Every major catastrophic accident, in particular those in the industrialized world, has led to a new safety regulation and subsequent design measures imposed by the IMO and the classification societies. Today however, a clear tendency to move from prescriptive to goal-based regulations is emerging.

Changes in scientific and technological developments at an ever increasing pace and an overall better technical capability at a much larger scale are fuelling innovation in the shipping sector to meet the demand for larger, more complex and specialized ships. This is taking place in an environment that is still fragmented, undermanned and intensively competitive, while society is more demanding on issues related to human safety and the protection of the environment. Safety could easily be undermined and the consequences could be disastrous. Therefore, the way safety is being dealt with is changing and with the adoption of holistic and risk-based approaches to maritime safety, balancing the elements affecting safety cost-effectively and throughout the life cycle of the vessel, safety will be dealt with as a key aspect with serious economic implications rather than a simplistic add-on in the design process seeking compliance with prescriptive regulations.

Fuelled by expected continuous growth of maritime transport and the need to provide sustainable shipping, economic opportunities drive proposals for ever more innovative ships and shipping concepts. Recent examples include cruise ships with huge shopping malls inside the superstructure and compressed natural gas transporters. With risk-based approaches firmly established in the maritime industry, ship owners will be able to implement those innovative ships and maritime transport solutions which (partly) cannot be approved today because of the current rules and regulations’ prescriptive limitations. Shipyards and equipment manufacturers will also benefit from the introduction of risk-based approaches through enabling novel and optimized ships and systems incorporating new functions and materials. The benefits arise from the fact that yards acquainted with risk-based approaches are among the first to respond to the increasing demand from ship owners for those novel ships. In addition, production costs may be reduced through application of risk-based approaches when, e.g., novel systems allow for improved modularization. Although the recent focus of applying risk-based design was to passenger ships, examples for cargo ships also exist (for example, MSC 76/INF.15 and MSC 82/23/3).

1.1.2 An Enhanced Design Process

Risk-based ship design introduces risk analysis into the traditional design process aiming to meet safety objectives cost effectively. This is facilitated by use of advanced computational tools to quantify the risk level of a particular design and its variants. Risk is used to measure the safety performance. With safety becoming measurable, the design optimization can effectively be expanded and a new objective – minimize risk – is addressed alongside traditional design objectives relating to earning potential, speed and cargo carrying capacity. It is expected that with the introduction of safety as an objective into the design optimization process rather than being treated as a constraint, new technical solutions will be explored: the design solution space becomes larger.

Even though, deriving from the above, risk-based design is principally associated with introducing safety objectives explicitly in the design process; two clearly distinct motivations for risk-based design could be identified. First, it is the realization of an idea for a new transport solution which challenges (possibly outdated) rules – meaning that the new solution cannot be approved. Risk-based design and approval are then used to identify the issues and prove that the new solution is at least as safe as required. A requirement can be either based on a reference vessel or defined by specified risk acceptance criteria. This approach is exemplified within regulation 17 of SOLAS-II.2 on fire safety. This first variant of risk-based ship design has become widely known as "Safety Equivalence". Second, it is the optimization of a rule-compliant vessel aiming to increase the level of safety at the same costs or to increase earning potential at the same level of safety. An example for this variant of risk-based design is optimization within the new probabilistic damage stability regulations.

For both variants of risk-based design and for risk-based design in general, the same technology and frameworks are needed, which derive from the introduction of safety as an objective in the design process. First, a design methodology needs to be developed, aligned with the traditional design process that includes safety as objective and integrate any associated computational tools to quantify pertinent risks. Second, the regulatory framework must be in place to facilitate risk-based design – core elements of this are risk evaluation criteria which preferably should be agreed at IMO.

1.2 How Did It Start?

1.2.1 Probabilistic Damage Stability

Risk-based approaches in the shipping industry started with the concept of probabilistic damage stability in the early sixties, but it took more than a decade for this concept to be introduced in the SOLAS regulations (SOLAS74) as an alternative to deterministic damage stability regulations. SOLAS II-1, regulation 25, indicates that alternative arrangements are acceptable if at least the same degree of safety as represented by the deterministic damage stability regulation is achieved. However, each case must be reported to IMO individually. Resolution A.265 (VIII) defines subdivision and stability of passenger ships in terms of the probabilistic concept as an equivalent to the regulation 25 of SOLAS. The rules require that an attained subdivision index A is larger than or equal to the required subdivision index R. The subdivision index R, which has been derived by statistical analysis of the A data of ships with satisfactory level of safety, is prescriptive in nature as it depends on ship length, persons onboard and life boat capacity. No operational aspects are included in R. The attained subdivision index A summarizes the probability of flooding for each compartment or group of compartments in case of collision multiplied with their contribution to the probability of sinking.

The amendments of these rules, which have been intensively developed over the past decade, are based on the "probabilistic" method of determining damage stability. They make use of results from a detailed study of accident data collected by IMO relating to collisions. Because they are based on statistical evidence concerning what actually happens when ships collide and in view of the probabilistic nature of the approach, the new probabilistic concept is believed to be far more realistic than the previously used "deterministic" method (SOLAS 90) for passenger ships and the outdated probabilistic concept used for dry cargo ships, despite the fact that some part of the determination of A is prescriptive (and deterministic) in nature. The project HARDER (1999–2003) investigated all elements of the existing approach and proposed new formulations for the probabilistic approach to damage stability taking into account enhanced probabilistic data. The final recommendations were submitted as SLF 46/3/3. The new *harmonized* damage stability regulations for passenger and cargo ships were adopted by MSC 80 (May 2005) and are entering into force on 1 January 2009. It is expected that the new requirements will lead to ship designs incorporating novel sub-division concepts (Papanikolaou 2007).

An early application of the safety equivalence concept to damage stability was proposed for the approval procedure of alternative hull structures in line with SOLAS II-1/25, see SLF 46/INF.10. The approach addresses the critical deformation energy in case of side collision of a strengthened design compared to that of a reference double hull design complying with the damage stability calculations detailed in SOLAS II-1/25. The proposed approach introduces a prescriptive procedure into the probabilistic framework of SOLAS II-1/25. Although the target is to demonstrate an equivalent level of structural resistance, the procedure is quite strict and many details like, e.g., the generation of finite element models, material properties and structural failure criteria are fixed.

1.2.2 Offshore Industry

Within the offshore industry in Norway, risk analysis is required to be carried out since 1986 to identify risks, implement risk reducing measures, and to alert operators to the risks connected with their activities, see for example Skjong (1999). The legislation requires that the authorities be allowed having insight into the decision-making processes of the individual enterprise, including policies and target safety levels, and that they have access to all safety relevant documentation. The Petroleum Safety Authority of Norway then acts – as regulator- on situations that are considered not acceptable, but does not approve the documentation or the safety targets (as in the United Kingdom); this is the responsibility of the owner. The approach is called “self-regulatory”. The Norwegian offshore regulations are designed to reflect that the operators have full responsibility for their activities.

For the approval of offshore activities in the United Kingdom, a safety case has to be produced since 1992 for submission to the Health & Safety Executive. The primary objective of a safety case is to ensure an adequate level of safety for a particular installation, based upon the management and control of the risks associated with it. A central feature of a safety case is that the owner takes responsibility for assessing the risks associated with his installation, and for documenting how his safety management system limits those risks to an acceptable level. The safety case regime is mandatory, i.e. operations cannot legally be commenced or continued until a safety case has been compiled by the owner and submitted to the official regulator for scrutiny and approval (Peachey 1999).

A safety case will include a comprehensive description of the installation itself, and of its operation and the environment within which it operates. Risks will be quantified to the extent it is appropriate to do so. Risk acceptance criteria will be set, relevant to the installation and its operational context, and usually in accordance with the ALARP (As Low As Reasonably Practical) principle.

Typically, for a new installation, a design safety case would initially be compiled. This would subsequently be developed and expanded into an operational safety case as the installation enters service. Thereafter, the safety case would normally be subject to regular review, with updating as necessary, to take account of changing conditions, ownership, activities, modifications, etc. The effectiveness of the safety management system is usually monitored and verified by means of regular audits, and compliance with the requirements of the safety case is checked by means of inspections.

1.2.3 Structural Reliability Analysis

The development of structural reliability analysis started as a new discipline in engineering in the seventies, when it was shown that a probabilistic theory could be developed that linked reliability to rules. Structural reliability analysis represents a risk-based framework for developing and documenting rules for structures. The theory has now been continuously developed over a period of over 35 years and it is supported by standardized methods, textbooks and related software tools. The basis for the methods and terminology may be found in CEN (2002).

In the maritime area, the DNV offshore rules were the first international standards applying the new knowledge (see for example the review book on use of Structural Reliability Analysis, (Sundararajan 1995, Skjong 1995) and the review on risk and reliability in marine structures by Guedes Soares 1998). This was linked to the development of all-year offshore operations in the North Sea, which required a higher reliability level than required in the American Petroleum Institute's offshore standards for the Gulf of Mexico where offshore structures were abandoned in case of hurricanes.

In shipping there was little published systematic use of structural reliability analysis for rule development or ship design apart from the European funded research project SHIPREL which advocated the use of reliability theory in codes and proposed a reliability based format based on ultimate strength (Guedes Soares et al. 1996). Starting around 2000, new rules for the hull girder capacity of oil tankers were developed using structural reliability analysis within the so-called *Joint Tanker Project* of three major class societies which resulted in the Common Structural Rules for tankers (IACS 2006). The approach and selected results were also submitted to IMO as MSC 81/INF.6.

1.2.4 Alternative Design and Arrangement for Fire Safety (SOLAS II.2/17)

The development that resulted in SOLAS II.2, Regulation17, started already back in the late eighties with the design of the cruise ship "Sovereign of the Seas", which had an atrium, a public space extending to three or more decks, within one fire zone. The approval of this ship involved a reference to the standard for equivalent arrangements under SOLAS I/5. The atrium solutions were extended to three fire zones in the design of the cruise ship "Voyager of the Seas" delivered in 1999 and again involved equivalence considerations and reference to SOLAS I/5 (Bahamas 2001). The large RoPax/Cruise ferry "Color Fantasy" and the Ultra-Voyager-class of vessels have atria extending over four fire zones, and using the new SOLAS II-2/17 for approval. The freedom in design introduced by these regulations facilitates optimization of various design parameters. Various software tools, e.g., for analyzing evacuation performance of passenger ships, have been developed and can be used in design optimization. Guidelines are published to direct the fire engineering analysis (IMO 2001).

1.2.5 Alternative Design for Oil Tankers (MARPOL Annex I-4/19)

Regulation 19 addresses double hull and double bottom requirements for oil tankers. However, paragraph 5 of Reg.19 states that other methods of design and construction of oil tankers may also be accepted as alternatives to the requirements prescribed in Reg. 19, provided that such methods ensure at least the same level of protection against oil pollution in the event of collision or stranding and are approved in principle by the Marine Environment Protection Committee (MEPC) based on the revised interim guidelines adopted in resolution MEPC 110(49).

The guidelines provide the framework for the assessment and the oil outflow performance of the alternative design. The performance of the proposed alternative design is compared with that of a reference design which complies with the prescriptive requirements. The assessment employs a probabilistic method and utilizes damage statistics. However, the approval procedure requires as first step the *approval in principle* by the IMO-MEPC before the final design can be approved by a flag state administration. It is noted that the required preliminary approval by MEPC has effectively limited innovations in this area.

1.2.6 Special Craft

Annex 4 of the High-Speed Craft code (HSC 2004) details the procedures for failure mode and effects analysis (FMEA) for selected systems such as for directional control systems, machinery systems and their associated controls, electrical system, taking into account the effects of electrical failure on the systems being supplied, and the stabilization system. However, FMEAs are only considered as a part of a broader safety assessment and are not integrated into a whole ship analysis. Each system is analyzed as stand-alone system.

IMO (2002a) released interim guidelines for wing-in-ground (WIG) crafts which are supported in their main operational mode solely by aerodynamic forces which enable them to operate at low altitude above the sea surface but out of direct contact with that surface except for start and landing. The interim guidelines for WIG craft were developed in view of the configuration of WIG craft, which falls between the maritime and aviation regulatory regimes. The basis for the interim guidelines is risk management. Although this is a paradigm shift from the prescriptive standards forming the basis of the HSC Code, the intention was to achieve safety standards comparable to those of the 1974 SOLAS Convention. However, relevant provisions of the HSC Code have been included in the interim guidelines. This means that the interim guidelines include prescriptive requirements and risk-based issues. The safety assessment follows the established procedure of the aerospace industry (SAE 1996).

Although not many WIG craft are operated today, the interim guidelines are a good example of new rules for novel vehicles that cannot be regulated only with existing rules. The interim guidelines also showed how to combine existing elements into a new regulatory framework. The preamble of the interim guidelines stresses the fact that risk and safety levels need to be assessed on a holistic basis, recognizing that high levels of operator training, comprehensive and thoroughly implemented procedures, high levels of automation and sophisticated software can all make significant contributions to risk reduction. The general part of the interim guidelines introduces requirements related to operator management, similar to the International Safety Management code (ISM 2004) and operation limits (good weather, near place of refuge and rescue facilities available).

1.2.7 Formal Safety Assessment

Formal Safety Assessment (FSA) has been developed as tool to support decision making at IMO. Following a UK proposal in 1993, guidelines for FSA were eventually adopted for use in the IMO rule making process (IMO 2002b), following a series of trial applications according to the interim guidelines. The guidelines have been updated recently (IMO 2007). With FSA, the maritime industry followed others sectors in adopting a risk-based approach to support rule-making. FSA delivers in a transparent way the costs and benefits of proposed changes to the regulatory framework and supports decision makers at IMO. FSA comprise five interrelated steps:

1. Identification of hazards
2. Assessment of the risks arising from the hazards identified
3. Identification of options to control the risks
4. Cost/benefit assessment of the risk control options
5. Recommendations for decision making

To date, only a couple FSA studies performed within the maritime industry resulted in IMO decisions. One early application was related to the provision of helicopter landing areas (HLA) on passenger ships and the FSA showed these to be not cost-effective for non RoPax passenger ships. The requirement was eventually dropped, though many ships, including non-Ro-Ro passenger ships, have in the meantime an HLA installed. More prominent is the bulk carrier safety "story" when a couple of FSA studies were prepared which concluded, among other issues, that double skins are cost-effective, see MSC 76/23. However, this recommendation was later also not adopted. A recent FSA study on cruise vessel navigation (NAV 51/10) focused on events leading to collisions and groundings. It concluded in documenting a number of risk control options related to navigation as being cost-effective, among them ECDIS (Electronic Chart Display and Information System). A dedicated FSA study on ECDIS addressing also other ship types was performed following the FSA on cruise vessel navigation. It confirms the cost-effectiveness of ECDIS for selected cargo vessels; see MSC 81/24/5. A series of so called high level FSA studies were performed recently for main ship types as follows (with the INF-papers containing the full studies):

- Container vessels, submitted as MSC 83/21/2 and MSC 83/INF.8
- Liquefied natural gas tankers, submitted as MSC 83/21/1 and MSC 83/INF.3
- Cruise vessels, submitted as MSC 85/17/1 and MSC 85/INF.2
- RoPax ferries, submitted to MSC 85/17/2 and MSC 85/INF.3
- Oil tankers, submitted to MEPC 58/17/2 and MEPC 58/INF.2

1.2.8 Selected Recent Research Activities

Following a number of tragic accidents with RoPax ferries in Europe, research was initiated to study possible means to improve the safety of those vessels. A thematic network was established in 1997 to coordinate and align related European research projects, mainly those funded by the EU-Commission. The theme was called "Design for Safety" which called for integrating safety as an objective into the design process; and it can be seen as first version of risk-based ship design (Vassalos et al. 2000, University of Strathclyde 2003). Coordinated projects focused on development of tools to predict the safety performance in accidental conditions like, e.g., collision and grounding (e.g., Otto et al. 2001,Vanem and Skjong 2004a), bow door and green water extreme hydrodynamic loads (e.g., Sames et al. 2001, Sames 2002), loss of structural integrity (e.g., Chan and Incecik 2000), fire (e.g. Vanem and Skjong 2004b), flooding (e.g., Papanikolaou et al. 2000, Vassalos 2004), mustering and evacuation (e.g., Vassalos et al. 2001, Dogliani et al. 2004). In addition, projects developed the basics for a new design framework which integrates safety and demonstrated the integration of tools for fast optimization of ship designs. Particular attention was focused on developing a new probabilistic damage stability assessment concept for passenger and dry cargo ships that formed later the basis for the new harmonized damage stability regulations adopted by IMO. The most recent analysis, design and integration of risk-based approaches were performed for Aframax oil tankers (Papanikolaou et al. 2006). In the European research area, research into ship safety was later concentrated into the large project SAFEDOR which included also developments towards a modern regulatory framework and a large number of sample design applications for ships and ship systems (Breinholt et al. 2007b). A list of related research projects is provided in the references to this chapter.

Research into risk-based approaches took also place outside Europe, in particular in Japan and South-Korea. Kaneko (2002) presented a holistic methodology for risk evaluation of ships. He focused on prediction of collision probability and fire scenarios and showed a cabin fire as example application. An overview of current research activities in Asia is provided by Yoshida (2007). Kaneko (2007) presented an overview of approaches in risk modeling and pointed towards uncertainties involved. An ongoing development into a total risk management system was presented by Lee (2007) focusing on integrating available tools for design, regulation and operation. The system is supposed to run in real time delivering input for a simulator, too. Risks are computed using standard risk models, e.g., event and fault trees, for a number of scenarios. A database holding generic data aims to accelerate the computation.

1.2.9 Recent Regulatory Developments

Goal-based Standards (GBS) were put on the agenda of the Maritime Safety Committee (MSC), by a decision of the IMO Council (89) in 2002. The first working group on GBS was established in December 2004 at IMO, MSC 79, and the discussion resulted in general agreement of a definition of GBS, and a general five-tier system of regulations. The working group reconvened at MSC 80, MSC 81, MSC 82 and MSC 83 and three correspondence groups were active in between.

Two clearly distinct directions to GBS have emerged. First, a deterministic approach is followed which is currently piloted for bulk carrier and tanker using the IACS Common Structural Rules as subject case to finalise the verification process. This deterministic approach is not truely goal-based and has no connections to risk-based design. Second, the so-called Safety Level Approach (SLA) was introduced (MSC 81/6/2) aiming to establish a risk-based regulatory framework building on principles already known from formal safety assessment (FSA). GBS, when based on SLA, use the IMO approach to risk acceptance to define a level of acceptable reliability at any level (ship, ship function, system, subsystem or component). This facilitates the development of modern rules or regulations in a consistent, transparent and reliable manner.

At MSC 82, a new guideline on alternative design and arrangements for SOLAS chapter II-1 and III was developed and agreed to enter into force in 2009 (IMO 2006). These guidelines complement the tool set for ship designers but, unfortunately, introduce a number of new terms which were not used before. An alternative approval procedure for ship systems, fully inline with earlier published guidelines and terminology was presented by Hamann (2007).

In 2010 the new SOLAS regulations for cruise ships II-1/8-1, II-2/21 and II-2/22 will come into force. Collectively, these regulations call for a new approach to passenger ship safety, called "Safe Return to Port". Requirements for ship systems in accidental conditions like fire and flooding will be specified for the first time. The new requirements may lead to novel ship designs and higher redundancies.

1.3 A High-Level Introduction to Risk-Based Design and Approval

1.3.1 Linking Risk-Based Design and Approval

Risk-based design is considered an enhanced variant of the traditional design process and it integrates safety as additional design objective. Therefore, one additional constraint enters the design optimization as follows:

$$R_{Design} \leq R_{acceptable} \tag{1.1}$$

with R_{Design} the risk of the considered ship or system and $R_{acceptable}$ the acceptable risk. In general, risk is the product of the frequency of an event times the associated consequences. Different risk categories like, e.g., human life, environment or property, need to be distinguished

The risk of the design R_{Design} is typically the sum of partial risks coming from different accident categories like, e.g., collision, fire or grounding. Each partial risk can be computed with the help of risk models like, e.g., event trees or Bayesian networks. The choice of a risk model depends on the application. Fault trees are widely used for system analysis. Event trees and Bayesian networks have been used in FSA studies. Risk models expressed by mathematical formulae were developed for fast design optimization.

The acceptable risk $R_{acceptable}$ is specified by the approval authority (flag state administration and/or classification society) in case of human life and environmental protection. The acceptable risk related to loss of property and business is usually defined by the owner or operator, and is not considered any further in the following. Two options exist to specify the acceptable risk: relative or absolute. In the first case, a reference design is selected which complies with current rules. In the second case, IMO risk acceptance criteria are used or referenced.

1.3.2 How Risk-Based Design and Approval Work Together

Currently accepted and used risk-based design approaches are two-step approaches involving qualitative and quantitative steps (Breinholt et al. 2007a). The currently proposed risk-based approval process is also a two-step process. The qualitative step ends with a preliminary approval which documents the requirements for the full approval. The obvious question for future risk-based design is how much effort is needed upfront to explore the design solution space without preliminary approval from an approval authority. Additional activities within risk-based design and approval processes have to be aligned with existing schedules for owners, yards and suppliers. Ideally, a yard seeks to build-up complete knowledge of the expected risk analysis and its results before the contract with the owner is signed. This means that a significant amount of analysis may need to be carried out prior to the application for preliminary approval and before the detailed approval requirements are issued. On the other hand, investing too much effort before an indication of feasibility is not advisable.

Key milestones in the combined design and approval schedules are design concept, final design, letter of intent, contract, preliminary approval and final approval. It is emphasized that the alignment of these milestones will vary according to the actual case. The alignment of schedules for a smaller risk-based design case indicates that after signature of the letter of intent, the yard starts to produce a full design concept which is then previewed with the approval authority to decide whether a risk-based approval is needed or not. If needed, the qualitative phase of the design and approval is entered which concludes with the preliminary approval by the approval authority. Once the conditions attached to the preliminary approval are known – and are acceptable – the yard approaches the owner to sign the contract. Following this key milestone, a quantitative analysis is started which – together with the traditional design activities in this stage – eventually results in an approved design.

For truly challenging and larger risk-based design projects, the quantitative part of the risk assessment is most likely carried out before the letter of intent and, therefore, well before the preliminary approval. The main reason is that yards do not want the process to be interrupted by the relatively late preliminary approval. Yards ideally seek to have all issues affecting the design and approval process solved before applying for approval. It is noted in this context that one additional objective of risk-based design is to increase the knowledge about the ship design in the early design phase and, therefore, to facilitate an advance of the decision making. Thus, with advanced tools available, a risk analysis on key aspects can be performed cost-effectively before a letter of intent is signed.

1.4 What is Needed to Make Risk-Based Design and Approval Work?

1.4.1 Regulatory Framework

The regulatory framework comprises IMO regulations, classification societies' rules, regional and national regulations and industry standards. Details of a modern risk-based regulatory framework are described in Chap. 3. This includes a comprehensive review of Formal Safety Assessment developments in the shipping and other industries. The approval of risk-based design is detailed in Chap. 4.

To facilitate risk-based design and approval, three main elements are needed and most of these are already in place:

- Provisions for risk-based designs
  SOLAS I/5 and MARPOL Annex I, I/5 have the necessary provision to allow alternative designs and arrangements. In addition, alternatives are possible related to fire safety and in the near future for electrical systems and lifeboats.
- Approval procedures
  A number of IMO documents exist to guide the approval process for alternative designs. In addition, SAFEDOR developed a high-level approval process and a system-level approval process for risk-based designs.
- Risk evaluation and acceptance criteria
  The FSA guidelines detail criteria related to human life safety, addressing individual and societal risks. Risk acceptance criteria related to the environment are not yet agreed at IMO but were proposed by Skjong et al. (2006). Furthermore, all FSA studies submitted and reviewed by IMO can be used as a reference.

1.4.2 Design Framework and Tools

The design framework couples traditional design with risk-based thinking. It describes the integration of safety as an additional design objective. Risk-based design is described in detail in Chap. 2. Advanced methods and simulation tools are discussed in Chap. 5.

The toolbox of the engineer engaged in risk-based designs should comprise

- Safety-performance prediction tools
  The necessary software tools derive from the actual application. In general, tools to predict frequency and consequences for all accident categories are needed.
- Risk models
  These models also depend on the actual application. In general, fault trees may be used for system analysis, event trees and Bayesian networks in FSA studies, and risk models expressed by mathematical formulae for fast design optimization.
- Optimization platform
  As for the traditional design, optimization is required to achieve best designs. With new constraints and objectives in the risk-based design being added to the optimization problem, parametric ship models are needed, too.

1.4.3 Qualified Engineers

As with all technical disciplines, the qualification of the people involved is decisive for the economic success. Training, proper documentation and dissemination are among the issues which SAFEDOR has addressed by a variety of activities aiming to improve the qualification and knowledge base of both young and more experienced marine engineers and naval architects. This book on risk-based ship design should be understood as one basic element of the SAFEDOR training and dissemination plan.

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Chapter 2
Risk-Based Ship Design

Dracos Vassalos

Abstract This chapter aims to present an overview of risk-based design developments over the recent past and to attempt to demonstrate that substantial pre-requisite scientific and technological developments are in place for Risk-Based Design to be fully implemented in the maritime industry. To elucidate the realisation of the risk-based ship design concept through application, a variety of examples at basic and holistic levels using RoPax and cruise liners are presented and discussed in the second part of the present chapter.

2.1 Methodological Approach to Risk-Based Ship Design

Phenomenal changes in scientific and technological developments at an ever increasing pace and an overall improved technical capability at a much larger scale are fuelling innovation in the shipping sector to meet the demand for larger, faster, more complex and specialised ships. This is taking place in an industry that is still fragmented, undermanned and intensely competitive and in a society that is more vigilant and more demanding on issues pertaining to human life safety and the environment. Safety could easily be undermined and the consequences would be disastrous. This is particularly true for knowledge-intensive and safety-critical ships, such as the giants of the cruise ship industry being built today, where the need for innovation creates unprecedented safety challenges that cannot be sustained by prescription. In this state of affairs, a new design paradigm that treats safety as a design objective rather than through rule compliance (Design for Safety) and a formalised methodology capable of embracing innovation through routine utilisation of first-principles tools, thus leading to cost-effective ways of dealing with safety (Risk-Based Design) are being advocated by the EU maritime industry as the “bridge” for the emerging gap. Surprisingly, the biggest influence so far is seen at the birth place of prescription: “The future is Risk-Based” was proclaimed recently at the International Maritime Organization (IMO), the new harmonised

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probabilistic rules for damage stability, SOLAS Chapter II-1, due for enforcement in 2009, have already found a way to the design offices of major yards, application of SOLAS Chapter II-2 Reg.17 on safety equivalence is becoming almost routine and Goal-Based Standards too trendy to resist. It would seem obvious that some owners and consequentially yards and classification societies are venturing to exploit the new degrees of freedom afforded by goal-based approaches whilst others are finding it rather difficult to move away from the prescription mindset that has been deeply ingrained in their way of conceptualising, creating and completing a ship design. "Inertia" and "momentum" are not the best of friends and when they clash there is a lot of "dust". Is it all going too fast and where is it going? What is the common thread and how do we get hold of it? Total freedom it appears is hard to cope with and a helping hand is needed to guide cross the line from prescriptive to goal-setting design and regulation. Moreover, the adoption of risk-based approaches in the maritime industry is not as straight forward as it was thought and risk-assessment not as amenable to traditional naval architecture tools as rule compliance. Furthermore, the use of first-principles tools and the volume of analysis required addressing safety as a life-cycle issue within integrated design environments and holistic approaches are not meeting fertile ground among the maritime profession. Not withstanding the above and the monumental effort required to crossing this bridge, it is gratifying for all the proponents of Risk-Based Design to experience the crossing of the bridge and very rewarding to see early results that fully justify such effort. The real problem that remains is one of inculcation, education and training.

Assisting in this direction, this chapter aims to present an overview of risk-based design developments over the recent past and to attempt to demonstrate that substantial pre-requisite scientific and technological developments are in place for Risk-Based Design to be fully implemented in the maritime industry and to elucidate its realisation through application examples at basic and holistic levels using RoPax and cruise liners through a Design Story that follows this section.

2.1.1 Introduction

The need to change the way safety is being dealt with is forcing the realisation that the marine industry is a "risk industry", thus necessitating the adoption of risk-based and hence performance-based approaches to maritime safety. This, in turn, is paving the way to drastic evolutionary changes in ship design and operation. Notable efforts to respond to these developments in the marine industry led to the establishment of the first significant EU Thematic Network SAFER EURORO (1997–2001), aiming to promote a new design philosophy under the theme "Design for Safety" with the view to integrating safety cost-effectively within the design process in a way that safety "drives" ship design and operation. This in turn led to the development of a formal state-of-the-art design methodology (Risk-Based Design) to support and nurture a safety culture paradigm in the ship design process by treating safety as a design objective rather than a constraint. It also provided the inspiration and the foundation for SAFEDOR (2004 – Design/Operation/Regulation for Safety), a 20-million Euro EU FP6 Integrated Project of 4 years duration, aimed at integrating safety research in Europe and beyond and to fully implement Risk-Based Design (RBD) from concept development to approval.

Considering the above, adopting a RBD methodology that embraces innovation and promotes routine utilisation of first-principles tools will lead to cost-effective ways of dealing with safety and to building and sustaining competitive advantage, particularly so for knowledge-intensive and safety-critical ships, such as the giants of the cruise ship industry being built today; knowledge-intensive, as such ship concepts are fuelled by innovation and safety-critical as with such ship designs safety is indeed a design "driver". In this respect, the continuously increasing regard for human life and the rapid escalation in ship size (the age of mega-ships is clearly upon us and it is here to stay) have prompted thorough revision of pertinent safety standards to the extent that risk containment, in a way that public confidence is assured, has become a top agenda item at IMO. Experience finds no fertile ground to breed and the regulatory system is stretched to breaking point. Conjecture will not do, for the risk is too high. Difficult questions demand (and deserve) answers that can be measured, verified and defended. Responding to societal expectation for ship safety by setting goals that encourage zero tolerance, with regard to human life loss and environmental impact, demands close scrutiny of all the issues that could upset such expectation, first and foremost, survivability in case of a casualty. Striving to understand what is to be done and how best to achieve it led to the introduction of new "buzz" words such as "casualty threshold", "time to flood", "safe area", "safe return to port", safety level", which tend to cloud the problem at hand. Similarly, revision of safety standards demands a critical review of all pertinent issues ranging from accident causality (leading to identification of principal hazards and design scenarios), accident consequences (e.g. damage survivability and fire safety analysis) and mitigation measures, either in place historically (e.g., evacuation and rescue) or potential new measures (e.g. residual functionality of ship systems in an emergency).

But whilst the intention has been good, the pace of development has been too fast for comfort, leading to a rather unclear situation that engulfs the whole profession. The need for clarity is immediate and it is paramount. It also provides the motivation for this Chapter, which draws from developments over the past 13 years to present the current state-of-the-art on RBD as it is being applied, mainly to the cruise ship industry, and how it relates to the rule making process at IMO. The Chapter starts by briefly addressing rules-based design before delineating a roadmap to risk-based design development as a goal-setting approach that is linked directly to the IMO framework for passenger ship safety and to the more overarching and more fundamental issue of measurable safety levels through quantitative assessment of total risk. RBD implementation results at concept design level are presented where appropriate, using a generic cruise ship design, to facilitate better understanding of the methodology and of the pre-requisite scientific and technological developments necessary for such implementation.

2.1.2 The Ship Design Process

2.1.2.1 Rules-Based Design

The aim in ship design practice today is to deliver a vessel that performs in accordance with the expectations defined by the owner's operational or functional requirements while complying with the statutory rules and regulations (hence "Rules-Based Design") as well as ensuring that the construction process keeps to budget and schedule. The role of the yard in this process must not be overlooked; the fact that shipyard practice is reflected in ship design suggests that instilling a safety culture in the yard is of paramount importance in dealing with safety in ship design. A possible generic and high-level representation of the ship design process is shown in Fig. 2.1, (Vassalos et al. 2006). This representation is by no means unique or exhaustive but it will be used subsequently as a basis for underlining the expected contribution and implications of risk-based design.

As illustrated in Fig. 2.2, design input concerns "performance" expectations on one hand and on the other requirements deriving from the ship owner's own market, business and logistics analysis as well as from other expectations from pertinent stakeholders (e.g., shareholders, public opinion, charterers, customers and shipyards).

Design studies as depicted in Fig. 2.3 concern in the main design optimisation, a juggling act of many factors including among others safe operation, technical performance, preferences, cost, logistics and aesthetics. In this list, safety is not considered later than anything else, but it is limited to rule compliance and hence it is treated as a design constraint – not as a design variable satisfying set criteria. At the early design stages, where major design decisions are made and cost items assigned,

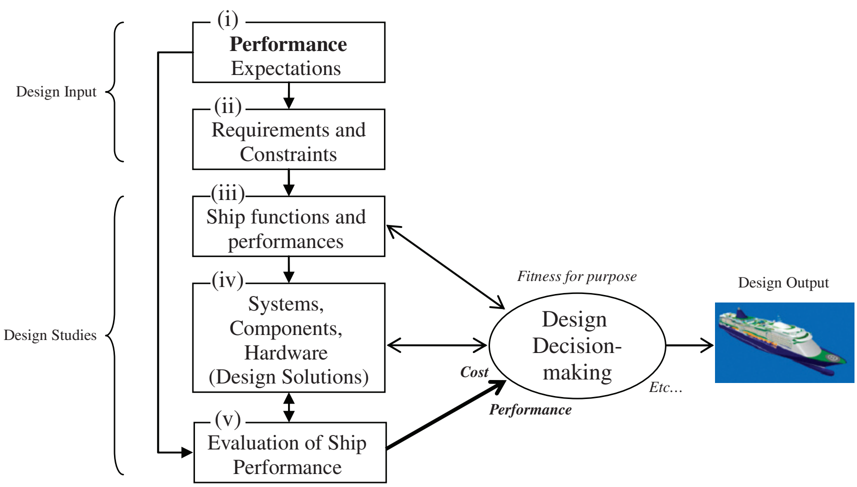

Fig. 2.1 High-level conventional design process (rules-based design)

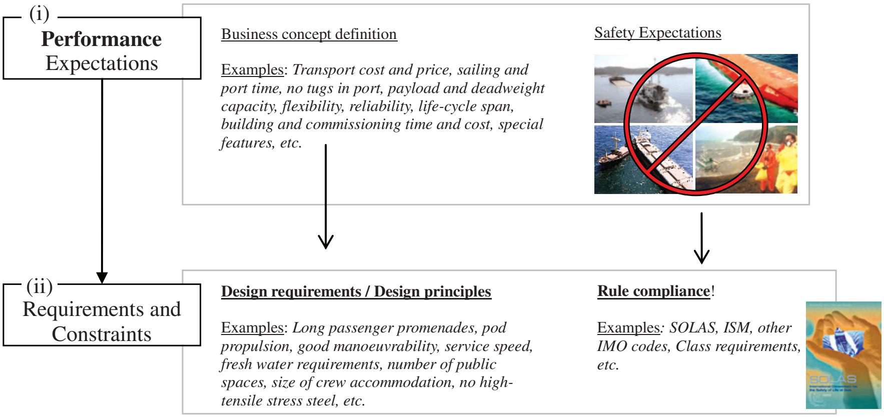

Fig. 2.2 Design input

design decision making is based mainly on the designer's experience, engineering judgment and the level of creativity possible within the prescriptive rule envelope. In rule-based design, safety performance is prescribed by rules, i.e. rules define what the safety performance parameters are and what values should be attained (design criteria). Some examples of these are listed next:

- To avoid structural failure: minimum scantlings, corrosion margins, design loads, etc.
- To avoid loss of stability: GZ-curve requirements, etc.
- To mitigate the consequences of a collision: introduce longitudinal bulkheads at B/5, A index, etc.

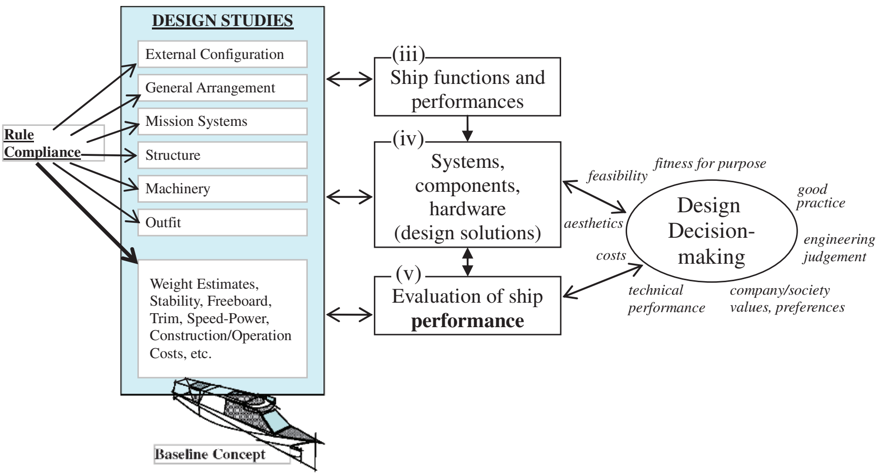

Fig. 2.3 Safety considerations

- To mitigate the consequences of grounding: double bottom extent and height, etc.
- To mitigate the consequences of a fire: fire rating $\rightarrow$ 1 h fire protection ($\Delta T_{max} = 180\,^{\circ}C$, etc.), maximum length and area of a Main Vertical Zone (MVZ) (48 m, 1600 m^2, respectively), etc.

This approach implies that development of "competitive" designs is based on the designer's competence rather than on rational and more informed bases. In so doing, more often than not, potentially good designs are not allowed to progress further as they do not comply with this or the other safety rule. As a result, this has lead to the ill-based concept that investment in safety compromises returns.

Moreover, compliance with prescriptive regulations implies absolute trust that the minimum safety level implicit in them is deemed to be appropriate for the type of vessel and operation intended; unfortunately this often proves to be conjecture. There are of course positive as well as negative sides to "rule-compliance" as outlined next:

- Rules are minimum requirements that reflect average safety, hence may not be appropriate, consistent, and/or optimal in all cases (e.g., SOLAS A.167, SOLAS'95, even SOLAS 2009).
- Most rules are developed in the wake of major accidents; as such, they are targeting to reduce consequences to appease public outrage; in some cases, emphasis or even relevance to design is all but lost.
- If the evaluated design does not correspond to the data set used to derive the rules, then the design may be unnecessarily penalised or its safety-performance might not be optimal or it might even be unsafe. For instance, would the probabilistic rules in their current form be applicable to multi-hull vessels?
- In a rule-based regime "there is no chance to beat the competitors", as advances in technology are conveyed to others by the (prescriptive) rules. On the other hand, with safety imposed as a constraint to the design process, the transfer of knowledge between the design, production and operational phases is hindered (rule evolution is too slow).
- By specifying minimum requirements, a design that fulfils a requirement by far is considered to be of the same safety level as a design that just "passes" the requirement – this is normally why designers do not achieve a balance (best compromise) and a key reason leading to the conclusion that "safety costs" or at best "safety does not pay".
- More importantly, knowledge of the actual safety level provision within prescriptive rules is missing (i.e., compliance with rules does not guarantee satisfactory safety performance). Do we know, for example, what is the risk in designing one or two compartment passenger ships, as provided in SOLAS today (see Fig. 2.4)?
- Moreover, the rule-making process is consensus-based and reflects more often than not "unjustifiable" compromises that defy the very source of knowledge, such rules derive from (experiential or statistical). For example, statistics show (see Fig. 2.5) that the B/5 longitudinal bulkhead, used in SOLAS'90 to provide protection from flooding of a ship's internal spaces in a side collision, would be breached in 45% of such collisions.

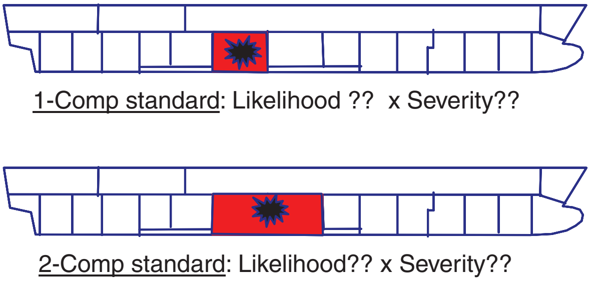

Fig. 2.4 Collision risk containment today

- Rules are however easier to fulfill and facilitate class/flag changes (desirable). They are easy to apply and easy to check for the unskilled (which is rather undesirable).

Summarising the foregoing more succinctly, the main pitfalls of rules-based design are:

- Treating safety as a constraint (rule compliance) implies that meeting safety expectations cost-effectively is left to chance.

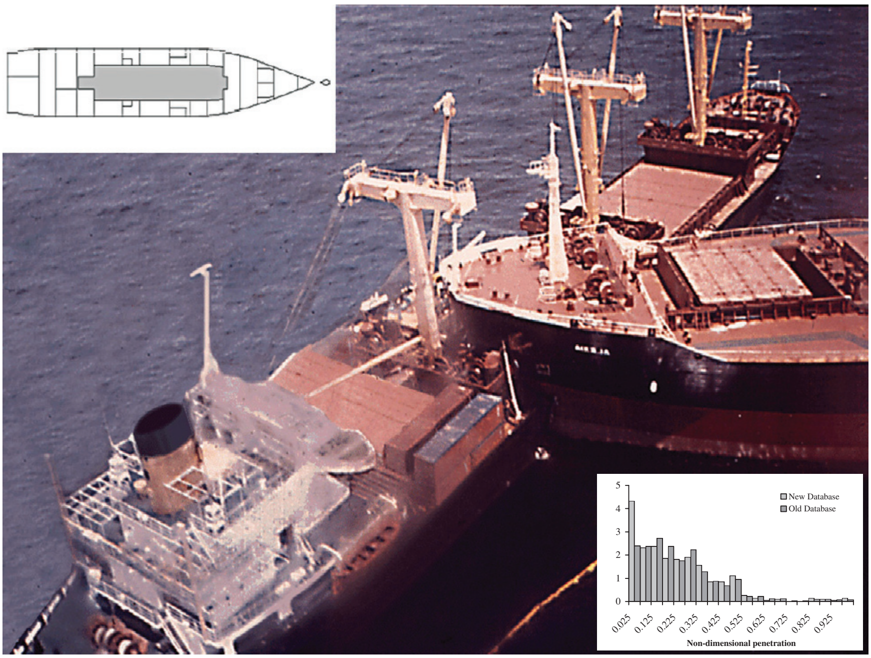

Fig. 2.5 Rules do not always reflect experience

- Incompatibility of design and performance evaluation tools, time limitations, lack of an integrated design environment; all hinder design optimisation in the design process.
- Lack of a formal optimisation process also implies that life-cycle issues (future costs/earning potential) are not being taken "explicitly" into account in design decision-making.

Despite these pitfalls, over the years, most rules have proved to "serve reasonably well" the design objectives and most changes and improvements have been the result of individual high-profile accidents (e.g., the ferry MV Estonia in 1994) or significant changes in casualty statistics (e.g. bulk carrier losses in the early 1990s and development of SOLAS Chapter XII). However, rather than waiting for an accident to happen and then act in haste to set up new rules that may even end up undermining rather than improving safety, all pertinent knowledge deriving from such accidents could be analysed and stored in a structured way and used as early as possible in the design process (as shown in Fig. 2.6), then a drastic shift of emphasis on prevention must surely be witnessed. Further more, doing so would allow for trade-offs between safety and other design factors and would lead to safer and more competitive designs.

It is indeed the concept design stage that holds the greatest potential for introducing product and safety innovations. Ship design, in particular, is uniquely characterised by the fact that some of the most important decisions regarding the vessel are taken at the early stages of the process. This allows little possibility to positively affect cost and performance in all later design actions, which are inevitably bound within the set frame prescribed by the early decisions as illustrated in Fig. 2.7. As the design process proceeds, the knowledge about the design increases while at the

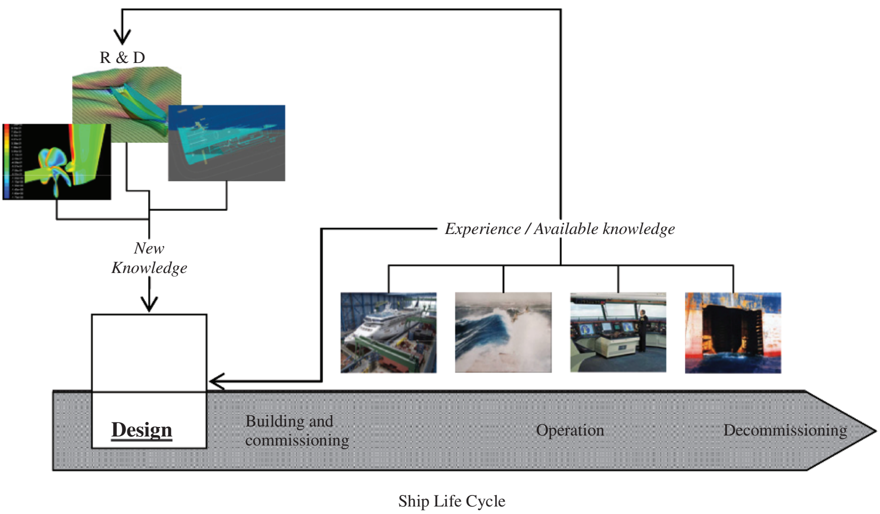

Fig. 2.6 A "common sense" approach to ship design

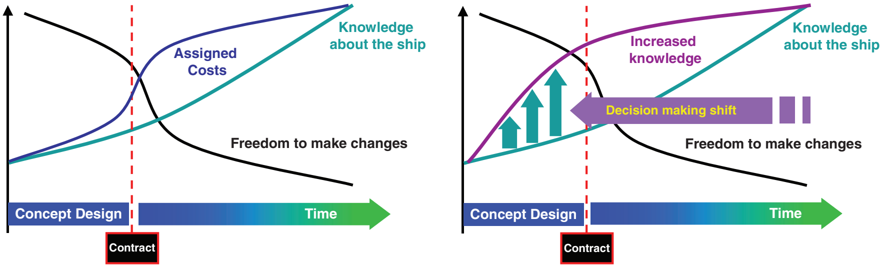

Fig. 2.7 Design decision-making shift

same time the freedom to make changes decreases due to the large costs associated with these changes. To become more competitive, a decision-making shift is required towards the pre-contract stage and hence efforts must be deployed to maximise knowledge that can be achieved only by advanced first-principles tools.

Emphasis towards approaches that use routinely first-principles calculations for explicit consideration of safety performance would allow for goal-setting and performance-based design and hence for the possibility of optimising ship performance without regulatory constraints. This would make a significant difference in ship design decision-making as the best design solution (from all relevant perspectives) may lie outside the regulatory envelope. Established optimisation tools and techniques can help the designer to explore a much wider design solution envelope (see Fig. 2.8) within the time scale available during early design concept development and beyond.

All these common sense steps provide the foundation for the adoption of "risk-based" approaches in design and operation. There is of course an added complication and a fundamental difference: the simultaneous consideration of multiple risks (major deviation from prescriptive rules and SOLAS in general) that requires a holistic approach to safety as described in the next section.

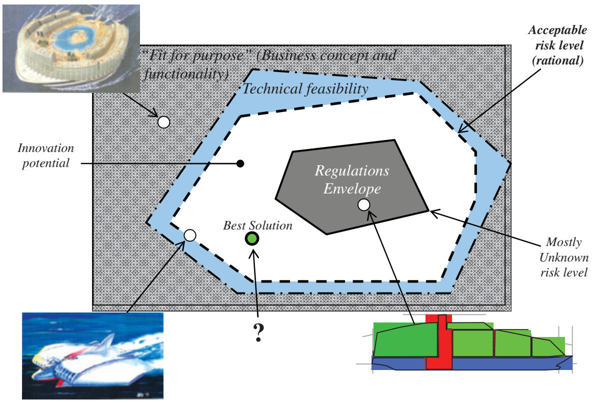

Fig. 2.8 Possible design solution envelopes

2.1.2.2 Risk-Based Design

Recent discussions at IMO concerning Goal-Based Standards have given rise to the term “Safety Level” designating the through-life level of acceptable “risk” associated with a particular ship concept and, as such, becoming the new guiding philosophy to attaining safety cost-effectively. What this entails, however, is no mean task; it is nothing less than being able to quantify the life-cycle risk of a vessel by considering all “passive” (design) and “active” (operational) safety measures and to do so during the concept design stage under extremely tight cost and time constraints. This is an enormous and exciting undertaking but the benefits will be massive and hence any investment to realise an efficient way to measure safety will be justified. The notion of “risk” is usually associated with undesirable events and with shipping operations being undoubtedly “risky”; ships should be designed with this in mind. In order to address safety explicitly, a consistent and transparent framework needs to be adopted for its provision. In this respect, explicit calculation and use of risk is considered to provide the most flexible means of setting up such a framework. Hence explicit consideration of safety is equivalent to evaluating risk during the design; hence the term Risk-Based Design. Application of RBD is biased towards design concepts with high levels of innovation (see Fig. 2.9). Hence the need to use knowledge in all its forms: best practice, engineering judgment, state-of-the-art tools and data; all part of Quantitative Risk Analysis (QRA).

The essential advance attributable to RBD is the explicit, rational and cost-effective treatment of safety. To achieve this, the following principles need to be adhered to:

1. A consistent measure of safety must be employed and a formalised procedure of its quantification adopted (risk analysis). For this to be workable, considering the complexity of what constitutes safety, a clear focus on key safety “drivers” is necessary (major accident categories). Numerous formal procedures for risk quantification, risk assessment and risk management exist in various contexts (for instance FSA in rule making, safety case for specific design/operational

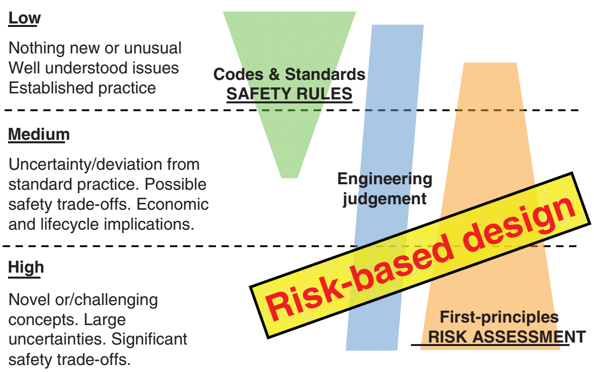

Fig. 2.9 Risk-based design and innovation

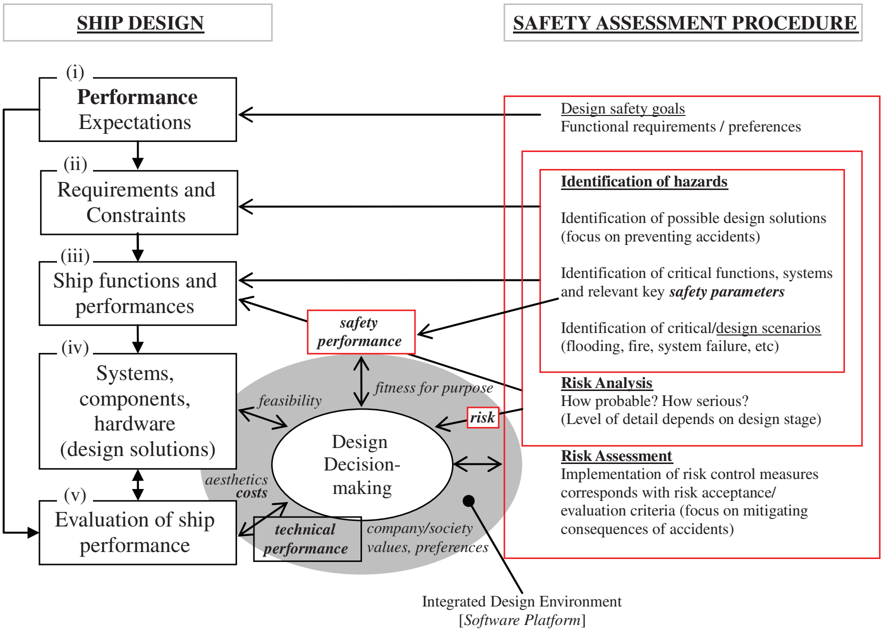

Fig. 2.10 A high level framework for risk-based design

solutions, among others). The right-hand-side of Fig. 2.10 illustrates the elements of a typical "safety assessment process".

2. Such procedure must be integrated in the design process to allow for trade-offs between safety and other design factors by utilising overlaps between performance, life-cycle cost considerations, functionality and safety. The interfaces between the ship design process and the safety assessment procedure are illustrated in Fig. 2.10. Consequently, additional information on safety performance and risk will be available for design decision-making and design optimisation.
3. Considering the level of computations that might be necessary to address all pertinent safety concerns and the effect of safety-related design changes on functionality and other performances, a different handling is required; namely, the use of parametric models to allow for trade-offs through overlaps at parameter level and access to fast and accurate first-principles tools. The design optimisation process becomes thus a typical case of multi-objective, multi-criteria optimisation problem. A common ship design model managed within an integrated design environment (software) will also be required for that process to be conducted efficiently.

The aforementioned RBD principles are reflected in the high-level definition promulgated by SADEFOR: *RBD is a formalised methodology that integrates systematically risk assessment in the design process with prevention/reduction of risk embedded as a design objective, alongside "conventional" design objectives*. Key to understanding RBD is the integration of risk assessment in the design process and decision-making towards achieving the overall design goals but also as part of a parallel (concurrent) iteration within the safety assessment procedure to meet safety-related goals/objectives, as depicted by the high-level framework of Fig. 2.10.

Related to this, key elements and implications for ship design are considered next.

Safety Assessment Procedure

In principle, the safety assessment procedure referred to above is a systematic and formalised risk assessment process, which can be carried out in a variety of ways. The selection of the right approach may be viewed in the context of the following drivers (HSE 2001):

- *Design stage*: will determine the level of flexibility to possible design changes as well as the level of design knowledge. At concept design stages (pre-contract) there is flexibility for major design trade-offs; on the other hand, there is lesser knowledge about the ship, hence risk assessment must be limited to coarser methods. The risk assessment can – of course – be refined during advanced design stages (as more design detail becomes available) and up to construction and commissioning processes.
- *Major hazard potential*: the greater the potential exposure to total loss or multiple fatality, the less desirable is to use only conventional rules-based approaches for decision-making. Hence the focus on major ship accident categories.
- *Risk decision context*: higher elements of novelty, uncertainty or stakeholder concern will also push towards more thorough risk assessment, hence the bias of risk-based design towards high innovation, high-value vessels.

Definition of Safety Goals

Safety goals – as other design goals, are related to the ship's mission and ship's purpose. Explicit safety goals are already part and parcel of the design input. Examples of design goals driven by safety considerations (mainly associated with company values and policies) include:

Top-Level Goals

- No accidents leading to total ship loss (collisions, groundings, stranding, fires, etc)
- No loss of human life due to ship related accidents
- Low impact to the environment (no air emissions, low noise, low wash)
- Minimum impact to the environment in case of a ship accident

Specific Technical Goals (Objectives)

- Vessel to remain upright and afloat in all feasible operational loading and environmental conditions
- Vessel to remain upright and afloat in case of water ingress and flooding
- Ship structure to withstand all foreseeable loads during its lifetime (e.g., no extreme load structural failure or fatigue failure of key structural members)
- Sufficient residual structural strength in damage conditions
- High passenger comfort (no sea sickness, low vibration levels, low noise levels)

Similar safety goals (objectives) may be implicit in statutory or class requirements for risk acceptability – if such are available for approval purposes. Other design goals may include turnaround time, service speed, capacity, services and, in general, requirements rendering the ship fit for purpose.

Identification of Hazards

In order to achieve generic safety goals (objectives) as those stated above, more specific functional requirements must be defined so that compliance with such requirements would ensure achievement of the safety goals (objectives). In line with risk-based approaches, the identification of such requirements must be based on a systematic and rational assessment of what can impede the achievement of the safety goals; thus the "what-can-go-wrong" question must be explored systematically. This can be accomplished using hazard identification techniques. Hazard identification is usually a qualitative exercise based primarily on expert judgment. Various techniques and formats for reporting are available depending on the case, the purpose and the level of the design knowledge available (HAZID, FMEA, SWIFT, HAZOP, etc.).

Identification of Critical Design Scenarios

What makes risk-based design feasible and manageable, hence practicable, derives from the fact that ship safety, as a top-down process, is governed only by a handful of factors which, when considered individually or in combination, define a limited set of design scenarios with calculable probabilities of occurrence and consequences that could collectively quantify the life-cycle risk of a ship at sea. These relate to accident categories with major hazard potential, thus can be derived from hazard identification. When generic design scenarios are available, these must be adapted and customised to the specific design features and expected performances of the vessel in question (Fig. 2.11).

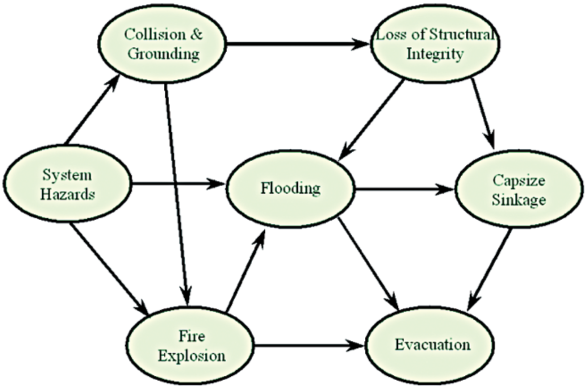

Fig. 2.11 Typical structural links of design scenarios

Definition of (Safety-Related) Functional Requirements

Once a list of prioritised hazards is available (based on qualitative ranking of risk) along with relevant design scenarios, specific functional requirements and evaluation parameters need to be formulated. These can be seen as an additional set (in relation to the normal set of performances) of safety performance requirements. These, of necessity, must be based on engineering judgment and available safety knowledge. With a consolidated list of safety-related functional requirements, the design process can proceed as normally. Such requirements will, alongside other conventional design requirements, be used by a designer to put together the first base line design and to identify design disciplines for evaluation.

Design Decision-Making

Use of risk analysis or alternatively of risk-knowledge models in ship design would provide additional information on safety performance and risk levels to the design decision-making process. The use of risk-knowledge models would allow such information to be easily re-calculated if design changes are made. If similar parametric models existed for other ship performances (weight, efficiency, capacity, etc.) and economic implications (relative initial and running costs, earning potential, etc.) then it would be possible to make major design decisions and trade-offs optimally and cost-effectively in a practical time-scale.

In relation to design decision-making, in the same way as there are explicit ship performance evaluation criteria (design criteria), and economic "targets" (within owner's requirements) there is a need to define safety performance evaluation criteria and risk acceptance criteria. The latter could be related to safety performance criteria, so that safety performance could be used in the design iterations, alongside or even instead of explicit risk acceptance criteria. As a result, key design aspects of the initial baseline designs (watertight subdivision, structural design, internal layout, main vertical zones, bridge layout, materials, major ship systems, etc.) can be optimised from the point of view of ship performance, cost implications, potential earnings whilst ensuring that the safety performance level (as quantified) is appropriate and commensurate with acceptable and quantified risk levels (provided that such do exist).

It is obvious that some design decisions determine the construction costs, other determine the operating cost and potential earnings. Whilst ship designers are, to a large extent, able to manage the construction costs, it is unlikely that they would be able to do the same with the operational economic profile of the vessel. For the former, shipyards possess detailed knowledge and empirical models (indeed such relationships do exist within shipyards) to estimate construction costs. For the latter, it is the shipyards' clients (the ship owners) who possess detailed knowledge and working models of their operational costs and earnings profile. Notwithstanding the above, the ultimate decision about the design parameters and variables lies of course with the designers themselves and other involved stakeholders (ship owner, shipyard, etc.). The quantified ship performances (technical performance, safety performance, costs, earning potential, and risk) would be weighted alongside other factors that are outside the design studies themselves (preferences, company policies, etc). In this context, ship design decision-making could be illustrated as indicated in Fig. 2.12.

A key aspect to risk-based design is that any ship design decision will be well-informed and will lead to design concepts that are technically sound (at least to a level commensurate with the current available state-of-the-art), fit for purpose, and last but not least, with a known level of safety that is more likely (than by following rules) to meet modern safety expectations.

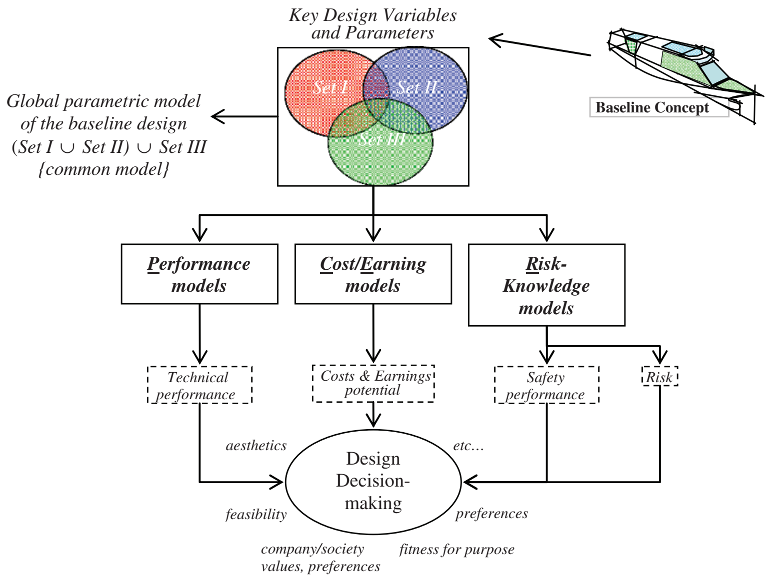

Fig. 2.12 Making in risk-based design

2.1.3 Contemporary Developments

Contemporary regulatory developments are already a step ahead, necessitating concerted effort at global level to ensure safe transition from deterministic to goal-based safety. More specifically, in May 2000, the IMO Secretary-General called for a critical review of the safety of large passenger ships noting that "what merits due consideration is whether SOLAS requirements, several of which were drafted before some of these large ships were built, duly address all the safety aspects of their operation – in particular, in emergency situations". This visionary prompt led IMO Maritime Safety Committee (MSC) to adopt a new "philosophy" and a working approach for developing safety standards for passenger ships. In this approach, illustrated in Fig. 2.13 (SLF 47/48), modern safety expectations are expressed as a set of specific safety goals and objectives, addressing design (prevention), operation (mitigation) and decision making in emergency situations with an overarching safety goal, commensurate with no loss of human life due to ship related accidents. The term "Safe Return to Port" has been widely adopted in discussing this framework, which addresses all the basic elements pre-requisite to quantifying the safety level (life-cycle risk) of a ship at sea.

More specifically the following elements are explicitly addressed:

1. ***Prevention/Protection:*** Emphasis must be placed on preventing the casualty from happening in the first place as well as on safeguards (in-built safety) to limit consequences.
2. ***Timeline Development:*** The focus is clearly on the timeline development of different events. For the first time in the history of rule-making, it is not only important to know whether a vessel will survive a given casualty in a given loading condition and operating environment but also the time the vessel will remain hab-

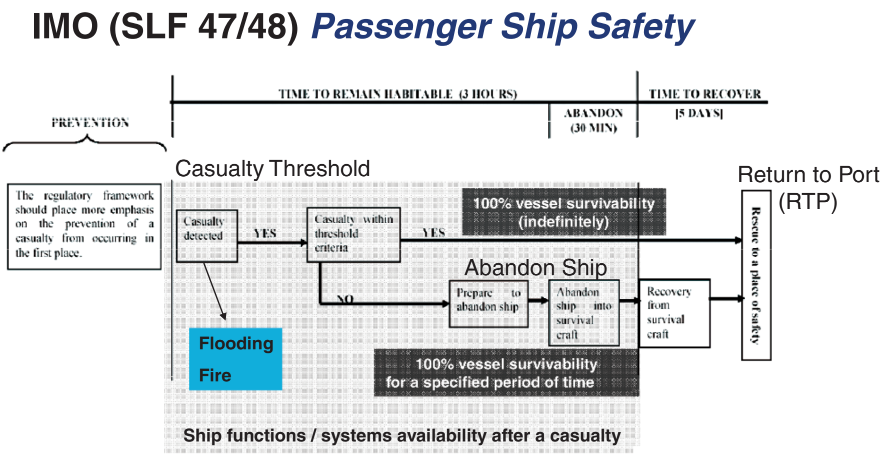

Fig. 2.13 The IMO framework – passenger ship safety

Fig. 2.14 Casualty threshold concept

itable, the time it takes for safe and orderly abandonment and for recovery of the people onboard.

3. ***Casualty Threshold:*** This advocates the fact that the ship should be designed for improved survivability so that, in the event of a casualty, persons can stay safely on board as the ship proceeds to port. In this respect and for design purposes (only), a casualty threshold needs to be defined whereby a ship suffering a casualty below the defined threshold is expected to stay upright and afloat and be habitable for as long as necessary (5 days recommended) in order to return to port under its own power or wait for assistance (Fig. 2.14).
4. ***Emergency Systems Availability/Evacuation and Rescue:*** Should a casualty threshold be exceeded the ship must remain stable and afloat for sufficiently long time to allow safe (3 hours recommended) and orderly evacuation (assembly, disembarkation and abandoning) of passengers and crew. Emergency systems availability to perform all requisite functions in any of the scenarios considered is, therefore, implicit in the framework. In addition, the ship should be crewed, equipped and have arrangements in place to ensure the health, safety, medical care and security of persons onboard in the area of operation, taking into account climatic conditions and the availability of SAR functions and until more specialised assistance is available.

Considering the above, it is worth emphasising that none of the questions arising (survival time? functional availability post-casualty? time needed for abandonment?) can be addressed in terms of rule compliance. Nonetheless, achievement of these goals in the proposed holistic, goal-based and proactive approach would ensure safety of human life commensurate with the safety expectations of today, by implicitly addressing all key elements of risk, for total risk (Safety Level) estimation and for direct use in RBD as explained in Sect. 2.2. An evaluation framework (Fig. 2.15, already being applied in the design of cruise/RoPax ships) and the ensuing scope of work are given next. The detail of this is considered in the next section.

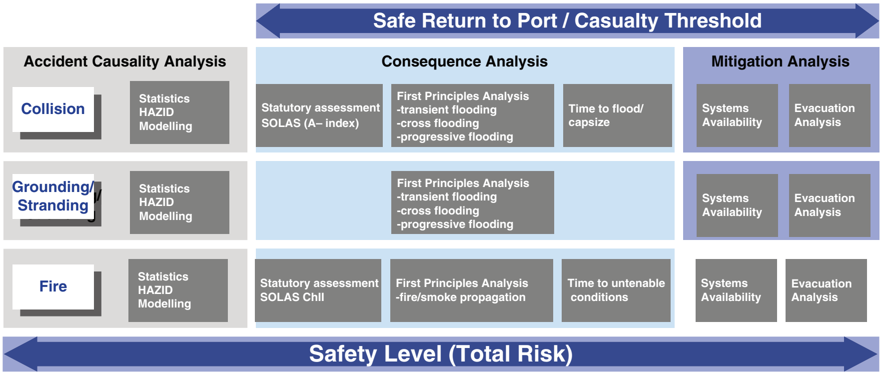

Fig. 2.15 Risk-based design implementation (safety level)

2.1.3.1 Scope of Work

Flooding survivability analysis:

Compliance with SOLAS 2009 damage stability rules
Vulnerability to flooding (dynamic ship survivability analysis) for all statistically possible cases of collision and grounding
Time to capsize

Fire safety analysis:

Fire risk screening of all spaces onboard (including special and external spaces)
Vulnerability to representative fire scenarios (fire engineering analysis)
Probabilistic evaluation of casualty threshold exceedance

Post-accident (flooding or fire) system availability analysis

Systems availability for each evaluated casualty scenario
Quantification of residual functional capacity
Probabilistic evaluation of Return to Port capability

Evacuation and rescue analysis

Quantitative risk assessment of the abandonment process
Time necessary for abandonment in representative flooding scenarios and in critical fire scenarios

2.1.4 Total Risk (Safety Level)

A common way of presenting graphically the chance of a loss (risk) in terms of fatalities is by using the so-called F-N diagram, the plot of cumulative frequency of *N* or more fatalities. However, while conceptually useful and, indeed, accepted widely as an expression of risk especially when plotted together with related criteria, (Skjong et al. 2005), it has been well known that for the purposes of consistent decision making, some form of aggregate information, derived on the basis of such distributions, is required. Commonly used summary statistics, such as expected value, are examples of such aggregate information. Unsurprisingly, the expected number of fatalities *E(N)*, often referred to as the potential loss of life, *PLL*, has been used among the pertinent profession routinely. On this basis, an F-N diagram clearly implies that the risk to human life of a ship carrying more people is greater than that carrying a lesser number. However, this simple truth can be reversed if the bigger ship is designed to a higher safety standard/level.

Arguably and with support from intuition, the bigger ship offers a better platform for achieving a higher safety level but intuition, conjecture or engineering judgment will not suffice when the argument concerns 10,000 human lives. All forms of knowledge must be called to play a role, provided that a comprehensive risk model and framework are available to calculate the total risk for a ship type (risk to human life for passenger ships). An attempt in this direction was presented in (Jasionowski and Vassalos 2006), and is outlined here in the following:
Risk Model

$$\mathrm{Risk}_{PLL} \equiv E\left(N\right) \equiv \sum_{i=1}^{N_{\max}} F_N\left(i\right) \tag{2.1}$$

Where $N_{\max}$ the maximum number of persons onboard and the F_N curve is given as:

$$F_N\left(N\right) = \sum_{i=N}^{N_{\max}} fr_N\left(i\right) \tag{2.2}$$

The frequency $fr_N(N)$ of occurrence of exactly N fatalities per ship year is modelled as follows:

$$fr_N\left(N\right) = \sum_{j=1}^{n_{hz}} fr_{hz}\left(hz_j\right) \cdot pr_N\left(N \left| hz_j\right.\right) \tag{2.3}$$

Where, n_{hz} is the number of loss scenarios considered, and hz_j represents a loss scenario, identifiable by any of the principal hazards, the major of which as recognized today are shown in Fig. 2.16. Furthermore, $fr_{hz}(hz_j)$ is the frequency of occurrence of scenario hz_j per ship year, and $pr_N(N|hz_j)$ is the probability of occurrence of exactly N fatalities, given that loss scenario hz_j has occurred. Shown also in Fig. 2.16 are estimates for the annual frequencies of occurrence for flooding- and fire-related hazards have been derived based on statistics, (Vanem and Skjong 2004). In addition, efforts in SAFEDOR (2005–2009) and elsewhere are ongoing aiming to derive these from first principles. With passenger ships, flooding- and fire-related scenarios comprise over 90% of the risk (regarding loss of life) and almost 100% of all the events leading to decisions to abandon ship. Therefore, it would be possible to estimate the total risk (safety level) of a passenger vessel by addressing these two principal hazards alone in a consistent manner and framework, allowing for their contribution to risk to be formally combined as indicated schematically in Fig. 2.15.

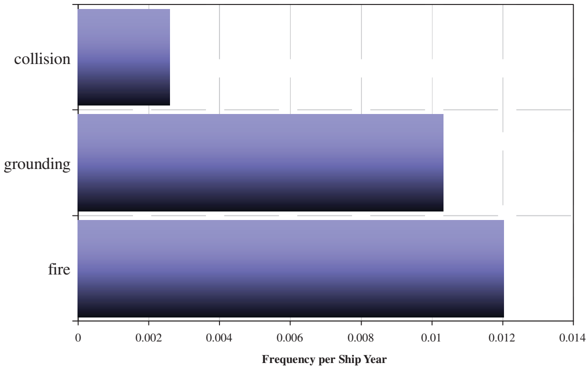

Fig. 2.16 Principal hazards – frequency of event occurring (cruise ships, [2.4]): hz_1-*flooding*; hz_2-*fire*

Deriving from this, and as indicated in the foregoing, the following specific issues need to be addressed and are considered, next:

- Flooding survivability analysis (collision and grounding)
- Fire safety analysis
- Post-accident systems availability analysis
- Evacuation and rescue analysis

2.1.4.1 Flooding Survivability Analysis

Using the harmonised probabilistic rules for damage stability as basis, substantive elements of the risk model (Eq. (2.3)) have been developed, (Jasionowski and Vassalos 2006), as indicated next:

$$pr_N\left(N\,|hz_1\right) = \sum_{i}^{3}\sum_{j}^{n_{flood}} w_i \cdot p_j \cdot \sum_{k}^{n_{Hs}} e_k \cdot c_{i,j,k}\left(N\right) \tag{2.4}$$

$$c_{i,j,k}\left(N\right) = \left(-\ln\left(\varepsilon_{i,j,k}\right)\cdot\left(\varepsilon_{i,j,k}\right)^{\frac{t_{fail|j}(N)}{30}}\right)\cdot\frac{\left|\partial t_{fail|j}\left(N\right)\right|}{30} \tag{2.5}$$

Where, the terms w_i and p_j are the probability mass functions of the 3 specific loading conditions and damage extents and n_{flood} the number of flooding extents, respectively, calculated according to the harmonised probabilistic rules for ship subdivision, (SLF47/17 2004). The term e_k is the probability mass function derived from the statistics of sea states recorded at the instant of collision and n_{Hs} is the number of sea states considered. The term $c_{i,j,k}\left(N\right)$ is the probability mass function of the event of capsizing in a time within which exactly N number of passengers

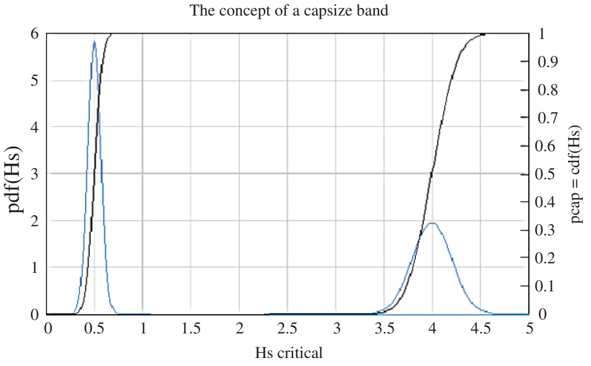

Fig. 2.17 Principal the concept of "capsize band", (Jasionowski et al. 2004), for critical sea states of 0.5 and 4.0 m

fail to evacuate, conditional on events i, j and k occurring, and can be tentatively estimated from Eq. (2.5) based on the harmonised probabilistic rules; the formulation shown accounts for ship geometry, loading and each individual sea state in any given flooding event. The term $\varepsilon_{i,j,k}$ (with σ_r) represents the so-called capsize band shown in Fig. 2.17, that is the spread of sea states where the vessel might capsize. These can be estimated as follows:

$$\varepsilon_{i,j,k} = 1 - \Phi\left(\frac{Hs_k - Hs_{crit}(s_{ij})}{\sigma_r(Hs_{crit}(s_{ij}))}\right) \tag{2.6}$$

$$\sigma_r(Hs_{crit}) = 0.039 \cdot Hs_{crit} + 0.049 \tag{2.7}$$

Where $\Phi(.)$ is the cumulative standard normal distribution and $Hs_{crit}(s)$ is given by Eq. (2.8) below, (Jasionowski and Vassalos, 2006):

$$Hs_{crit}(s) = Hs_{collision}(s) = \frac{0.16 - \ln(-\ln(s))}{1.2} \tag{2.8}$$

The s_{ij} is the probability of survival, calculated according to (SLF47/17 2004).

$$\partial t_{fail}(N) = t_{fail}(N) - t_{fail}(N-1) \tag{2.9}$$

$$t_{fail}(N) = N_{fail}^{-1}(t) \tag{2.10}$$

$$N_{fail}(t) = N_{\max} - N_{evac}(t) \tag{2.11}$$

Finally, the term $N_{evac}(t)$ is the number of passengers evacuated within time t, as shown below.

As illustrated in Fig. 2.18, two parameters are of paramount importance in evaluating risk meaningfully: the first is the time required for orderly evacuation of passengers and crew in any given event $(N_{evac}(t))$, derived from numerical simu-

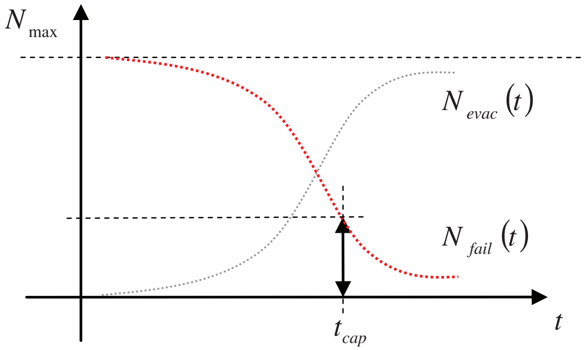

Fig. 2.18 Interplay between time to capsize and evacuation time

lations using advanced evacuation simulation software, (Vassalos et al. 2002); the second is the time to capsize/sink (t_c), which is evaluated by using two methods, as explained next.

The time to capsize $(\mathrm{t_c})$, given a ship hull breach, is a random variable, (Vassalos et al. 1998) hence only known as a distribution determined through probability methods Moreover, it is dependent upon a number of parameters (e.g. flooding condition, sea state, damage extent) all of which are also random in nature. In this respect, accounting only for the damage scenarios implicit in the new harmonised rules for damage stability (normally over 1,000 for a typical passenger ship) and considering the 3 loading conditions, also implicit in the rules, and some 10 sea states per damage case, it becomes readily obvious that brute-force time-domain simulations is not the "route to salvation". In view of this, two lines of action are currently being pursued. The first relates to the development of a simple (inference) model for estimating the time to capsize, for any given collision damage scenario; the second entails automation of the process using Monte Carlo simulation, as outlined next.

Method 1 – Univariate Geometric Distribution – Collision

Considerable effort has been expended over recent years to develop an analytical expression, which could replace the need for expensive numerical simulations, and still provide an overall description of the character of the stochastic process of ship capsize when subjected to collision damage in a seaway. Although not yet considered to be as generic and comprehensive as the time-domain solution, a first prototype of such an engineering tool has been proposed in Jasionowski and Vassalos (2006) and Jasionowski et al. (2004, 2006), which is the model underlying Eq. (2.5). The inference model here is based on a geometric probability density distribution for time to capsize for each flooding scenario. Deriving from the above and shown here in Eqs. (2.12) and (2.13) is the probability density distribution for the time to capsize, using the same terms used in the probabilistic rules for damage stability, as defined earlier:

$$p(t_{cap}) = \sum_{i}^{3} \sum_{j}^{n_{flood}} w_i \cdot p_j \cdot \sum_{k}^{n_{Hs}} e_k \cdot c_{i,j,k}(t_{cap}) \tag{2.12}$$

Where

$$c_{i,j,k}(t_{cap}) = -\ln(\varepsilon_{i,j,k}) \cdot (\varepsilon_{i,j,k})^{\frac{t_{cap}}{30}} / 30 \tag{2.13}$$

Convergence between this expression and results from time-domain simulations provides the validation needed for typical damage cases, as shown in Fig. 2.19 for a typical cruise ship, and the confidence that this simple inference model, is capable of predicting the likelihood of a vessel to capsize in any given flooding scenario within given time in fractions of a second. This is a significant development.

Considering all pertinent flooding scenarios for a typical ship, the outcome is the marginal cumulative probability distribution for time to capsize, shown in Fig. 2.20.

A close examination of Figs. 2.19 and 2.20 reveals the following note worthy points:

As a random variable, time to capsize can only be predicted in probabilistic terms. In other words, the deterministic number (3 h) postulated at IMO is inappropriate. The correct term should be "time to capsize within 3 h with prob ability of x%".

If a vessel did not capsize within the first hour post-accident, capsize is unlikely, on average.

The marginal probability distributions for time to capsize tend to asymptotic values defined by (1-A).

Ability to estimate the probability of the time to capsize (in fractions of a second) could prove a very important tool to aid decision making in emergencies, particu-

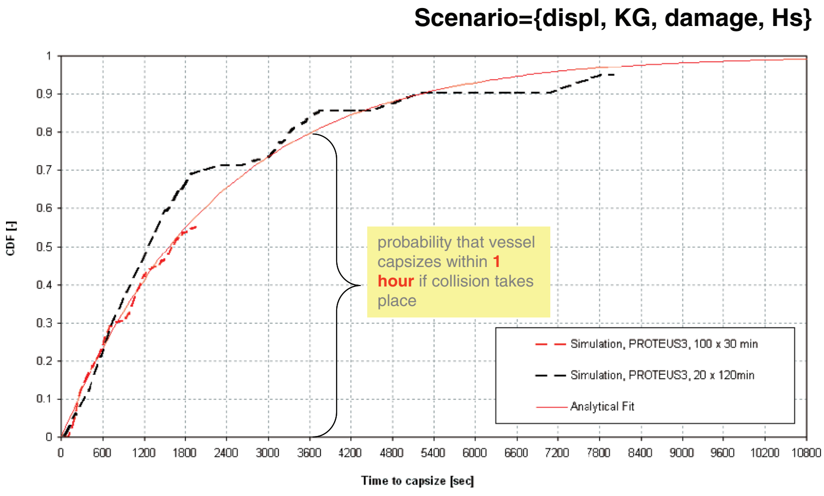

Fig. 2.19 Cumulative probability function for time to capsize (scenario level) – comparison between analytical model and numerical simulation results

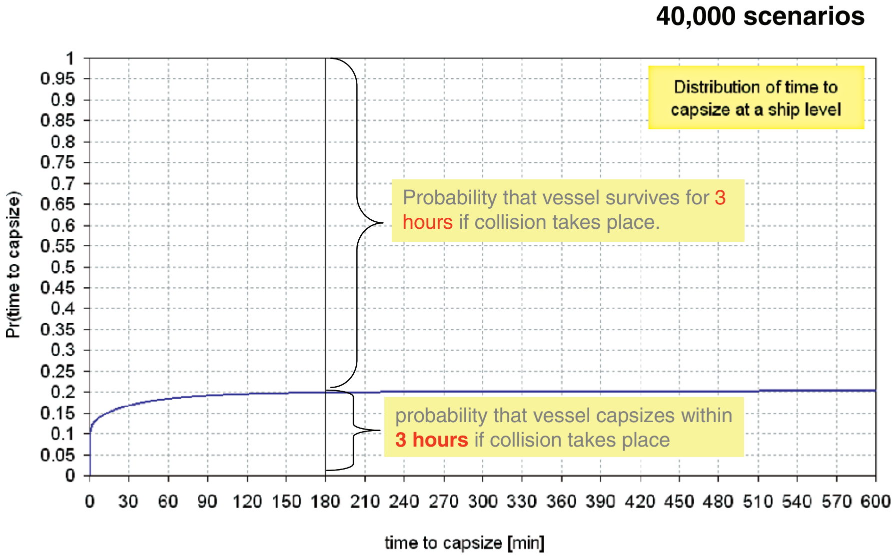

Fig. 2.20 Cumulative marginal probability distribution for time to capsize within a given time for a ship

larly when knowledge specific to the accident in question is accounted for and resolution of the model is enhanced by the time domain simulation results, shown next.

Method 2 – Monte Carlo Simulation – Collision and Grounding

To overcome problems associated with "averaging" (e.g., average probability of survival) and other approximations and potential weaknesses that might be embedded in the formulation of the probabilistic rules, the random variables comprising loading conditions, sea states and damage characteristics (*collision*: location, length, height, penetration according to the damage statistics adopted in the probabilistic rules; *grounding*: location, length, height, width, as determined in-house (The Ship Stability Research Centre – SSRC) using statistics from the EU Project HARDER, (2003) are sampled using Monte Carlo sampling and each damage scenario is simulated using explicit dynamic flooding simulation by PROTEUS3, (Jasionowski 1997–2005). The resolution could be as high as necessary (every second of each scenario) accounting for transient- cross- and progressive-flooding, impact of multi-free surfaces, watertight and semi-watertight doors (relevant to passenger ships) and of course any damage scenario (collision, grounding, raking, etc.). Applications of this method indicate that 500 scenarios would be sufficient (for typical cruise ship / RoPax vessels the absolute sampling error for the cumulative probability of time to capsize derived was of the order of 4%–5%). Examples of a Monte Carlo simulations setup are shown in Fig. 2.21 (generic) and Fig. 2.22, Fig. 2.23 for collision.

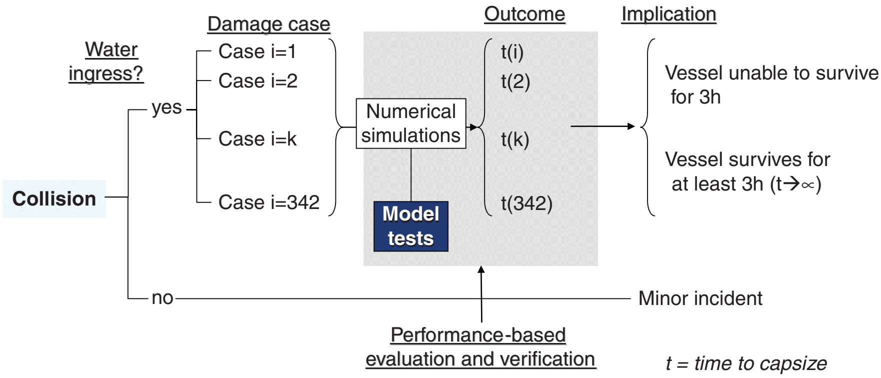

Fig. 2.21 Monte Carlo simulation – collision and grounding

Typical results are shown in Figs. 2.20 and 2.24 as cumulative distribution functions of time to capsize within a given time. From the latter it will be seen that differences between the two methods of nearly an order of magnitude have been encountered and this led to renewed scrutiny of the probabilistic rules, as reported in (Vassalos and Jasionowski 2007).

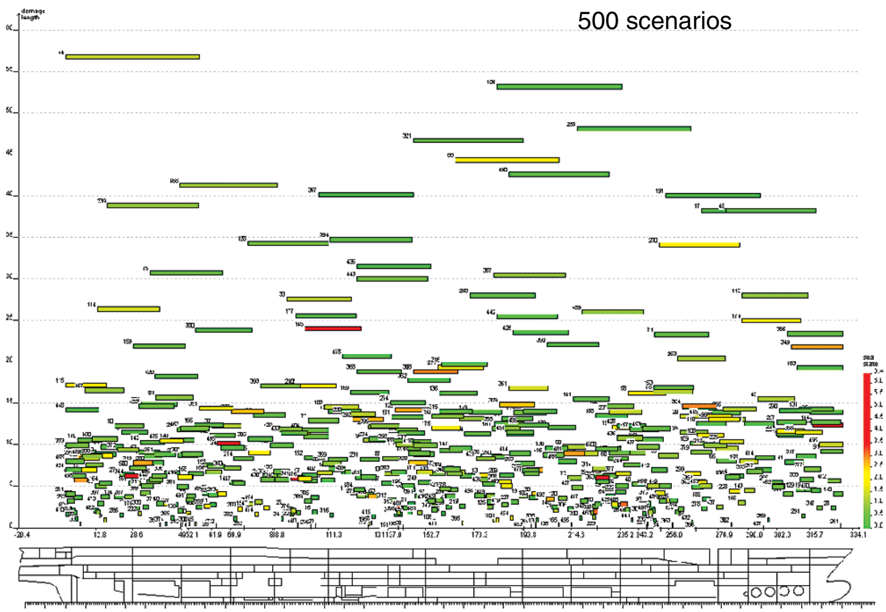

Fig. 2.22 Monte Carlo simulation set up – collision

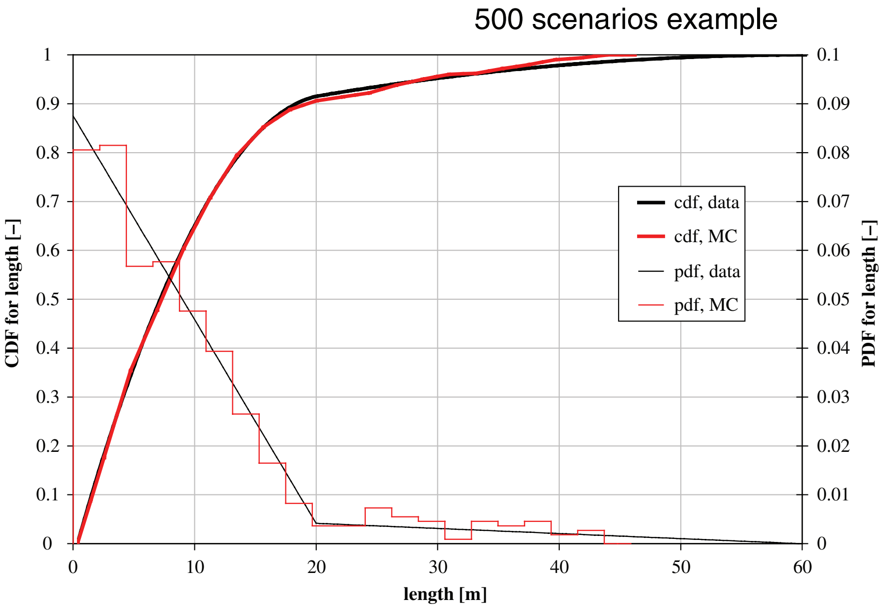

Fig. 2.23 Monte Carlo sampling – Length

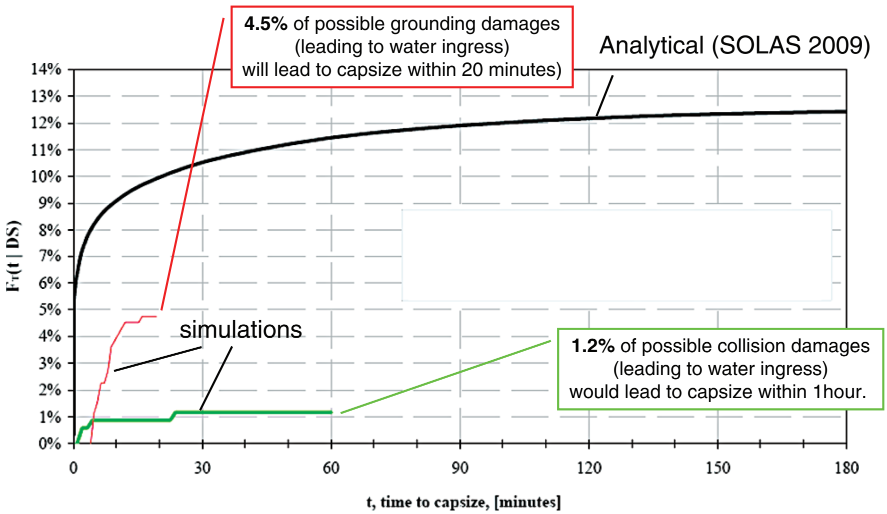

Fig. 2.24 Probability distributions of time to capsize

2.1.4.2 Fire Safety Analysis

Fire safety is currently dealt with through statutory means for established design solutions and through a performance-based approach for alternative design and arrangements not in line with prescriptive regulations. The latter is today undertaken in a manner consistent with 'traditional' risk assessment approaches. Whilst this takes place at qualitative level, in the first instance, quantitative analysis focuses thereafter on fire consequences (fire engineering) analysis for a limited number of representative scenarios. In this respect, the fire risk contribution to the total risk of a ship design is not being quantified and hence consistent risk summation is not possible for design, operation and regulatory purposes. In this respect and in the light of today's trend for bigger, more complex and safer ships, it becomes obvious that in addition to the current regulatory regime, a more systematic and rational design framework is needed to assist the design team to undertake pro-active fire *risk screening* as part of the early design iterations, in the same way as damage stability is addressed, so that better-informed decisions can be made when design decision-making is still cost-effective. This is particularly relevant when the design concept includes features that need to be evaluated under the alternative design and arrangements framework.

It was in this context, that the idea of a similar formalised framework for fire safety was conceived during the SAFEDOR project (Guarin et al. 2007a), and its development supported with industry-funded projects. The primary goal in this undertaking was to achieve consistency in the way in which the risk associated with flooding and fire (the two main contributors to risk) onboard passenger ships is quantified and evaluated, as discussed in (Jasionowski and Vassalos 2006). This would allow risk quantification and evaluation to be carried out efficiently within the constraints of the design process, one of the fundamental principles in risk-based design.

This section presents the concept of a probabilistic framework for fire safety being developed along the lines of the probabilistic framework for damage stability to support the quantification of the overall ship safety level, as outlined next.

Fire Risk Model

Consistent with flooding, the risk associated with fire onboard a ship is quantified in terms of the frequency of statistical fatalities (societal risk) and is estimated by adding the risk contribution from each space onboard (Fig. 2.25), i.e.:

$$R_F = \sum_{i=1}^{n} dR_i \; dR_i = f_i \times \sum_{k} \left(P\left(E\right)_{i,k} \; N_{i,k} \right) \tag{2.14}$$

where n refers to the total number of spaces onboard, dR_{i} is assumed to be associated with possible fire escalation outcomes, fire escalation (E) refers to failure to *contain, control and suppress fire and explosion in the compartment of origin*, (one of the main safety objectives implicit in SOLAS II-2), f_i is the frequency of a fire

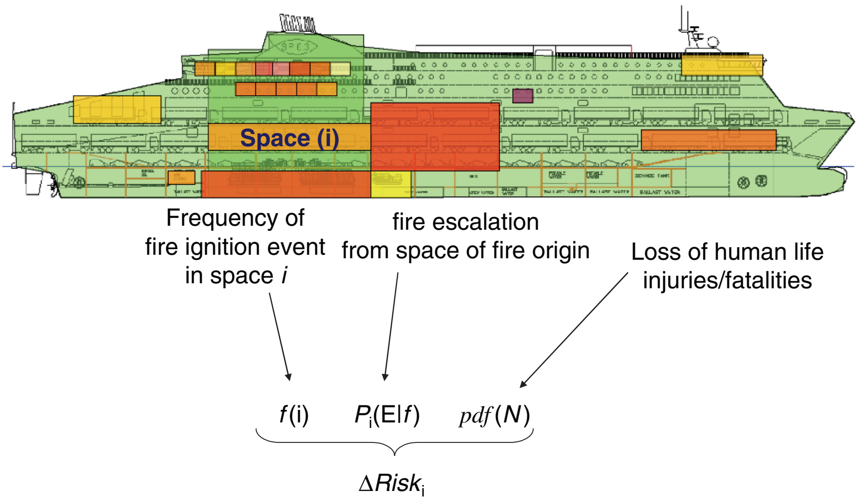

Fig. 2.25 Fire risk modelling

scenario (i) and $N_{i,k}$ the expected number of fatalities associated with all possible fire escalation outcomes (k), shown in Fig. 2.26. The frequency of fire occurrence in a space is a function of floor area and use of space. Fire escalation is evaluated

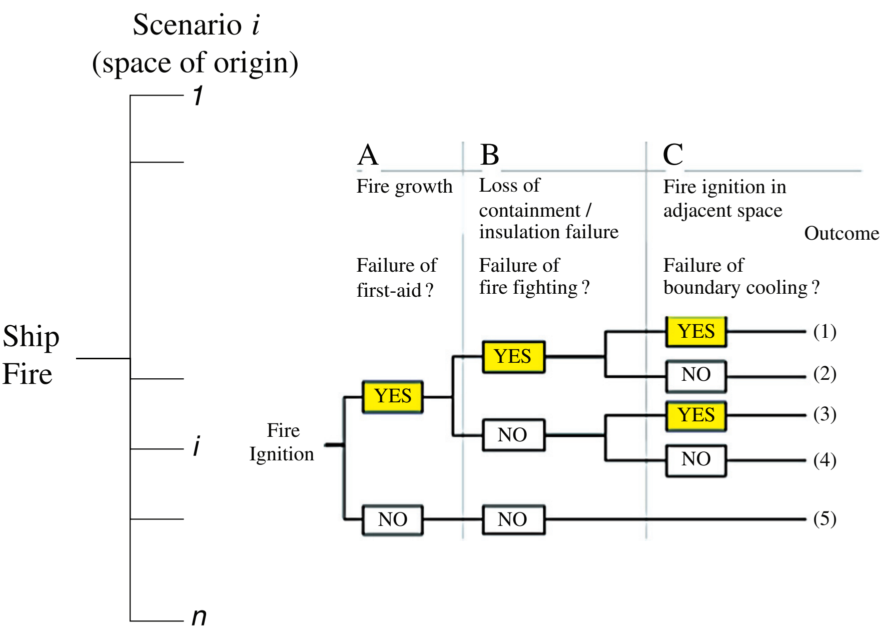

Fig. 2.26 Fire risk model for space (i)

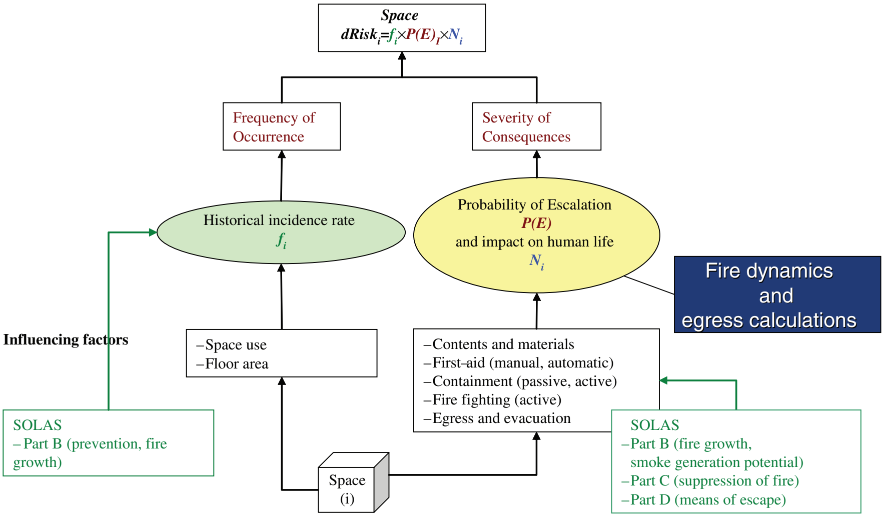

Fig. 2.27 Fire risk model overview

using various post-ignition models. The conditional probability of a fire escalation outcome $P(\mathrm{E})_\mathrm{k}$ largely depends on alarm, detection and suppression arrangements, fire growth potential and insulation class of boundaries. The associated number of fatalities N_k depends on the number of people exposed to the resulting fire hazards; hence it depends on the use, occupancy profile and location of the space, the capacity and occupancy of the fire zone, as well as the evacuation arrangements.

An overview of the fire risk model is presented in Fig. 2.27 next.

Continuing from the above and in order to aggregate the risk contribution from fire and flooding, as explained earlier and shown in Eq. (2.2) the probability mass function for the resulting fatalities of an outcome (k) of scenario (i) has to be estimated. Given this and adopting the notation of Eq. (2.3), the frequency of occurrence of exactly N fatalities is then calculated as follows:

$$fr_N(N) = \sum_{i=1}^{n} \left[fr_{hz}(hz_2)_i P(k)_i \quad pr_N(N/hz_2)_{k,i} \right] \tag{2.15}$$

$$fr_N(N) = \sum_{i=1}^{n} \left[fr_{hz}(hz_2)_i P(k)_i \frac{e^{-\lambda}\lambda^{N_{k,i}}}{N_{k,i}!} \right] \tag{2.16}$$

The parameter λ is the mean number of fatalities and can be estimated from regression analysis of evacuation simulation results for typical configuration arrangements and standard scenarios (night and day). Consequently the FN curve associated with fire is calculated using Eq. (2.2) as individual risk contribution or in combination with flooding risk.

The components of the risk model described above and shown in Figs. 2.26 and 2.27, were detailed in (Guarin et al. 2007b) and are briefly described next.

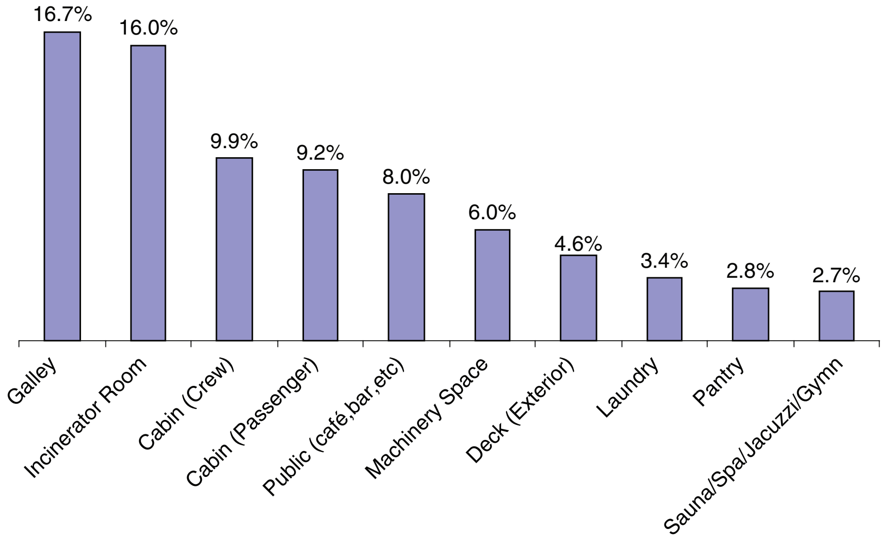

Fig. 2.28 Relative frequency of occurrence of fire incidents; 20% of space "uses" contribute to 80% of all fire occurrences

Fire Ignition Model. The ignition model is aimed at estimating the frequency of a fire ignition event f_i. It has been shown (Guarin et al. 2007b) that the fire incidence rate for a specific ship space is influenced by the type or "use" of space, determining the contents of the space (materials, dimensions), presence of heat sources and exposure to a hazardous situation that could lead to fire. In a typical cruise vessel, for example, 50 space-"uses" were identified, as illustrated in Fig. 2.28 with the top-ten highest relative frequency of fire incidence.

A review of available fire incident data onboard cruise vessels indicated that the most significant fuel sources include furnishings, floor, wall and ceiling coverings, fittings and other contents (e.g. oil and waste receptacles), which has been shown (Tillander 2004) to have a degree of correlation with the "floor area" of the spaces. In terms of heat sources the most significant include auto-ignition (stores), cigarettes, electrical (accommodation), hot surface (machinery, galleys), open flames (galleys), pyrotechnics (public), as well as hot work in crew and service spaces. The exposure to a hazardous situation depends on the exposure to different operational factors such as the level of occupancy, public/crew only access, time of the day, etc, all of which are associated with the actual "use" of the space. Hence, estimation of the frequency of ignition for a specific space type is based on the corresponding historical incidence rate per unit area, referred to as γ_i. Figure 2.29 illustrates the spaces with the top-ten highest values of γ_i. Thus, the frequency of fire ignition in a specific space type of given area a_i and "use" type, is calculated as follows:

$$f_i = \gamma_i\, a_i \tag{2.17}$$

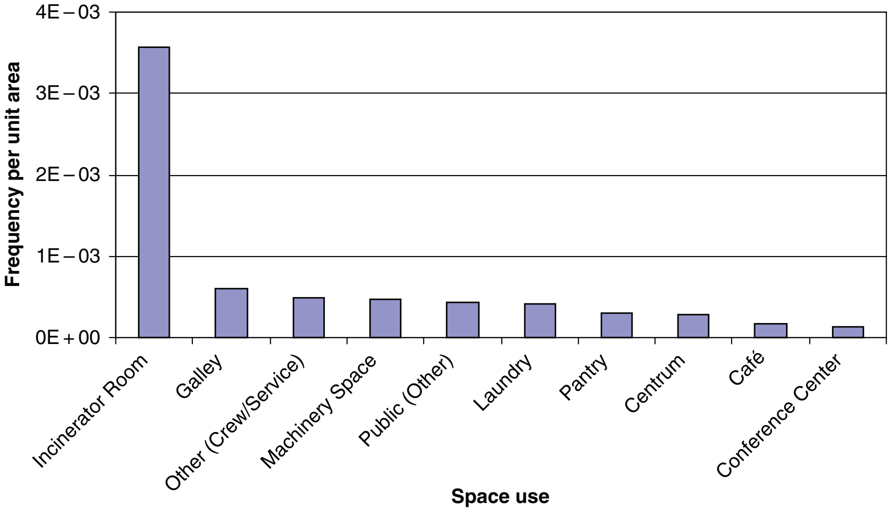

Fig. 2.29 Frequency of occurrence of fire incidents per unit area

Post-Ignition Models. Post-ignition models are aimed at quantifying the probability of fire escalation P(E) for a given scenario/space type (i), as illustrated in Fig. 2.30 and comprise the following:

Failure of First-Aid (A): this addresses the probability of failure of first-aid fire suppression P(A), which would lead to fire growth and depends on the automatic and/or manual first-aid fire suppression arrangements. Successful first aid implies

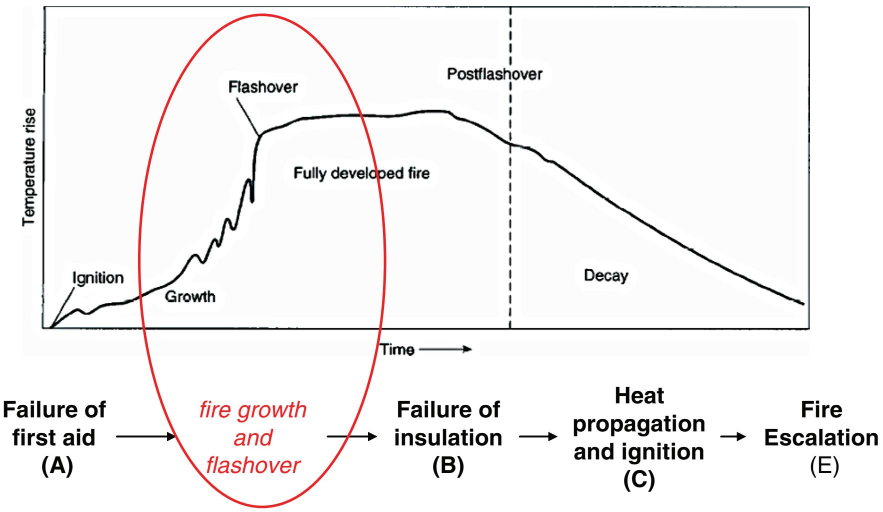

Fig. 2.30 Simplified fire dynamics modelling

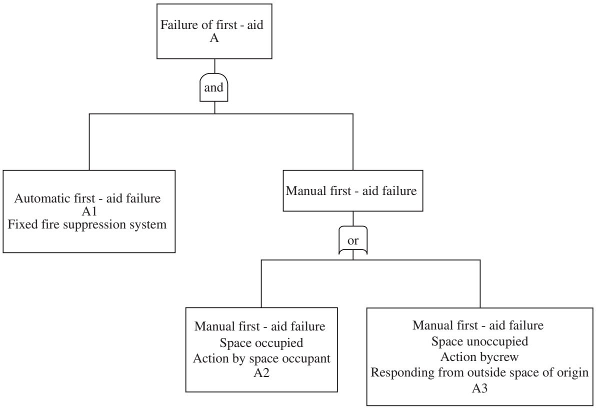

Fig. 2.31 Failure of first aid

that the fire is not allowed to grow and the outcome of a fire event is only minor, i.e., the fire does not escalate. Fire suppression first-aid failure can occur if fixed automatic and manual fire suppression failed. The corresponding failure model leads to Eq. (2.18) (see Fig. 2.31) for estimating the probability of first-aid failure:

$$P(A) = P(A_1) \cdot [P(A_2) + P(A_3) - P(A_2)P(A_3)] \tag{2.18}$$

Where, $P(A_1)$ is the probability of failure of the automatic (fixed) suppression system, $P(A_2)$ is the probability of failure of manual first-aid and $P(A_3)$ is the probability of failure of first-aid by an on-duty staff (manual first aid using portable or available fixed system). As explained in (Guarin et al. 2007b), this is derived on the basis of empirical formulations, reliability of pertinent systems, experiential knowledge and data.

The impact of first-aid on the rate of heat release from fire is illustrated in Fig. 2.32, showing that failure of any of these actions would result in fire growth to flashover situation.

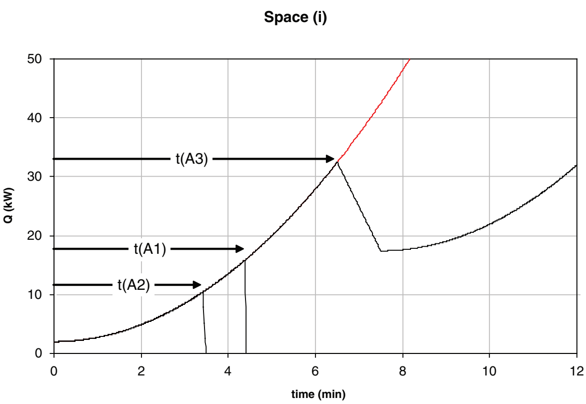

Fig. 2.32 Impact of first-aid on fire energy time line

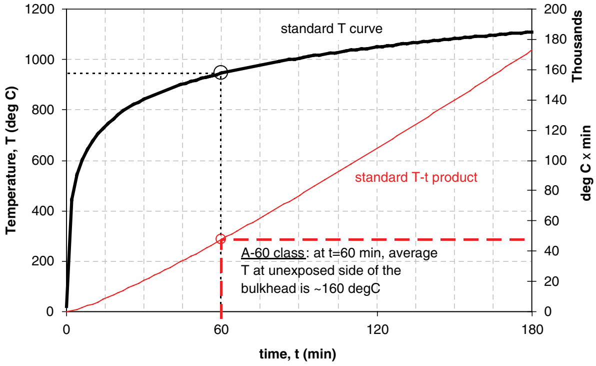

Fig. 2.33 Standard fire time line

Failure of Insulation (B): this addresses the probability of insulation failure *P*(B) – due to failure of fire fighting, which is assumed to be equivalent to loss of containment. It depends on the fire growth potential of the contents in a given space, the timing and effectiveness of the fire fighting activities as well as the insulation class of boundaries. As explained in (Guarin et al. 2007b), failure of fire insulation of boundaries is evaluated in accordance with the performance criteria implicit in SOLAS regulation 3.2, 3.4 and 3.10 for insulation class A, B and C respectively. These criteria refer to the times at which the temperature at the unexposed side of the bulkhead exceeds certain limits. If the criteria are exceeded it is assumed that loss of containment, conditional to failure of first-aid, will occur.

The standard times to failure, however, relate to the fire insulation performance in relation to the standard fire test. The standard temperature-time curve of the standard fire test is illustrated in Fig. 2.33. As can be seen, if the actual energy released by the fire, which is proportional to the temperature-time product $(\mathrm{T} \cdot \mathrm{t})$ is known, then it is possible to estimate the time to failure for a bulkhead with any of the SOLAS standard class insulation types.

As it can be implied from Fig. 2.33, the fire energy depends largely on the impact of fire fighting, which in turn is highly dependent on the time at which fire fighting is initiated. The time to fire-fighting is highly influenced by the alarm time and the time it takes for a fire fighting team to assemble and to reach the space of fire origin. Estimates are made on the basis of current cruise vessel experience.

The probability of insulation breakdown (e.g. loss of containment) is calculated on the basis of the ratio (r) between the temperature-time product of the actual fire (including the heat release reduction due to fire fighting) and the standard fire test for a given insulation class. Since boundaries of a space can be of different bulkhead insulation class, the probability of failure corresponding to the lower boundary class is used for calculation of fire risk.

Fire Spread into Adjacent Spaces (C): this model addresses the probability of fire ignition in an adjacent space *P*(C). It depends on the contents of the adjacent space and on the timing and effectiveness of boundary cooling (access and capacity) if relevant. Fire spread into an adjacent space occurs when the temperature in any of the adjacent spaces due to heat transferred from the space of fire origin, reaches the *flashpoint* temperature (T_{flash}) of its contents. The heat radiated from the boundary between the space of fire origin and an adjacent space, is proportional to the temperature T_{BHD} in the unexposed side of the bulkhead, which is determined by the type of insulation fitted and the released fire energy in the space of fire origin. In this respect, if the probability distribution functions of T_{flash} and T_{BHD} are known (normal distributions are assumed), then the probability of fire spread can be calculated, using standard reliability theory as follows:

$$P(C) = \int_{0}^{\infty} F(T_{\text{flash}})\, f(T_{\text{BHD}})\, dT \tag{2.19}$$

The parameters of $f(T_{\text{BHD}})$ and $F(T_{\text{flash}})$ are estimated on the basis of the average temperature in the space of fire and the flash temperature of the adjacent space contents, respectively. The probability of boundary cooling and its timing is estimated subjectively on the basis of expert opinion and available typical training patterns from the cruise industry. It is expected that this approach would give a conservative estimate of P(C) as heat radiation from the bulkhead in question and the location of the ignitable contents is not taken into account.

Injury/Fatalities: this addresses the expected number of fatalities N for a given escalation outcome. It incorporates factors affecting the egress time of the occupants and the time to reach untenable conditions (due to smoke toxicity, heat and optical density) inside the space of fire origin and in spaces within the same fire zone. This is further elaborated in Sect. 4.4.

2.1.4.3 Post-Accident Systems Availability Analysis

In the knowledge that a significant number of accidents do not necessitate immediate evacuation from the ship, and in the event of such accidents, subject to meeting the basic needs of the occupants, the damaged ship may be taken to a nearby port or safe refuge. Similarly, many accidents can be mitigated and the ship can continue with her planned voyage.

However, the quality allowing a ship to carry on following an accident can not be ensured incidentally. It has to be deliberately designed for. More specifically, in the knowledge that accidents lead to damage or destruction of onboard systems, and in order to withstand such consequences the overall design must have in-built redundancy from the point of view of a casualty, not only from the point of view of component reliability, which is the norm in designing for systems redundancy.

However, "designing damage tolerant ship systems" is a far more complex problem than one would initially imagine. Even though standard reliability engineering methods have been used in the evaluation of redundancy provisions, such methods rarely take into account the spatial "locality and historical frequency" of shipboard damage scenarios. Locality here implies the property that a damage scenario is more likely to simultaneously affect systems that are located close together. Hence, if two systems that can stand in for each other are located far away from one another they provide a greater degree of robustness than they would if they were located side by side. This consideration is implicitly used in design and positioning of ship systems, but an explicit and quantitative treatment incorporating this property and damage incidence frequency will substantially enhance system availability in emergencies. In order to address this need, and with funding from SAFEDOR and the cruise ship industry, SSRC are in the process of developing and testing suitable computer software, so-called SAVANT (Systems Availability Analysis Tool – Fig. 2.34) to facilitate probabilistic analysis of systems availability following the same probabilistic framework as in damage stability.

SAVANT requires the following data for the said analysis:

- The spatial subdivision of the ship.
- The placement of the shipboard systems.
- The mutual interdependence of systems.
- Damage cases as defined for probabilistic damage stability analysis.

The SAVANT system allows modelling of the functionality of the ship in terms of the way the functionality depends on other sub-functions and sub-systems within the ship. This dependency information is used in computing how systemic failure cascades in the event of an accident. This is illustrated in Fig. 2.35 (generic) and Fig. 2.36 (real data).

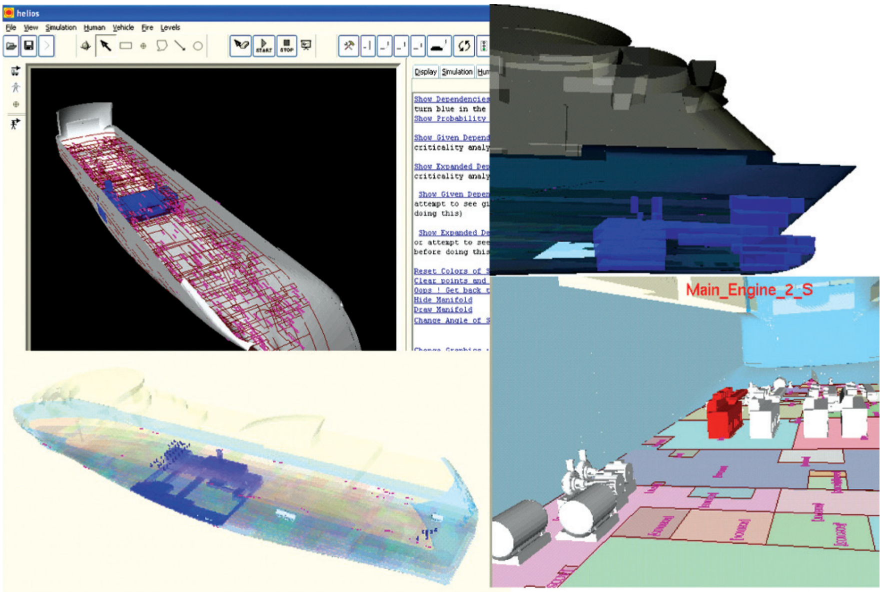

Fig. 2.34 SAVANT modelling (example: compartmentation and systems)

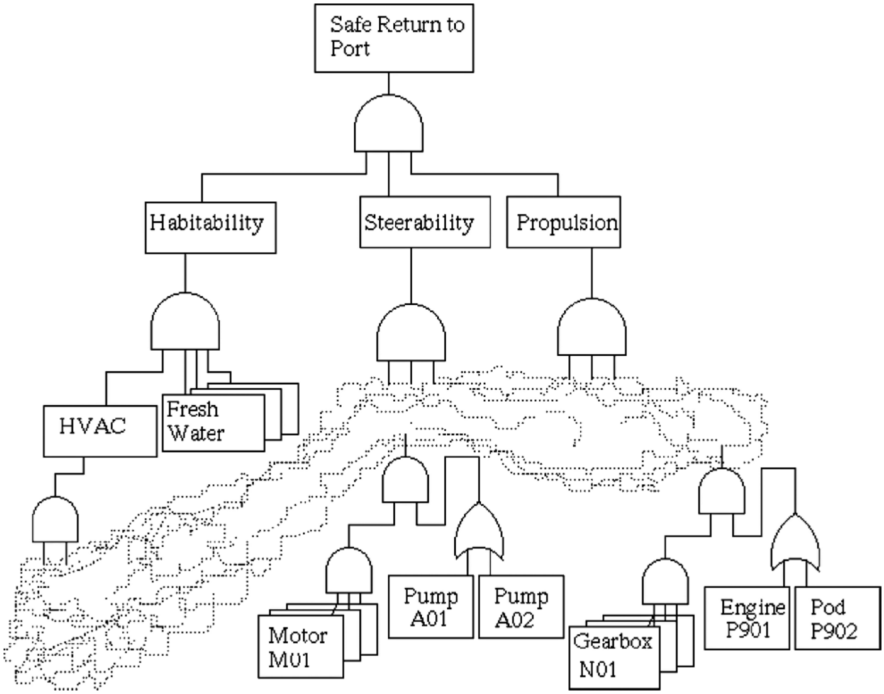

Fig. 2.35 Systems dependency tree (generic construct for safe return to port function)

SAVANT also uses the location and connectivity of the systems to determine which systems are directly affected by the immediate impact of an accident. If a single accident is considered in isolation, a given function either survives or fails. However, on aggregating over thousands of accident scenarios and weighing by the probability (or historical frequency) of each accident a probabilistic expectation is obtained of the failure of each function. In this regard, if $p(j)$ is the probability of the j_{th} damage case as defined in SOLAS 2009, and $g(F, j)$ is a function that takes the value ***one*** if the functionality F fails in the j_{th} damage case and ***zero*** otherwise, a probabilistic (failure) index can be defined for that functionality (much along the lines of Index of Subdivision A) as follows:

$$F_{index} = \frac{\sum_{i=j}^{N} p(j)g(F, j)}{\sum_{i=1}^{N} p(j)} \tag{2.20}$$

Monte-Carlo trials could also be used to accommodate probabilistic failure rates for flooded systems. However, to consider these developments in the context of risk and in line with the foregoing formulation, more resolution (information) is needed, namely the percentage of this functionality failure (residual functionality) over the

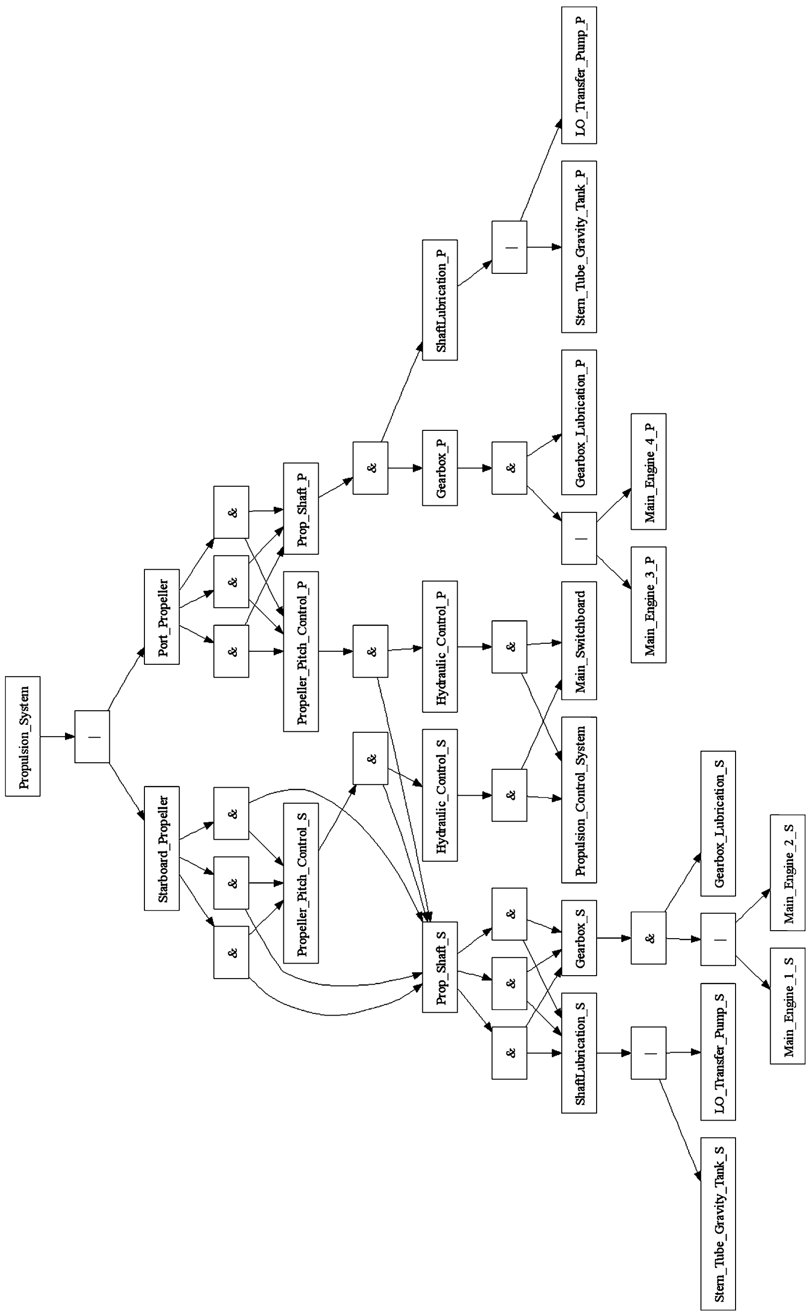

Fig. 2.36 System Dependency Tree Example (Propulsion System)

domain of the ship. In other words, if damage (j) occurred, what is the proportion of systems supporting the functionality (or what proportion of the functionality) is available. This is currently under development both within SAFEDOR and through industry-funded projects. On the basis of the influence of this development on the risk evaluation per se (from the point of view of LSA availability), this can be accommodated by introducing the following definition for $t_{fail|j}$ in Eq. (2.6).

$$t_{fail|j}(N) \cdot \frac{t_{fail}(N)}{1 - p\left(lsa\_systems\_fail \,\middle|\, damage_j\right)} \tag{2.21}$$

2.1.4.4 Evacuation and Rescue Analysis

The last element in addressing the issue of ship safety pertains to the evacuation process, Fig. 2.37.

The IMO evacuation analysis, undertaken for new cruise ships and existing passenger ships on a voluntary basis, allows for assessment at the design stage of passive safety (in-built) of the ship evacuation system only, while operational safety (active), pertaining to any measures to enhance emergency preparedness and to better manage crisis in case of an emergency, is only dealt with by means of a safety factor. In relation to this three issues need to be highlighted:

(a) The IMO evacuation scenarios address issues relating to layout and availability of primary evacuation routes as well as passenger distribution and response times. These however, do not address any real emergencies and hence the need to prepare for such through better planning, training and decision support, all related to the functionality of the crew onboard, a factor as crucial to passenger mustering as a good layout of the escape routes. Breaking away from the traditional approach of the marine industry, Registro Italiano Navale (RINa) has developed a notation dedicated to operational aspects onboard ships with help from SSRC and implemented it on the *Spirit Class* of Carnival, (Dogliani et al. 2004).

This Class Notation aims at assessing the effectiveness of crew functionality by comparing the evacuation performance of a ship in several specific scenarios (in addition to the 4 IMO scenarios), pertaining to social events, ship at berth and owner specified scenarios to reflect real emergencies with and without

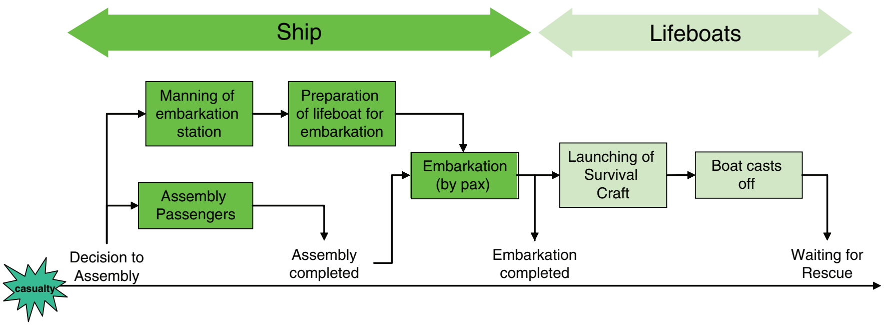

Fig. 2.37 The evacuation process

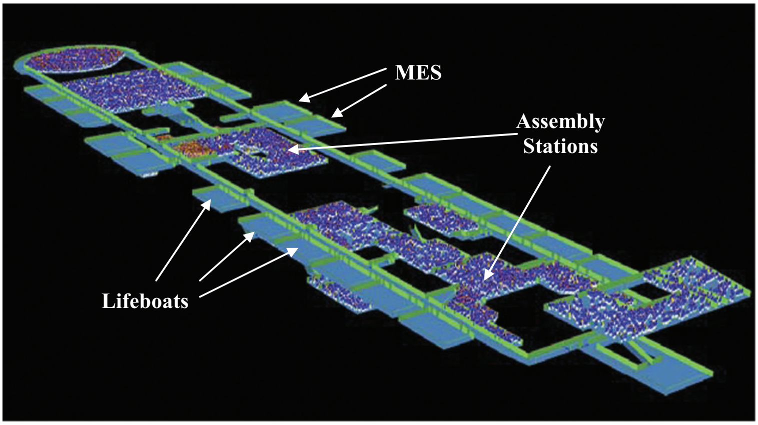

Fig. 2.38 Abandonment studies using *Evi*

crew assistance. This new concept makes evacuation analysis much more relevant offering real "means" for enhancing passenger evacuation performance as well as incentivising passenger ship owners to improve emergency procedures. Stemming from these developments, evacuation analysis in emergency situations through numerical simulations can now be undertaken meaningfully.

(b) The term "Evacuation" tends to be used interchangeably with that of "Mustering" or "Assembly" and in so doing the crucial element of vessel abandonment tends to be overlooked. Emphasis on quantification of time to abandon cannot be stressed enough. As shown in Fig. 2.37, this would involve, in addition to the assembly process (including counting of passengers), embarkation (into lifeboats and MES), launching of lifeboats and clearing the vessel.

All these would involve separate measurements using physical and numerical models (see Fig. 2.38).

(c) "Evacuability" post-accident, in addition to ensuring availability of emergency systems, the influence of floodwater/fire must be ascertained by using coupled flooding/fire evacuation models as described in (Vassalos 2006) and briefly outlined next:

Evacuation Analysis in Flooding Scenarios

The output from PROTEUS3, including time histories of the vessel motions and accelerations, as well as floodwater mass, elevation and attitude in every modelled compartment of the ship, is incorporated into the evacuation model environment (*Evi*) as explicit semantic information concerning the effects of: deck inclination, ship motions and inaccessibility due to floodwater (Fig. 2.39).

The simulation imports motion and flooding data, which is processed to give deck inclination to the horizontal (level) position. Using inclination, a correction factor is applied to the maximum walking speed of an evacuee (agent), based on the results

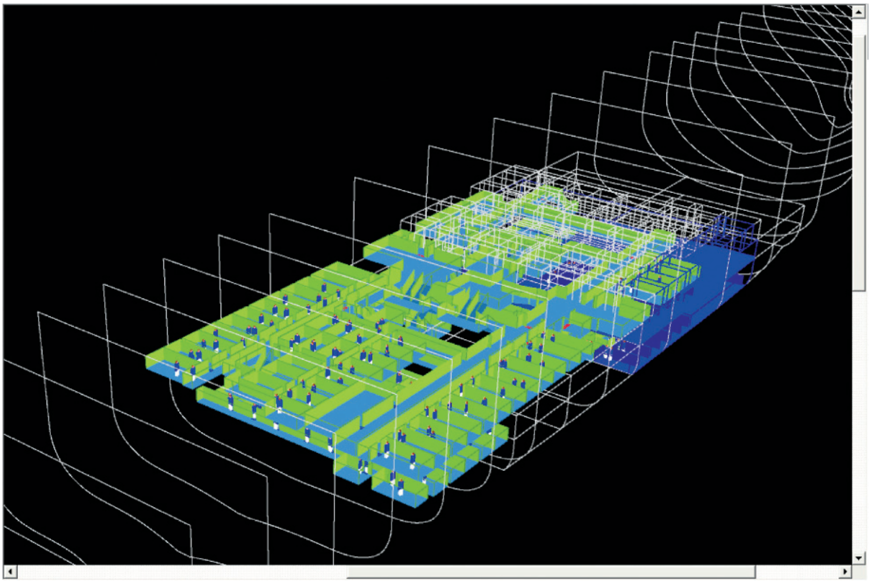

Fig. 2.39 Evacuation analysis – flooding scenarios

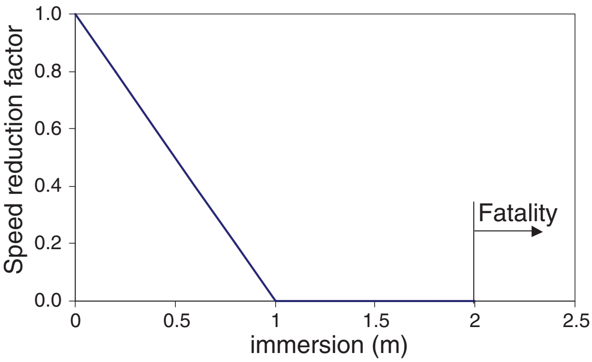

Fig. 2.40 Speed reduction factor due to effect of floodwater

of research undertaken in the MEPDesign project – this has been described in detail in (Vassalos et al. 2002). Thus, flooding data is used to control the awareness and walking speed of agents, reducing it as they become more affected by (immersed into) the floodwater, as illustrated in Fig. 2.40, (Guarin et al. 2004).

Evacuation Analysis in Fire Scenarios

In fire scenarios, the number of injuries/fatalities associated with a specific fire scenario depends on the number of people exposed to the resulting fire hazards.

In this respect, it is well known that when evaluating the consequences of fire effluent to human life, the basic performance criterion states that the time required for escape, normally referred to as RSET (Required Safe Egress Time) should be shorter than the time available for the fire and smoke hazards to reach untenable conditions, normally referred to as ASET (Available Safe Egress Time), (Cooper 2002).

$$\text{RSET} < \text{ASET}$$

The ASET is the interval between the time of ignition and the time at which conditions become untenable such that occupants can no longer take effective action to accomplish their own escape. Untenable conditions during fires may result from inhalation of asphyxiant gases, exposure to radiant and convective heat and visual obscuration due to smoke. A quantitative approach to evaluate the above criterion was implemented by (Guarin et al. 2004, 2007a) and shown here in Fig. 2.41.

Figure 2.42 illustrates an example of this assessment for a large public space. On the left hand side, a snap shot is shown of the time history of temperature calculated with a state-of-the-art field model (Guarin et al. 2007a). On the right hand side, egress simulations include a model for estimating the Fractional Effective Dose (FED) of heat of each occupant, based on the distribution of temperature in time and space. When the FED of an occupant exceeds the tenability criterion $(\text{FED} > 1)$, the occupant can be assumed to be incapacitated. The same can be followed for toxicity and visibility evaluation.

By adopting this approach, the actual human life loss is scenario-specific and is influenced by use of space, occupancy profile, and location of space within the main fire zone (MFZ) as well as the escape and evacuation arrangements. The criterion is evaluated in the space of fire origin and in spaces likely to be affected by smoke propagation within the same MFZ.

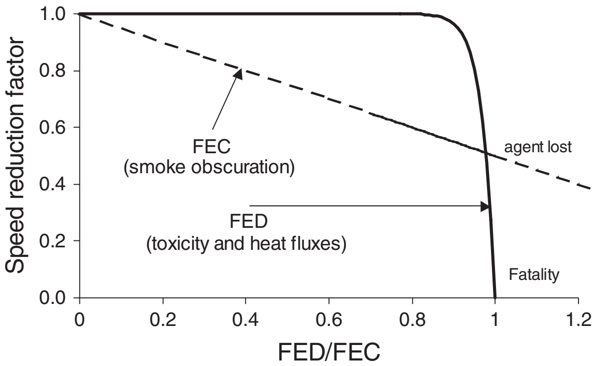

Fig. 2.41 Speed reduction factor due to fire hazards, based on conservative engineering judgement

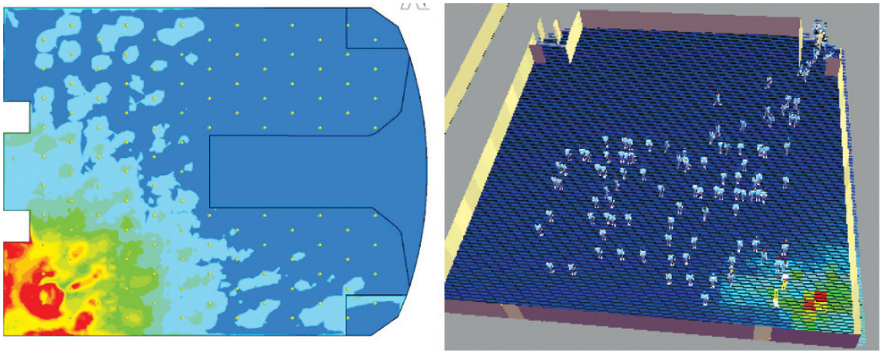

Fig. 2.42 *Left*: temperature at 1.5 m height from floor level for a large public space after 4 min from ignition (Horvat et al. 2007) *Right*: Human injury analyses for the same scenario (Guarin et al. 2007a)

2.1.5 Concluding Remarks

Based on the material presented in the foregoing, the following concluding remarks can be made:

- A new philosophy on "Design for Safety" and the development of a RBD methodology enable ship safety to be dealt with in a systematic and all embracing way by treating safety as an objective in the design process. RBD opens the door to innovation and offers competitive advantage to the maritime industry by facilitating cost-effective safety; without RBD optimal design solutions are not possible.
- In support of the above the use of first-principles tools is highlighted and a workable model presented for quantifying risk in passenger ships with regard to loss of human life. The integration of such tools allows for an explicit and direct evaluation of human life loss in any given loss scenario. Such capability is essential if a "holistic approach" to ship design is to be adopted, particularly in relation to passenger ships (IMO Document SLF 47/8).
- Such approaches reflect the trend toward goal-based standards and highlight the merits of a RBD methodology. This is particularly useful when dealing with innovative ship design concepts and alternative design and arrangements. In such cases, quantitative risk analysis is the only reliable route to ensure that an appropriate level of safety (equivalent to an acceptably low level of risk) and the set safety goals (e.g. safe return to port and "zero tolerance" to human life loss) are achieved.

2.2 RBD Case Story: Large Passenger Vessel

Risk-Based Design (RBD) as a holistic process is by no means mature. However, applications of the underlying principles and tools are evident in ship design, from concept development to detailed design evaluation. By way of demonstration, risk containment of passenger ships will be addressed in the following under the premise that at any given time society must aspire to having passenger ships designed and operated at tolerable (zero tolerance is advocated by the current IMO Framework for passenger ship safety – SLF 47/48) and ALARP risk levels by fully utilising all available knowledge and tools in the design process. More specifically, this can be assured in the design stage by demonstrating that passenger and crew can be safely evacuated in all critical design scenarios (those scenarios where the Casualty Threshold is exceeded, necessitating safe and orderly abandonment of passengers and crew). This can be achieved by addressing the risk of fire and flooding, the two principal accident categories, which as indicated in the foregoing, account for more than 90% of total risk and being responsible for 100% of all passenger ship abandonment cases. RBD can be approached in its simplest form of application (namely tackling a novel concept on the basis of equivalent safety at scenario level – Alternative Design and Arrangements) or at its fully fledged "glory" tackling all design scenarios for all pertinent accident categories and using risk summation to evaluate the safety level of the novel concept design. In either case, the three pertinent issues to be considered involve Evacuation (advanced evacuation simulation is a pre-requisite tool in assessing risk to human life), Flooding and Fire Risk Assessment using proprietary or publically available safety-performance prediction (first-principles) tools. In this chapter, these building blocks of RBD will be addressed first, before demonstrating the implementation of the proposed methodology by presenting design iteration at ship level. The material presented here needs to be considered in conjunction with the material in the Risk-Based Design Overview.

2.2.1 Building Blocks of Risk-Based Design

2.2.1.1 Advanced Evacuation Simulation

The process of evacuating a large passenger ship is very complex, not least because it involves the management of a large number of people on a complex moving platform, of which they normally have very little knowledge. These characteristics make ship evacuation quite different to evacuation from airplanes and buildings. To address the risk associated with passengers and crew at sea, the term *Evacuability* (passenger evacuation performance capability) has been devised, (Vassalos et al. 2002), entailing a wide range of capabilities that encompass evacuation time, identification of potential bottlenecks, assessment of layout, life saving appliances, passenger familiarisation with a ship's environment, crew training, effective evacuation procedures/strategies, intelligent decision support systems for crisis management and design for ease of evacuation. From a technical point of view, the mass evacuation of thousands of people from an extremely complex environment with unknown inaccessibility problems exacerbated by (potentially co-existing) hazards such as floodwater and fire/smoke and the inherent uncertainty deriving from unpredictability of human behaviour in a crisis situation, is a problem with severe modelling difficulties at system, procedural and behavioural levels.

Evacuation has been a high priority in the International Maritime Organisation's (IMO) Agenda since 1999 when SOLAS imposed evacuation analysis to be carried out early in the design stage of new Ro-Ro passenger ships. Following this, the Fire Protection Sub-Committee, after three years of work, issued in February 2002 a set of revised Interim Guidelines for new Ro-Ro passenger ships – new cruise ships and existing ships on a voluntary basis – to be carried out either by simplified analysis or computer-based advanced analysis. Such analysis allows for assessment at the design stage of passive safety (in-built) of the ship evacuation system only, while operational safety (active), pertaining to any measures to enhance emergency preparedness and to better manage crisis in case of an emergency, is only dealt with by means of a safety factor. In this respect, the IMO evacuation scenarios address issues relating to layout and availability of primary escape routes as well as passenger distribution and response times but does not address any real emergencies and hence the need to prepare for these trough better planning, training and decision support, all related to the functionality of the crew onboard, which is as crucial to passenger assembly as a good layout of the escape routes. To address this issue, RINa has developed and launched the first ever notation dedicated to operational aspects with help from the Ship Stability Research Centre (SSRC) and implemented it on the *Spirit Class* of Carnival, (Dogliani et al. 2004).

This Class Notation aims at assessing the effectiveness of crew functionality by comparing the evacuation performance of a ship in several specific scenarios (in addition to 4 IMO scenarios) pertaining to social events, ship at berth and owner specified scenarios to reflect real emergencies with and without crew assistance. This new concept makes evacuation analysis much more relevant offering real "means" for enhancing passenger evacuation performance as well as incentivising passenger ship owners to improve emergency procedures.

Stemming from these developments, evacuation analysis through numerical simulations can now be undertaken meaningfully. In this respect, the term *Evacuability* reflects ability to evacuate a "ship environment" within "a given time" (time to sink/capsize) and for "given initial conditions" and is defined as follows (Fig. 2.43):

$$\boldsymbol{E=f\{env,d,r(t),s[evacplan,crew,mii(g,y,hci)];t\}}$$

More specifically, *Evacuability* is a function of a set of initial conditions, $\boldsymbol{env}$, $\boldsymbol{d}$ and $\boldsymbol{r(t)}$, and evacuation dynamics, $\boldsymbol{s(n_i)}$ (where $\boldsymbol{n_i}$ describes all pertinent procedural and behavioural factors), directly related to and deriving from a loss scenario and provides a direct measure of risk to human life in a ship-sea environment as explained in (Dogliani et al. 2004).

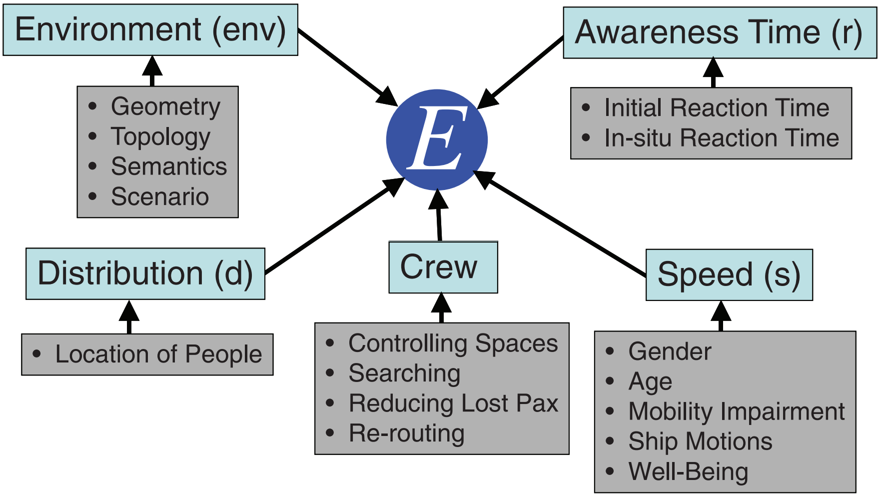

Fig. 2.43 The concept of *Evacuability* (E)

On the basis of the above, it may be stated that *Evacuability* is a well-defined problem that can be formulated and solved (simulated) for a given loss scenario, given initial conditions and passenger flow parameters. In fact, there exist several advanced passenger evacuation simulation tools, some of which are able to deal with design and operational issues as well as be coupled with other advanced prediction tools for flooding (e.g., PROTEUS3 – (Jasionowski 1997–2005) and fire (e.g., REUME – Guarin et al. 2007b), and be utilised to prevent/reduce risk to human life, as postulated in the foregoing. *Evi* (the SSRC advanced evacuation simulation tool), for example, uniquely incorporates capabilities to estimate the effects of both fire and flooding loss scenarios in the evacuation process. In the cases considered, data from external tools that address flooding and fire hazards independently (outside the evacuation simulation environment) is required. This data is then imported into *Evi* as additional semantic information for the agents (evacuees). The agent model considers human behaviour for a small set of crucial characteristics such as speed and awareness. A hazard within the evacuation simulation environment will affect these characteristics by changing the performance of the agents.

2.2.1.2 Flooding Risk Assessment

Background

Collision and grounding/stranding are the largest contributors to the risk of sinkage/capsize for passenger-carrying vessels. The probability of survival and eventually the time to sink/capsize are crucial factors in determining the actual level of safety of a ship design. Whilst the former can be reasonably estimated using empirical methods, the latter (time to sink/capsize) strongly depends on the geometry, topology and status of the internal compartmentation and openings (including doors, ducts, valves, etc) in addition to the random sea environment.

The dynamic response of a damaged vessel, and the progression of floodwater through it in a random seaway form a highly non-linear dynamic system, the behaviour of which can only be assessed through time domain simulation. Building on this view, the University of Strathclyde began to develop the first-ever numerical model of this kind over 25 years ago. Since then, this model has been amply validated and calibrated through its application in both research and consulting work, before arriving at its current version, PROTEUS3. This software suite is capable of simulating the vessel's behaviour (6-dof motions at zero or forward speed of intact or damaged ships, the latter of single or multiple compartment configuration) as well as the evolution of transient and progressive flooding through any damage compartment configuration and any shape and position of openings through which flooding takes place. In addition, a number of non-linear effects can be incorporated, such as wave generated drift, wind loading, dynamic effects of cargo shifting, impulsive excitation and mooring forces, among others. In PROTEUS3, the complex behaviour of floodwater is modelled with a simplified method, developed as an alternative to RANSE CFD techniques. This technique derives from an approximation of floodwater transfer by pendulum-like movement driven by ship-motion-related/gravity acceleration field and constrained by internal compartment geometry on one hand and undisturbed floodwater free surface on the other. Thus, fully non-linear interactions between the ship and floodwater, treated as two interdependent, albeit separate, dynamical systems is represented meaningfully and with sufficient engineering accuracy. The output from PROTEUS3, including time histories of the vessel motions and accelerations, as well as floodwater mass, elevation and attitude in every modelled compartment of the ship, is incorporated into the evacuation simulation environment (*Evi*) as explicit semantic information with the following effects:

- *Deck inclination*: Asymmetric flooding will heel the ship making it more difficult to walk and reducing the speed of agents;
- *Ship Motions*: Dynamic motions will affect peoples' orientation and movement capabilities, consequently, agents will move more slowly, make wrong decisions or may fall over;
- *Inaccessibility*: Flooding will make some areas of the ship inaccessible. This means that for people on lower decks certain evacuation routes may become unavailable.

The simulation imports motion and flooding data, which is processed to give deck inclination to the horizontal (level) position. Using inclination as input, a correction factor is applied to the maximum walking speed of an evacuee based on results of research undertaken in the EU FP4 MEPDesign project – this has been described in detail in (Guarin et al. 2004). Thus, flooding data is used to control the awareness and walking speed of agents, reducing it as they become more affected by the floodwater, as illustrated earlier in Fig. 2.40.

All the above-listed effects, would affect the time needed for orderly assembly and eventually, the time needed for safe evacuation of all people on board. Therefore, for any predetermined flooding scenario, the integrated simulation environment offers the means to evaluate set safety objectives. If these were not met, the effectiveness of potential solutions could be evaluated until an acceptable solution was found. This iterative process, allowing for a direct link between a given scenario and risk, in terms of pertinent parameters affecting frequency and consequences, hence risk prevention/reduction, affords an effective way of "de-risking" a passenger ship from collision/grounding risks.

Flooding Design Scenario

Containment of collision ∩ flooding risk has recently been advanced to a stage at least comparable to that of fire, particularly so with the development of harmonised regulations for damage stability calculations (SOLAS 2009). The relevant design iteration is shown in Fig. 2.44. In the process depicted in (Vassalos 2004), it is implied that if a collision damage case is "critical" (i.e. likely and probably non-survivable), there should be made an effort to find solutions (RCOs) to prevent the vessel from capsizing/sinking. These solutions may be of local and/or global character, enabling the vessel to survive in a "habitable" manner whilst waiting for help or to reach a port of safe refuge (SLF 47/48). When finding cost-effective solutions to survive collision damage passively becomes difficult (i.e. when the "damage threshold" has been exceeded) then the focus might shift to mitigating the ensuing risk to human life. This entails ensuring that **all** people onboard can be evacuated safely. In this sense, the expected time to capsize should be evaluated in conjunction with the

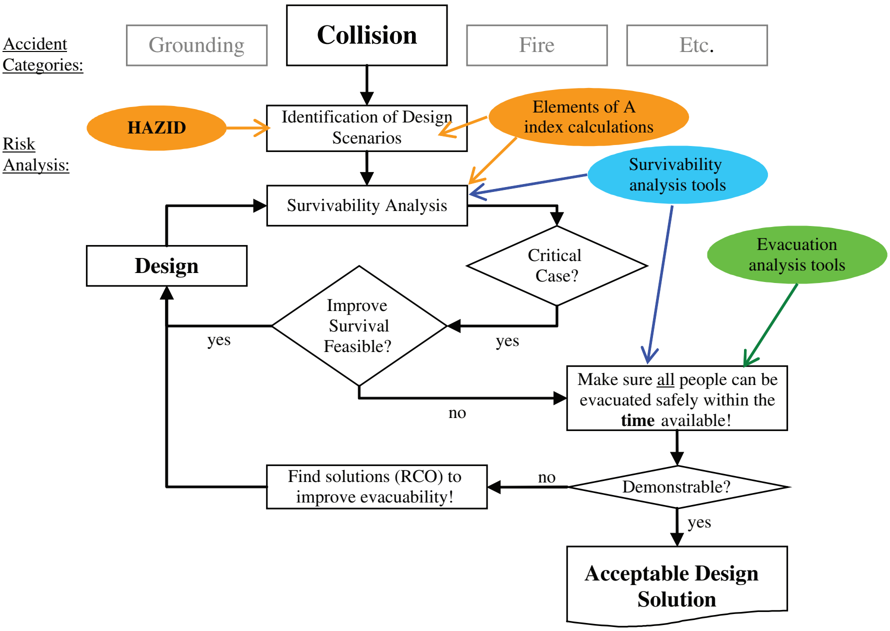

Fig. 2.44 Design iteration for collision damage (flooding scenarios)

expected time needed for evacuation. If this assertion can be demonstrated (through simulation using first-principles tools), then the risk implicit in the resulting design concept could be rendered as low as best knowledge available permits. This approach demonstrates that ship safety, ultimately risk to human life, can be evaluated explicitly and more rationally than just by following the rules.

Figure 2.45 presents schematically typical probability curves for time to capsize/sink and for surviving a given sea state (represented by significant wave height, Hs) corresponding to a damaged vessel subjected to progressive flooding as a function of loading condition (represented by metacentric height –GM– and freeboard).

Figure 2.46 illustrates the evaluation of potential loss of life through passenger evacuation advanced simulation tools, taking as input the available time to sink/capsize deriving from flooding survivability analysis. The figure shows a typical passenger objective completion curve and the quantification of the ensuing risk in terms of potential loss of human life (shaded area).

Deriving from the probabilistic rules for damage stability (SOLAS 2009) and building on the elements comprising Index-A, affords a way of identifying the relative risk contribution of each collision ∩ flooding scenario at an early design stage and hence devise an effective means of risk reduction by focusing primarily on the high risk-contributing loss scenarios. This concept is illustrated in Fig. 2.48 for a RoPax vessel (this is an actual study case). In this figure, a point on the horizontal axis corresponds to the mid coordinate of the flooded compartments. The "relative risk" of non-survival, $p_i \cdot (1 - s_i)$, is plotted on the vertical axis. For a specific damage location, there may be several damage case scenarios depending on the extent of flooding (longitudinally, vertically and transversely). The non-survival probability (relative risk) can be used to identify high-risk areas of the watertight subdivision; design changes in those areas will be the most effective in reducing risk, and of course in improving the subdivision index. This goal can be approached

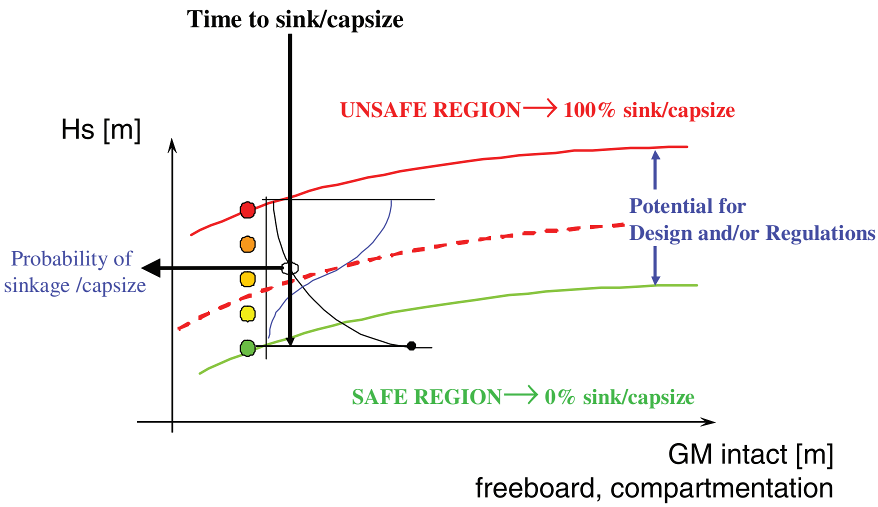

Fig. 2.45 Consequence analysis of a flooding loss scenario (time to capsize)

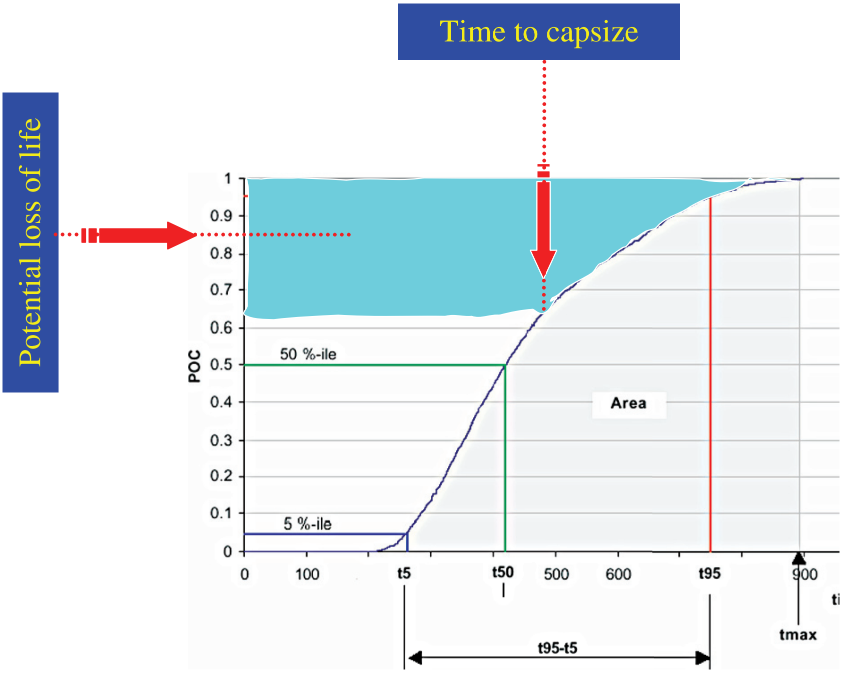

Fig. 2.46 Consequence analysis of flooding loss scenario (risk quantification)

either at scenario or at ship level, the latter by setting up an optimisation problem as explained in the following section.

The flooding design scenario presented here is a night time scenario focusing on an existing large passenger Ro-Ro vessel with 2502 passengers and 190 crew, which at her current configuration achieves an Attained Subdivision Index of A = 0.751, whilst the Required Index has a value of R = 0.821. This means that an improvement of $\Delta A = 0.07$ is needed for the vessel to comply with the probabilistic rules. Figure 2.47 illustrates the cumulative curve of the quantity p.v.(1 – s) (where "v" is a factor limiting vertical extent above the waterline) for all damage cases calculated for this vessel. It shows that in order to achieve the improvement $\Delta A = 0.07$ to ensure compliance, i.e., $A \geq R$, all damage cases with p.v.(1–s) > 0.0048 need to be addressed.

The longitudinal location of all damage cases with s < 1 – damage scenarios with p.v.(1 – s) above 0.0048 – represent critical scenarios with high likelihood in terms of p_i and low survivability in terms of $(1 - s_i)$. This analysis shows that there are 12 cases with the highest potential to improve A (if "s" is made equal to 1 for these cases, then A will be exactly equal to R). The longitudinal location of these damage cases is illustrated in Fig. 2.48. It should be noted that all critical damage cases are either two- or three-compartment damages (7 two-compartment and 5 three-compartment), hence cases that known design measures can be applied for improving the vessel survivability. It goes without saying that it might be more cost-effective to deal with, say, all two compartment damages even if their relative

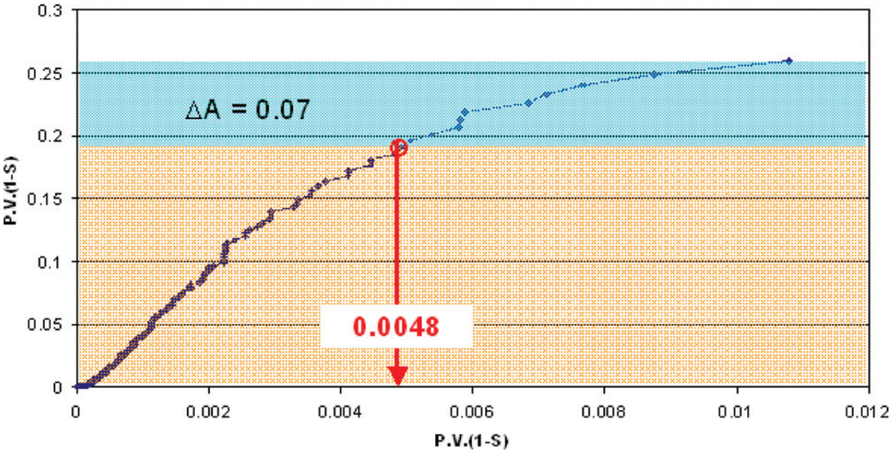

Fig. 2.47 Cumulative dA(risk) for selection of critical damage cases

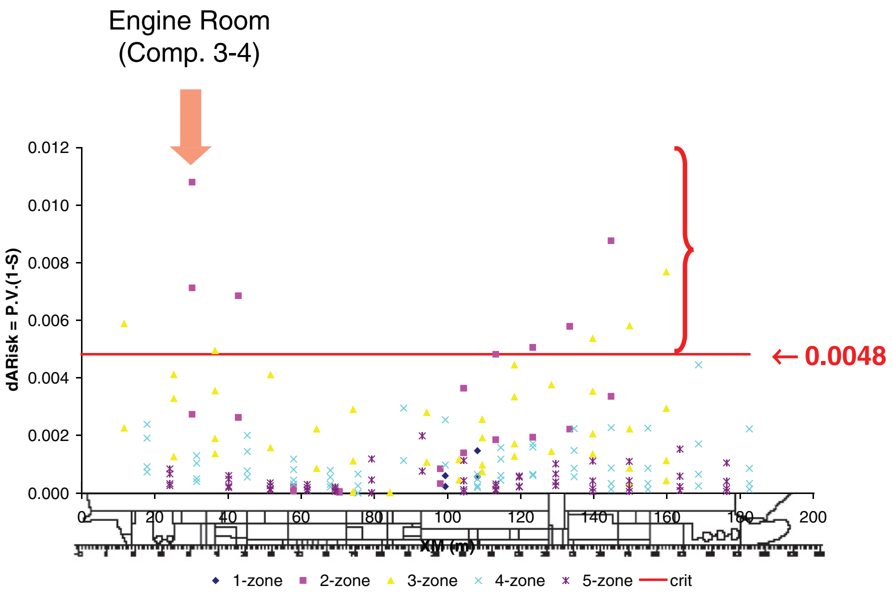

Fig. 2.48 Identification of critical design scenarios (basis ship)

risk contribution is less than the aforementioned value but it makes good sense to focus on high risk areas from top down.

The simplest way to proceed from here is o consider individually critical design scenarios (if only a limited number should be examined) with a view to assessing and negating potential loss of human life trough local design measures (RCOs – such as partial bulkheads, subdivision of side casings, void tanks, double hill and so on). To this end, survivability and time evolution of non-survivable scenarios need to be addressed, followed by assessment of Evacuability for the latter to allow the designer

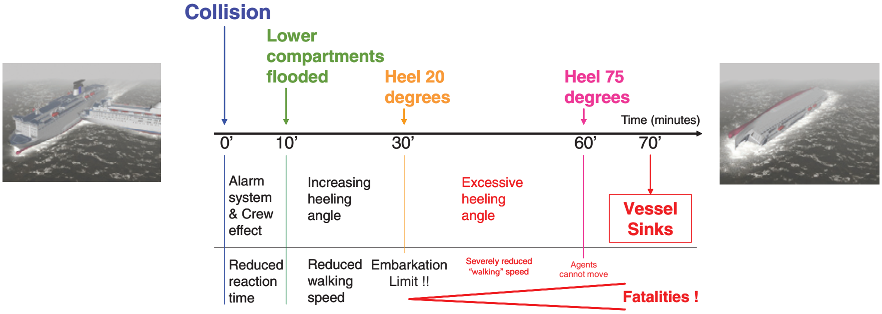

Fig. 2.49 Time evolution of the collision damage scenario

to identify and rank RCOs based on cost-effectiveness. From Fig. 2.48 it would appear that the most "risky" scenario is engine room damage – compartments 3–4). Using IMO Demographics (Vassalos et al. 2003), results from *Evi* show that after 31 min only 2,281 passengers will have abandoned ship, thus leaving 411 passengers in assembly stations (potential casualties). This is, of course, unacceptable and hence cost-effective preventive and mitigating measures need to be identified to contain risk, as explained in Fig. 2.44. The time evolution of this scenario and the effect that it would have on passenger evacuation, hence the ensuing risk, are shown in Fig. 2.49 below.

The optimum local solution identified to address this critical flooding scenario comprises a local repositioning of transverse bulkheads together with 1.2 m double hull in the engine room, up to the subdivision deck. It is interesting to note that using this solution alone results in Index-A of 0.823 ($R = 0.821$), hence compliance with the rules. A number of critical scenarios, however, as shown in Fig. 2.50, still remain critical. In addition, a close examination of Fig. 2.50 helps to demonstrate that even local small changes on a ship may have a wider and profound effect; hence considering isolated scenarios and equivalent safety might lead to overlooking the wide-ranging influence that invariably these changes have on the ship as a whole.

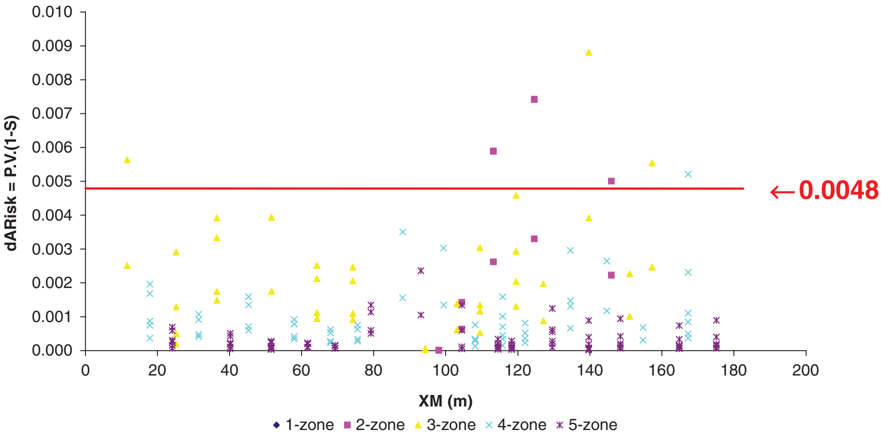

Fig. 2.50 Identification of critical design scenarios (design solution 1)

2.2.1.3 Fire Risk Assessment

Background

Despite the fact that prevention and mitigation of the most common fire events onboard ships are extensively addressed by current prescriptive regulations, fire continues to be one of the major hazards to ship operations. Currently, fire safety in ship design is addressed through compliance with prescriptive SOLAS regulations, dealing with issues of prevention, suppression and escape, among others. These regulations have a major impact on the resulting designs, in terms of layout, functionality and costs, in some cases inhibiting development of innovative, equally safe but potentially more cost-effective and more lucrative solutions. Such issues are important in all sectors of the maritime industry today. At the same time, the increased level of understanding of fire physics and of the influence of fire hazards on human behaviour as well as advances in fire modelling have encouraged the use of performance-based design codes d in the maritime industry.

In fact, the adoption of the provisions for alternative design & arrangements for fire safety (*IMO*, 2006) heralded the beginning of risk-based design and regulation and the advent of indoor promenades and atria in passenger ship design. This is reflected in the new SOLAS Ch. II-2/Regulation 17 (SOLAS 2004), which allows the use of performance-based fire engineering methods to demonstrate that design solutions not complying with some of the prescriptive regulations are as safe as an equivalent prescriptive design. This approach is commonly referred to as the "equivalence" principle, according to which the design solution, referred to as an "alternative" design, is set to achieve the same fire safety objectives and comply with the same functional requirements as an equivalent prescriptive design. Despite being more time consuming and expensive than the traditional prescriptive approach, performance-based ship design may lead to potentially safer, innovative, attractive and more cost-effective design solutions. Available statistics, for instance (Mather and Strang 1997), indicate that more than 60% of all fire casualties occur in general cargo ships, bulk carriers and oil tankers. Passenger ships (including RoPax) account for just 6% of all fire incidents. In spite of this, high numbers of people carried on board put newer passenger ships at significant risk of life loss (in relation to other ship types) arising from fire. Moreover, current trends in ship design suggest that alternative design solutions developed with performance-based methods for fire safety will be a feature mainly of passenger ships; hence the focus on fire safety from the point of view of passenger survival alone.

Even though experience with the use of alternative design for fire safety is being amassed, it has not yet become routine and there are good reasons for this: prescriptive design is easier (specific training is not needed), and fire-engineering tools are neither easily available nor easy to use; hence such studies are normally performed by specialist consultants. However, as far as passenger ships are concerned, there are many potential areas for exploiting benefits of alternative design (large internal promenades, larger than currently permitted public spaces, alternative ventilation strategies, alternative escape and evacuation arrangements, parks, theatres, atria, multi-storey restaurants and so on).

For these cases, the performance criteria are associated with safety of human life and mitigation of material damage to the ship for a specified fire event. Thus, parameters describing the hazards associated with fires (such as temperature, heat fluxes, toxic contamination and visibility obscuration) must be predicted with sufficient accuracy for large and small spaces of simple and non-standard geometries, e.g. with large horizontal or vertical dimensions (corridors, vehicle decks, staircases, atria, engine rooms). On the other hand, the level of uncertainty in the associated parameters necessitates that variational studies be conducted to ascertain the level of sensitivity of the results. Thus fire-engineering tools must be able to provide quick solutions even for large applications, ranging from few spaces to complete vertical fire zones spanning several decks. In terms of alternative design and arrangements for fire safety as stated in SOLAS Regulation 17, the use of consequence-analysis tools in conjunction with appropriate criteria for evaluating human life safety is essential, as explained next.

It is well established that when evaluating the consequences of fire effluent to human life, the crucial criterion for life safety is that the time available for escape from a ship space should be greater than the time required for safe evacuation of occupants. The time available for escape is the interval between the time of ignition and the time for conditions to become untenable such that occupants can no longer take effective action to accomplish their own escape. Untenable conditions during fires may result from:

- *Inhalation of asphyxiant gases*: these may cause loss of consciousness and ultimately death resulting from hypoxic effects, particularly on the central nervous and cardiovascular systems,
- *Exposure to radiant and convective heat*, and
- *Visual obscuration* due to smoke.

The above represent the fire hazards and can be imported and distributed in time and space into the evacuation environment (*Evi*) as explicit semantic information for the agents, much the same as in the case of flooding scenarios. These include concentrations of CO, CO_2 and O_2, as well as Temperature, Radiant Heat Flux and Optical Density directly affecting –at each time step– the awareness and walking speed of the evacuees (agents). In order to estimate the effect of the fire hazards, an approach presented in (Purser 2002) is adopted based on the concept of Fractional Effective Dose (FED, for toxicity and heat) and Fractional Effective Concentration (FEC, for visibility). The FED and FEC are values indicating the human vulnerability to the cumulative effects of exposure to heat and toxic gases as well as the level of visibility in a space. Their values are calculated for each agent individually and are used to control walking speed and awareness and determine the point at which an agent becomes fatally injured, as mentioned earlier and illustrated in Fig. 2.41.

Once again, by linking a given fire scenario to the ensuing risk directly through pertinent parameters affecting risk prevention/reduction, cost-effective solutions can be identified to “de-risk” passenger ships from fire risk.

Fire Design Scenario

In this case a fire design scenario is selected to demonstrate fire risk assessment and containment by using an alternative design and the principle of "Equivalent Safety". SOLAS Ch. II-2.24 states that a main vertical fire zone (MVZ) should not be of greater length than 48 m (to coincide with watertight subdivision bulkheads). In order to incorporate larger public areas, one is allowed to design beyond this length provided that the total area of the public space does not exceed $1,600\,\mathrm{m}^2$ (the latter could also be tackled similarly). In July 2002, SOLAS regulation II-2/17 (MSC/Circ.1002) was adopted, which allows designs not strictly complying with the existing prescriptive fire safety regulations to be accepted provided such designs can be shown to be at least as safe as the design made in accordance with the IMO rules. This allows modern passenger vessel designs to go beyond the fire safety limits in order to create more inviting and exciting passenger spaces. The iteration to be followed is illustrated in Fig. 2.51, whilst the scenario being addressed here is described in Table 2.1 and illustrated in Fig. 2.52.

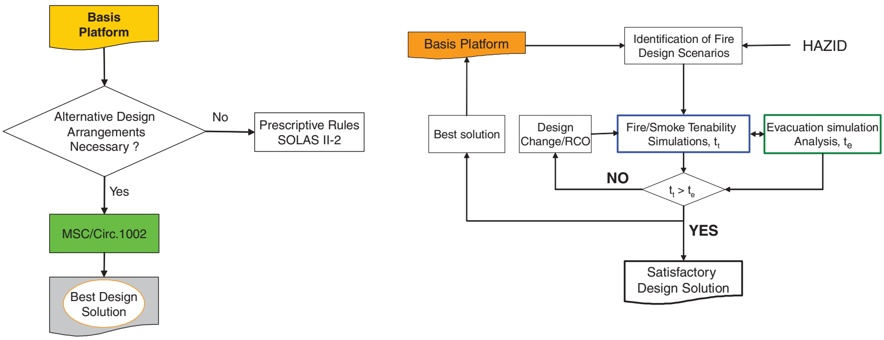

Fig. 2.51 Alternative design and arrangements iteration for fire safety

Table 2.1 Restaurant design parameters – 48 and 60 m restaurant designs

Restaurant design		Prescriptive	Alternative design
Length		48 m	60 m
Capacity	Lower deck	750 pax	690 pax
	Upper deck	550 pax	960 pax
	Total	1,300 pax	1,650 pax
Total exits' width	Lower deck	9.4 m	11.4 m
	Upper deck	10.8 m	10.8 m
Floor area	Lower deck	$1,154\,\mathrm{m}^2$	$1,872\,\mathrm{m}^2$
	Upper deck	$1,497\,\mathrm{m}^2$	$1,748\,\mathrm{m}^2$

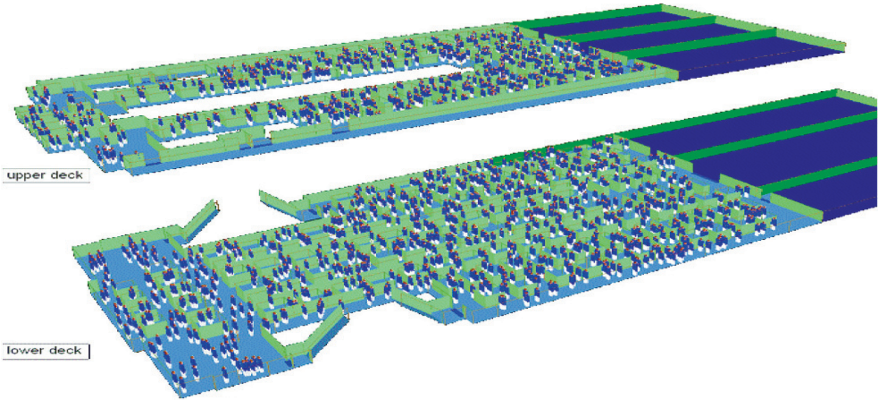

Fig. 2.52 Alternative design approach – upper and lower Decks of a 60 m restaurant

In the scenario considered, the fire ignites at the forward starboard end of the lower deck as illustrated in Fig. 2.53. Smoke propagates through the forward end of this deck and up through the central opening to the upper deck.

To determine the risk quantitatively, frequency (f_i) and consequences (c_i) for the scenario in question need to be estimated. In a general case, accident/incident statistics may be used for frequency estimation but in this particular case where an alternative design is considered only consequences will be used to quantify risk. The consequences are quantified on the basis of the number of injuries/fatalities and/or the expected damage to equipment and/or ship. The metric for risk calculation is defined a priory, consistently with an appropriate risk criterion. The number of injuries/fatalities is obtained from evacuation simulations using *Evi* in conjunction with output from fire engineering calculations using *REUME*. The latter is employed to assess the development of fire and smoke in the restaurant arrangement, and the

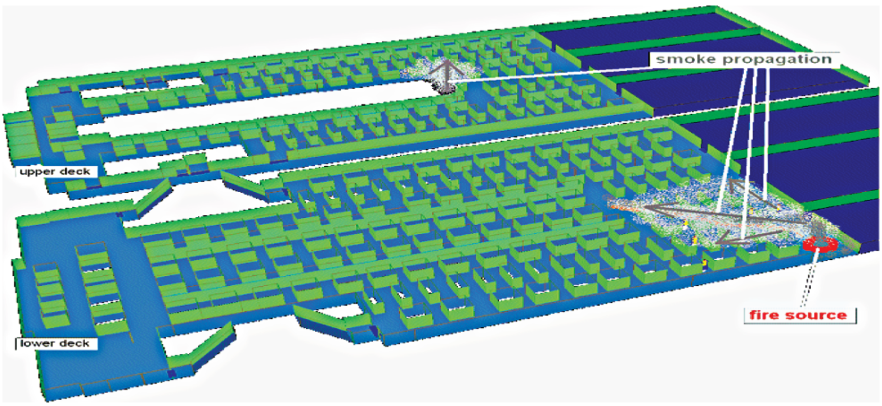

Fig. 2.53 Alternative design approach – illustration of fire and smoke through the lower and upper decks of the restaurant

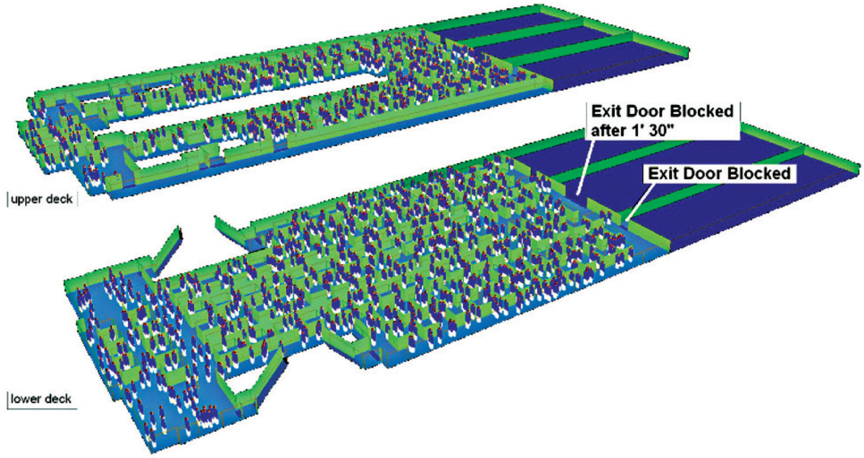

Fig. 2.54 Alternative design approach – exits blocked by fire

resulting distribution of fire hazards (quantified in terms of toxicity, visibility and heat) appropriately incorporated into *Evi* (Fig. 2.54).

The number of fatalities depends on the time to egress from the respective spaces (output from *Evi*) and the time to reach untenable conditions in these spaces, in terms of toxicity, visibility and heat. According to the risk metric used, appropriate risk acceptability criteria can be defined and hence the risk level evaluated against selected criteria as explained in the foregoing. If the risk level is not acceptable for any one evaluated scenario, potential RCOs will be evaluated based on cost-effectiveness analysis. In the scenario considered, smoke originates at the lower deck, starboard side forward of the restaurant and spreads to upper deck with untenable conditions (UC) being reached within 4–5 min. The fire blocks the primary escape route at the forward end of the restaurant and passengers have to use alternative (secondary escape) routes. This increases congestion and causes the total egress time to increase. In this respect, the egress time ought to be compared with the time required for conditions to become untenable as a means of assessing the ensuing risk. Table 2.2 and Figs. 2.55, 2.56 and 2.57 show the results deriving from evacuation and smoke spreading simulations.

The results clearly demonstrate unacceptable consequences and hence the need to contain the risk associated with the fire scenario being considered. To this end,

Table 2.2 Alternative design (ALT 1) – consequences analyses

Spaces	Egress time	Time to reach UC	No. of passengers affected
Upper deck	7–8 min	4–5 min	28 ($\sim$ 4%)
Lower deck	8–9 min	4–5 min	50 ($\sim$ 5%)

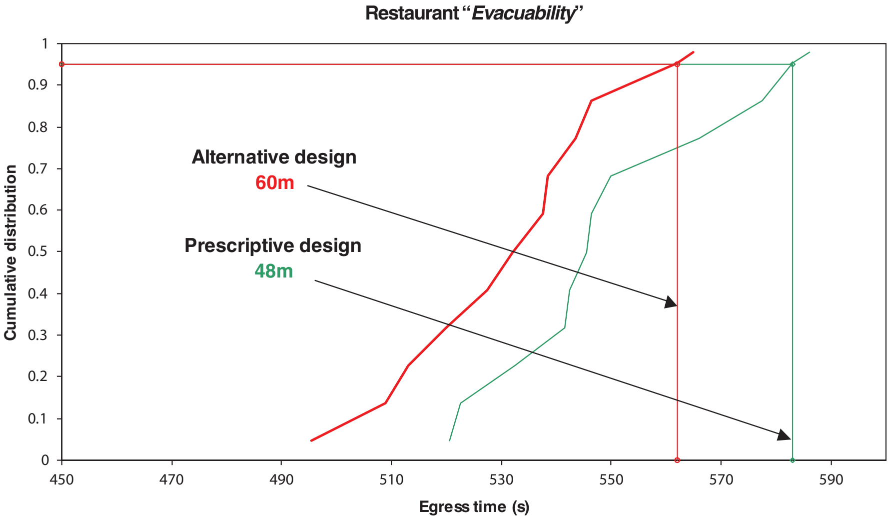

Fig. 2.55 Non-fire scenario – comparison between alternative and prescriptive designs

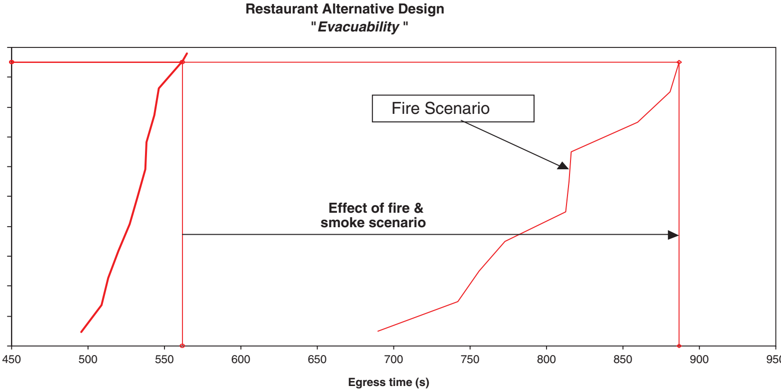

Fig. 2.56 Alternative design – normal vs. fire scenario

a number of RCOs were considered, the most cost-effective of which include the following:

- Increasing the number of smoke extraction fans from 2 to 4
- Increasing the number of inlet air fans from 2 to 4
- Widening escape ways

Following implementation of the aforementioned RCOs, the ensuing consequences are now as shown in Table 2.3 and hence acceptable.

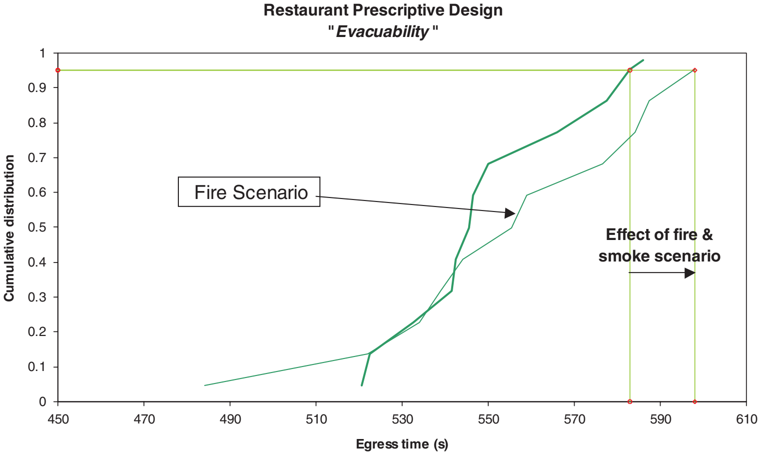

Fig. 2.57 Prescriptive design – evacuability – normal vs. fire scenario

Table 2.3 Alternative design (ALT 2) – consequences analyses

Spaces	Egress time	Time to reach UC	No. of passengers affected
Upper deck	5–7 min	8–9 min	0
Lower deck	6–7 min	8–9 min	0

2.2.2 Early Implementation Results

In this section, some early results will be presented aiming to provide answers and clarity to concepts pertaining to RBD implementation regarding evaluation of a ship's safety level. To this end, a hypothetical cruise ship is used with the following particulars:

The subdivision layout is shown in Fig. 2.61. Reference is made to the safety level evaluation framework, Fig. 2.15 and the ensuing scope of work that was introduced in RBD Overview.

2.2.2.1 Flooding Survivability Analysis

Flooding survivability analysis normally entails the following, which are addressed here at various levels of detail.

- Statutory Assessment
  - Compliance with SOLAS 2009 (probabilistic rules)
  - Optimisation of watertight subdivision

- Transient-, cross- and progressive-flooding assessment
  - Static vs. dynamic stability
  - Time to flood
- Time to Capsize
  - Probabilistic approach for selection of damage (collision and grounding) cases
  - Vulnerability approach for survivability assessment
- Systems availability for each flooding scenario
  - Geometrical and topological evaluation of main ship systems
- Evacuability assessment
  - Assembly and evacuation performance
  - Assessment of time to capsize against total evacuation time
- Evaluation of casualty threshold/return to port capability
  - Probabilistic approach; link to system availability post-casualty

Statutory Assessment

Acknowledging that emphasis on preventing a casualty from occurring in the first instance must take priority, focus on risk reduction by passive means (in-built safety) must come next and this must start at the beginning. To this end, the dilemma of prescriptive SOLAS-minded designers, illustrated in Fig. 2.58, in the simplest of levels, must be overcome. It is obvious that internal subdivision arrangement is a key issue affecting ship performance, functionality and safety, all of which have to date been catered for through the provision of rules and regulations that reflect, in essence, codification of best practice. Throwing this away and leaving on the table a blank sheet, makes ship subdivision a very difficult problem indeed. This was essentially the problem addressed in the EU project ROROPROB, (ROROPROB 1999–2002).

Building on the understanding of Index-A as outlined in Sect. 3.1, affords a straightforward way of determining the relative collision $\cap$ flooding risk profile of a vessel at an early design stage and hence devise an effective means of risk reduction by focusing primarily on the high risk scenarios.

The fully automated optimisation process typically produces several hundred design alternatives depending on the complexity of the ship's layout and the number of variables. Typical variables of the optimisation problem include: type of subdivision, number, location and height of watertight bulkheads, deck heights, tank arrangement, casings, double hull, and position of staircases, lifts and escape routes. Using the Attained Subdivision Index, payload capacity, steel weight and other regulatory requirements as typical objectives/constraints, the optimisation problem outcome typically includes: reduced number of bulkheads, reduced deck heights,

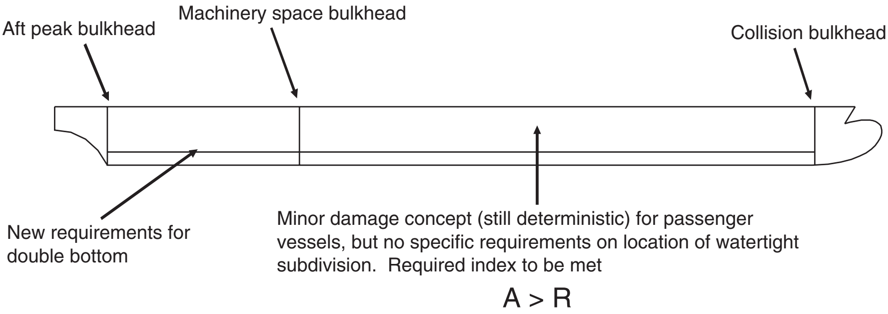

Fig. 2.58 Largely "unguided" subdivision (probabilistic rules)

reduced void volume, reduced number of escape ways and required staircases, reduced steel weight, reduced complexity in tank arrangements, increased crew and service areas, improved functionality and, if required, improved Attained Subdivision Index. In order to make the process effective, participation by all decision-makers (designer, owner and yard) is essential to properly define the optimisation variables, objectives and constraints as early as possible in the design stage. Using this approach, known as "platform optimisation", high survivability internal ship layouts can be developed, without deviating much from the current SOLAS practice, this making it easier for ship designers to relate to the proposed procedure. The actual process for platform optimisation as it is currently being applied to

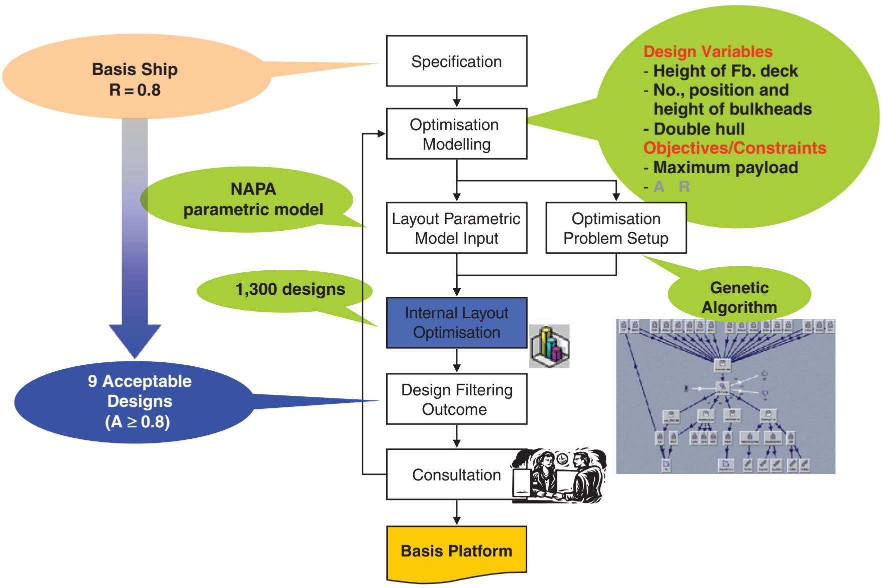

Fig. 2.59 Platform optimisation process

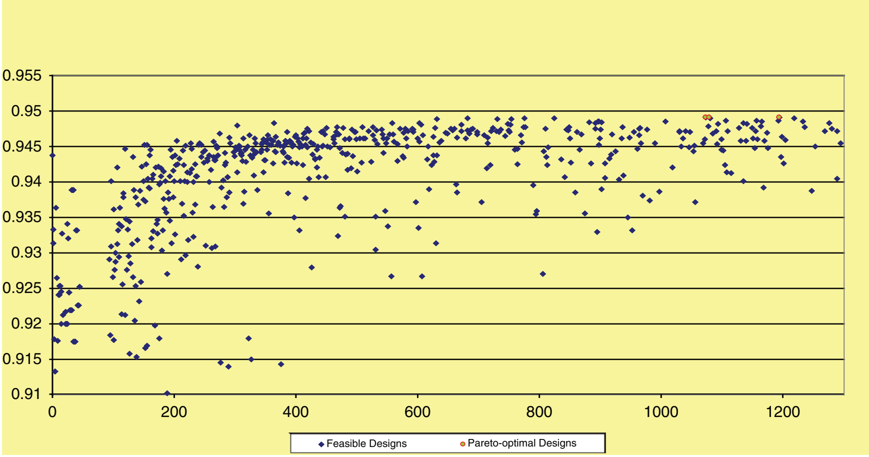

Fig. 2.60 Platform optimisation process – concept designs

newbuildings design is illustrated in Fig. 2.59. A sample of the optimisation problem outcome is presented in Fig. 2.60.

Using the hypothetical cruise vessel of Table 2.4 and Fig. 2.61 (Version 1) as a basis, Version 5 (Fig. 2.62) is produced using the process outlined above with $A = 0.92$. Taking additional measures from the available array of current best SOLAS practice, it was possible to further increase the attained A-Index to 0.985, without sacrificing any of the vessel's functionality. Time domain simulations with PROTEUS3 have shown that such a vessel would survive all probable damages up to 3-compartment damage for all sea states up to 4 m Hs (the international voyages limit for Stockholm Agreement).

Flooding Vulnerability Assessment

Following from Sect. 3.1, the risk profile of Version 1 of the example cruise ship is illustrated in Fig. 2.63 for all the statistically possible damage scenarios deriving

Table 2.4 Principal particulars of example cruise vessel

Length	270 m
Breadth	35.5 m
Draught	8.3 m
Displacement	56,500 tonnes
Metacentric Height	2.35 m
Number of passengers	2,300
Attained Index of Subdivision, A	0.8
Required Index of Subdivision, R	0.8

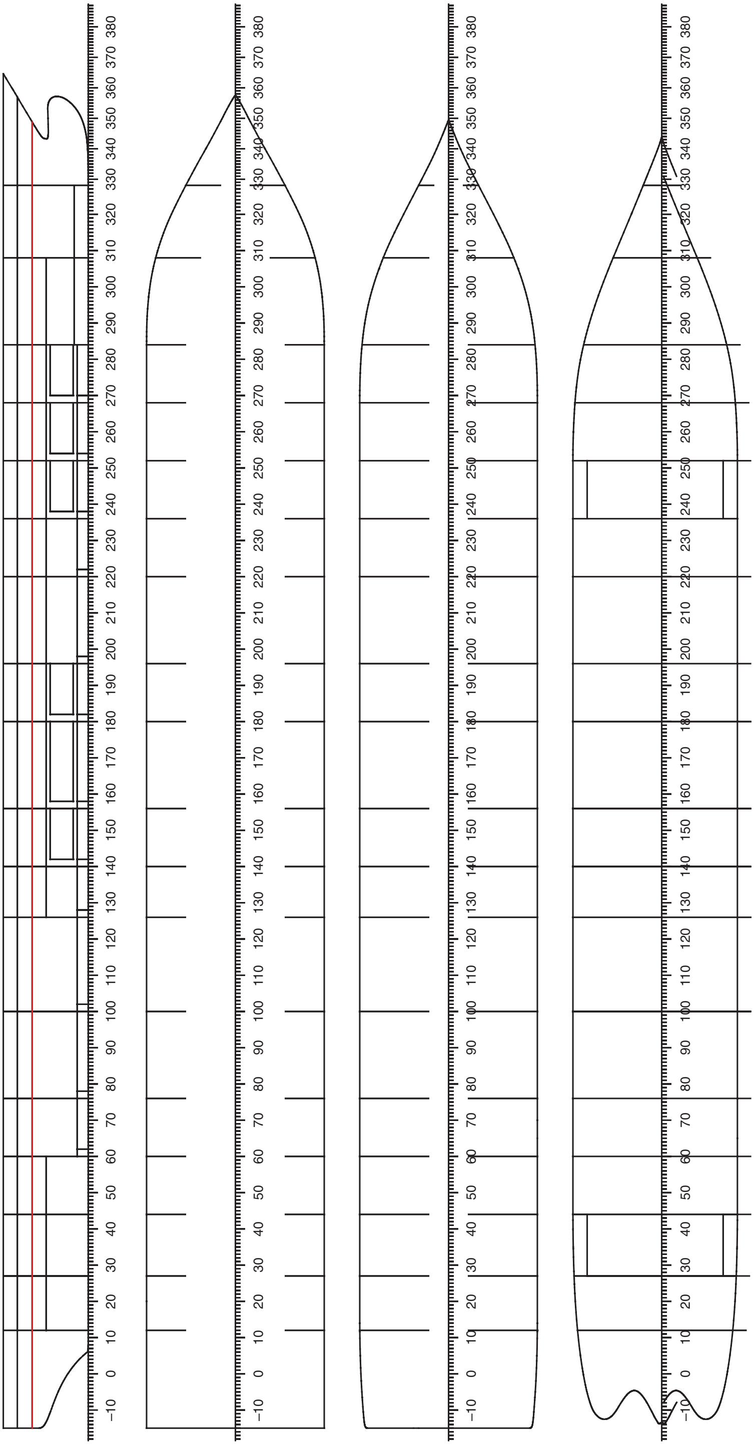

Fig. 2.61 Example cruise vessel subdivision, ver 1

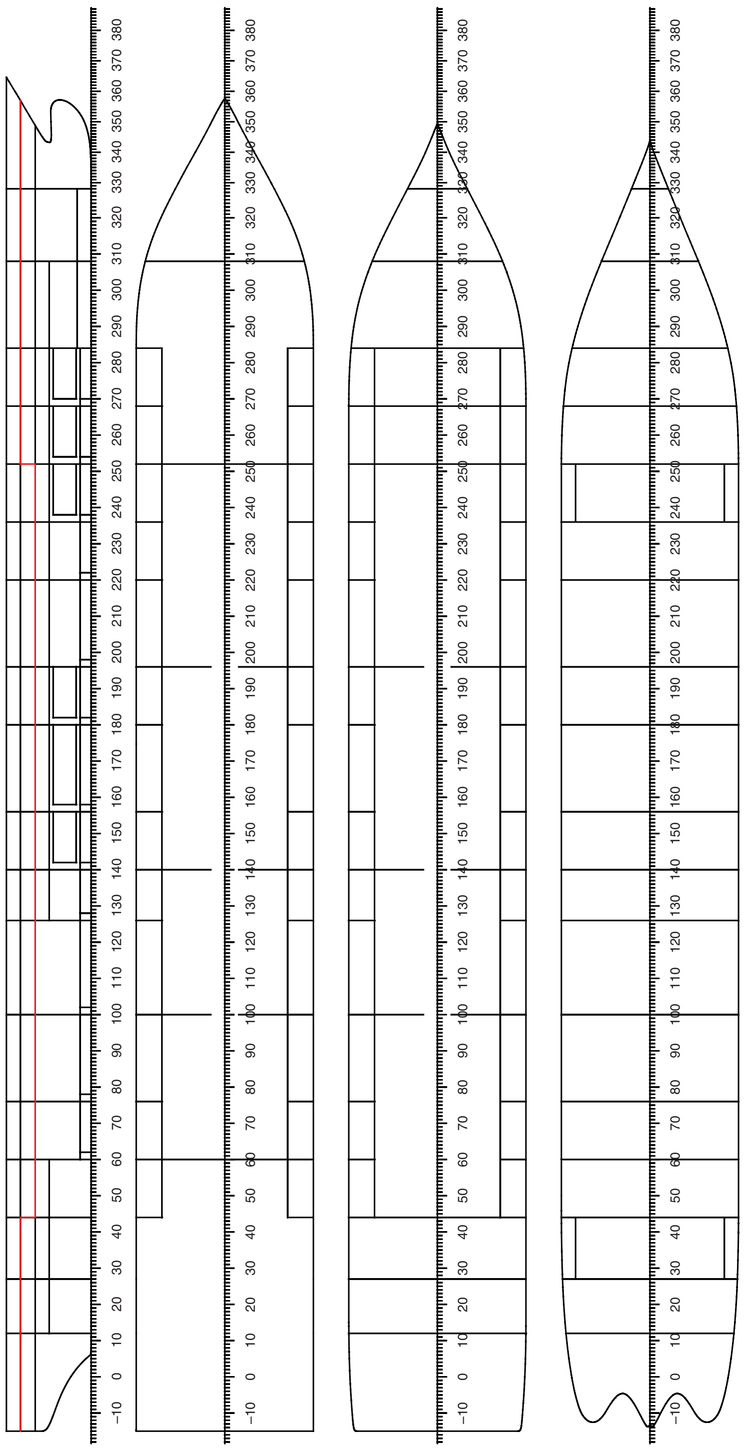

Fig. 2.62 Example cruise vessel subdivision, ver 5

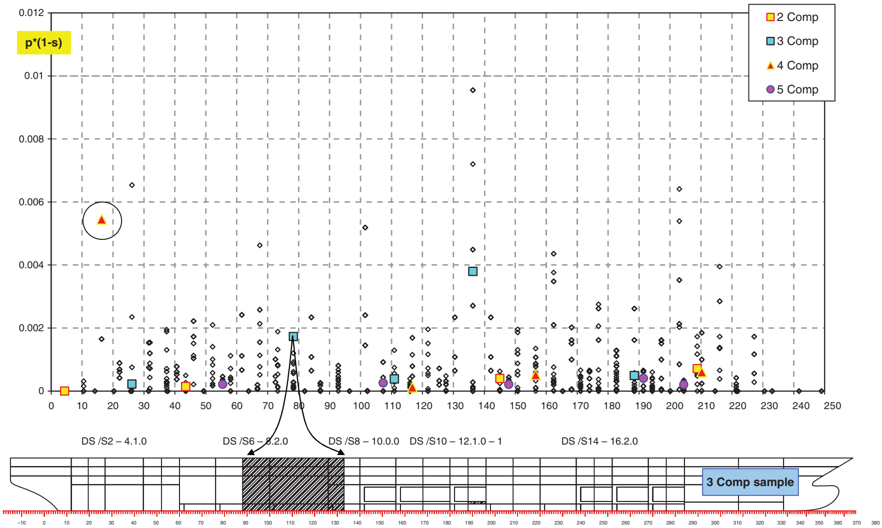

Fig. 2.63 Distribution of relative contribution to risk per damage case, ver 1

from the probabilistic rules for damage stability (Hs, loading condition, collision and grounding – the latter in addition to the current set of scenarios, which relate only to collision damage statistics).

As indicated in Sect. 3.1, these scenarios could be supplemented by using relevant experiential knowledge judiciously and through HAZID/brainstorming sessions with designer/yard/owner participating, aiming to identify any design vulnerability. Numerical simulations can then be used in calm water and in waves (as required) to establish the exact flooding mechanism and identify cost-effective changes for the local watertight arrangement using, for example, the PROTEUS3 software suite. The results are analysed in terms of occurrence of potentially dangerous behaviour or attitudes by addressing the following three modes of flooding explicitly, on a case by case basis and using a much more complex (in terms of

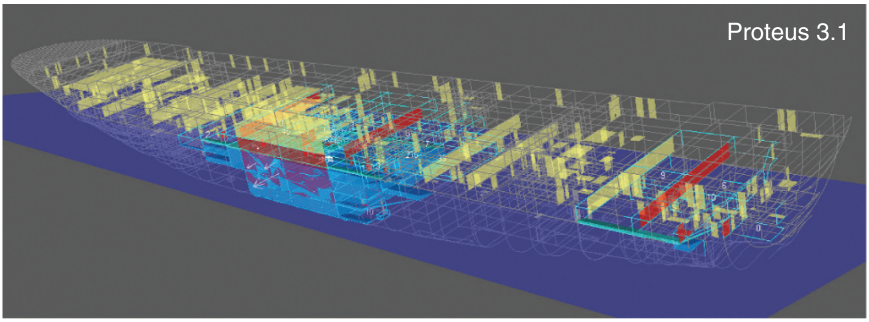

Fig. 2.64 Typical model used for flooding survivability analysis

number of compartments and number of openings) and more complete model (up to 5 decks are being modelled – see Fig. 2.64):

(a) Initial (transient) Flooding
(b) Cross-Flooding
(c) Progressive Flooding

Focus during intermediate stages of flooding targets risk associated with the following hazards:

Transient and Intermediate Flooding. Having to deal with such a complex geometry, explicit dynamic flooding simulation of a damaged ship in waves is a must. Static analysis simply will not do. Moreover, in some cases where cross-flooding through intricate connection arrangements becomes a problem in terms of long cross-flooding times, results from simplified time-domain simulation codes need to be supported using CFD as the only viable option for a proper treatment of such a problem. The fact that industry appears to be pre-ordained to use static analysis when addressing damage survivability could at best affect adversely the design process and at worst severely undermine safety. Figures 2.65 and 2.66 demonstrate two such cases. In Fig. 2.65, the s-factor results in zero, because the angle of inclination exceeds the statutory range, which does not reflect what actually happens.

Conversely, Fig. 2.66 shows a damage case where the s-factor results in zero based on the SOLAS 2009 formulation whilst numerical simulation results indicate progressive flooding, likely to result in capsize/sinking.

Multi-free Surface Effect. This mechanism of capsize is relevant to ships with complex watertight subdivision such as cruise ships. As the hull is breached, water rushes through various compartments at different levels (Fig. 2.67), substantially reducing stability even when the floodwater amount is relatively small. As a result the ship can heel to large angles, even for small damage openings, letting water into

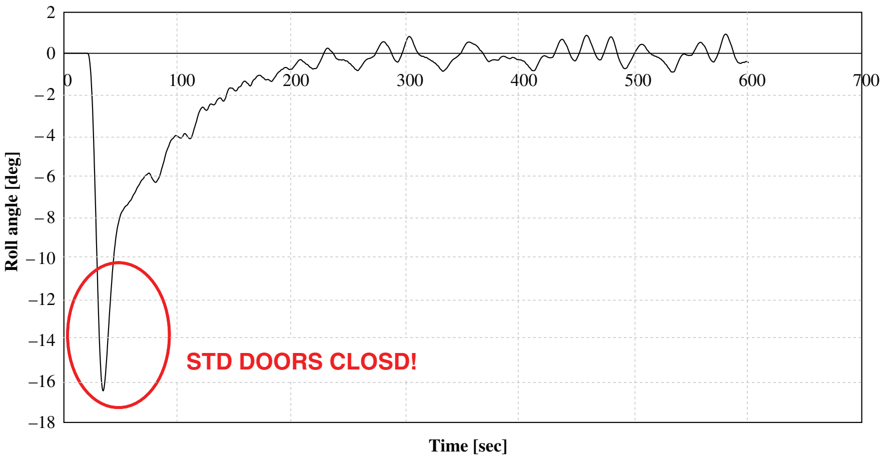

Fig. 2.65 Numerical simulation of transient flooding behaviour (calculated $s = 0$)

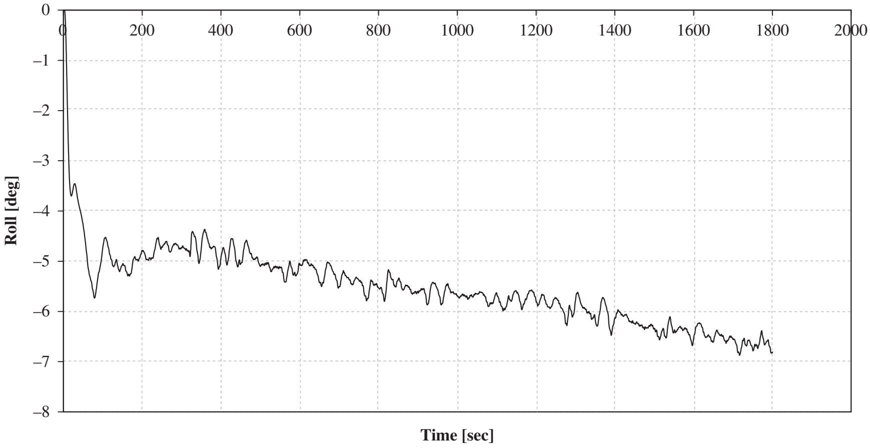

Fig. 2.66 Numerical simulation of transient flooding behaviour (calculated $s = 1$)

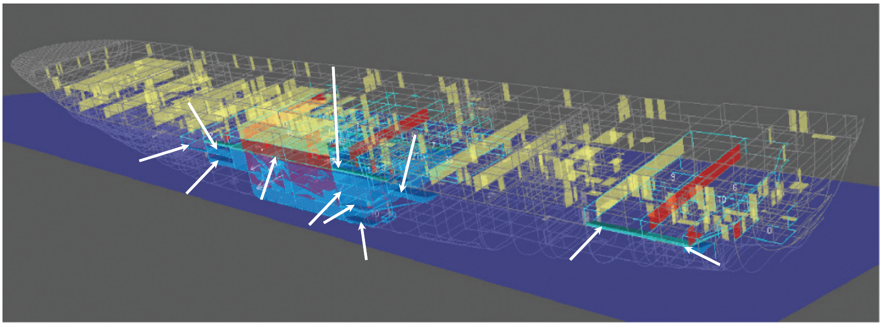

Fig. 2.67 Multi-free surface effect during intermediate stages of flooding

the upper decks that spreads rapidly through these spaces and may lead to rapid capsize at any stage of the flooding.

Bulkhead Deck Submergence and Progressive Flooding (Ducting, Piping, Doors, Windows, Shafts, etc). Scenarios of this nature demonstrate the need for explicit knowledge on how the flooding process evolves, as in many cases it proves to be rather straightforward to impede the evolution of flooding with easy and very cost-effective measures. Figures 2.68 and 2.69 show the post-processing that modern tools afford in this quest.

Time to Capsize

The results of the foregoing investigation is analysed in terms of the distribution for the time it takes the vessel to capsize/sink, one of the key parameters in flooding risk estimation. As outlined in the RBD Overview, accounting only for the damage

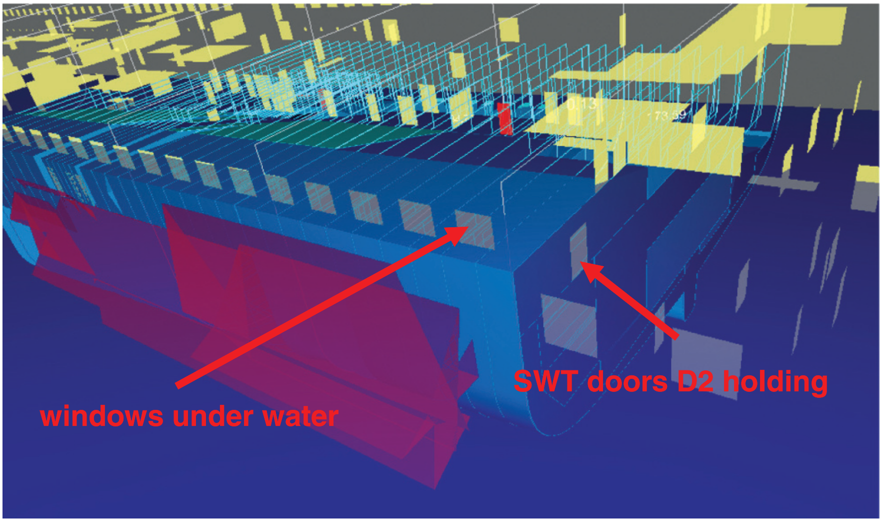

Fig. 2.68 Time-domain simulation of the flooding process (windows and SWT doors)

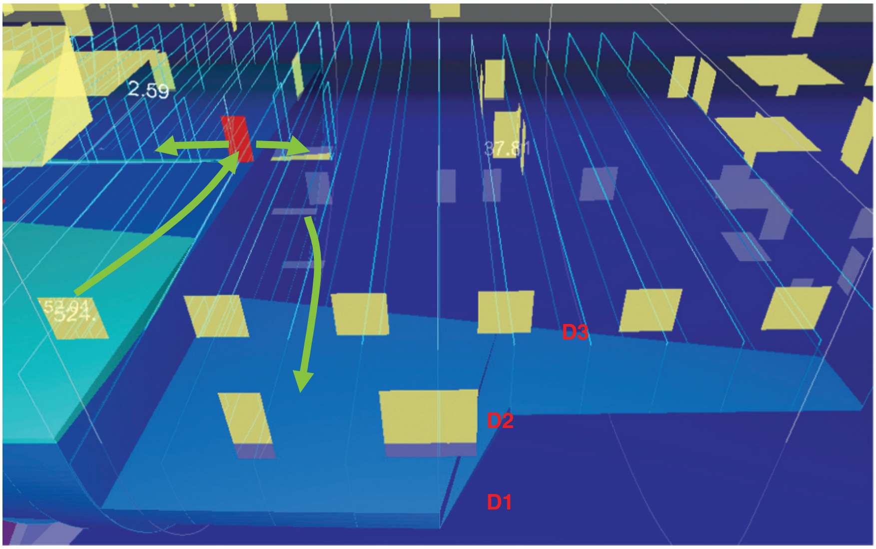

Fig. 2.69 Time-domain simulation of the flooding process (various openings)

case scenarios implicit in the new harmonised rules for damage stability (normally over 1,000) and considering the 3 loading conditions, also implicit in the rules, and some 10 sea states per damage case, one would have to deal with tens of thousands of scenarios. Therefore, as indicated earlier, two lines of action are being followed: the first entails automation of the process using Monte Carlo simulation; the second

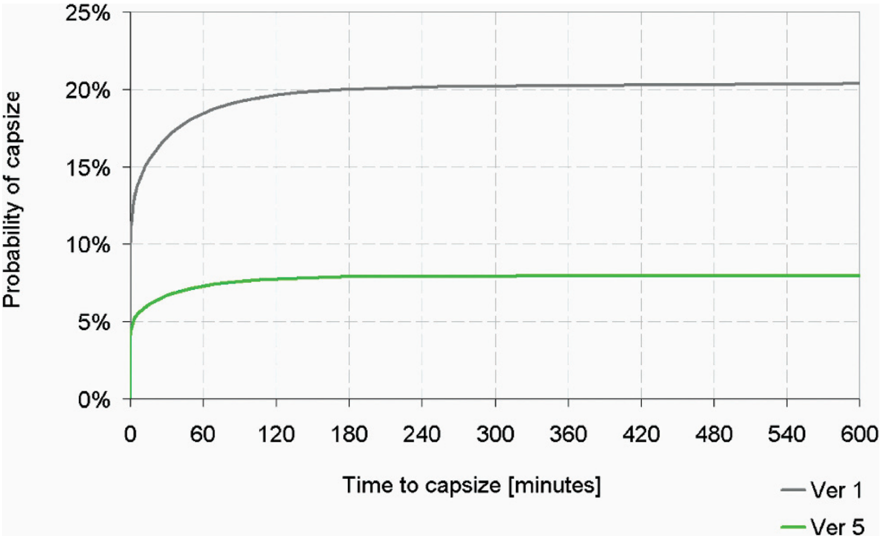

Fig. 2.70 Cumulative probability distribution for time to capsize within a given time for two ship layouts shown in Figs. 2.22 and 2.23

relates to the development of a simpler (inference) model for estimating the time to capsize for any given collision damage scenario.

For the example cruise vessel, results using the simpler model are displayed in Fig. 2.70, next.

A close examination of Fig. 2.70 reveals that a 15% increase in Index-A from Version 1 to 5 of the example cruise ship, results in a 60% reduction in the probability to capsize within 3 h. Knowledge of the probability of survival beyond [3] hours in all relevant flooding scenarios would provide the basis for ascertaining safe return to port capability as shall be explained next.

Casualty Threshold

Putting forward an argument for having a comprehensive risk model and framework to evaluate the total risk of a ship, it is important to appreciate that the aggregate number deriving from such a process, which will represent the safety measure of a ship (safety level), could not be used as the sole criterion for design or approval purposes. Risk components contributing to the total risk will still have to satisfy hazard-specific risk acceptance criteria to avoid undermining safety through what is known as "compensation effect" (e.g. having some of the high risk flooding scenarios, say one compartment damage, being compensated by the contribution to aggregate safety level of all the other damage cases, which might satisfy the rules but would still leave the vessel vulnerable and this in itself would not be acceptable). In such cases, it needs to be appreciated that severity and frequency are normally not interchangeable in the high stakes regime, meaning that individuals and society would (given an explicit choice) not act in accordance with normative decision theory.

In this respect, safeguards ought to be put in place for all component parts contributing to the calculation of this single number, right down to loss scenario level i.e., achieving a high Index of Subdivision by focusing on average safety standards must not be allowed in the knowledge that highly probable damage scenarios are non-survivable.

Therefore, focusing on the casualty threshold with respect to collision damage (damage extent) two complementary lines of action emerge. The first is to minimise total risk as an aggregate statistic (here equivalent to maximising Index-A) in the knowledge that all components contributing to risk are likely to be reduced. In addition, high-risk damage scenarios, normally associated with one- and two-component damage ought to be catered for. In fact, the argument could be taken one step further by stating that for design purposes a (large) passenger ship ought to survive up to two-compartment damage in all loading conditions and sea states. In fact, this was the intention in designing passenger ships under the deterministic SOLAS regime (e.g. SOLAS 1990), despite the fact that in reality this intention is not completely fulfilled. Such a safety-related performance criterion will provide a clear-cut, unambiguous threshold that could serve to reduce uncertainty drastically at a time when a decision to abandon ship in a flooding-related casualty is needed. Additional information available when the said casualty occurs will help to further aid decision making.

Indeed, an introspective look into the results of the example cruise ship, shown below in Fig. 2.71, reveals that this requirement is not difficult to achieve. Even

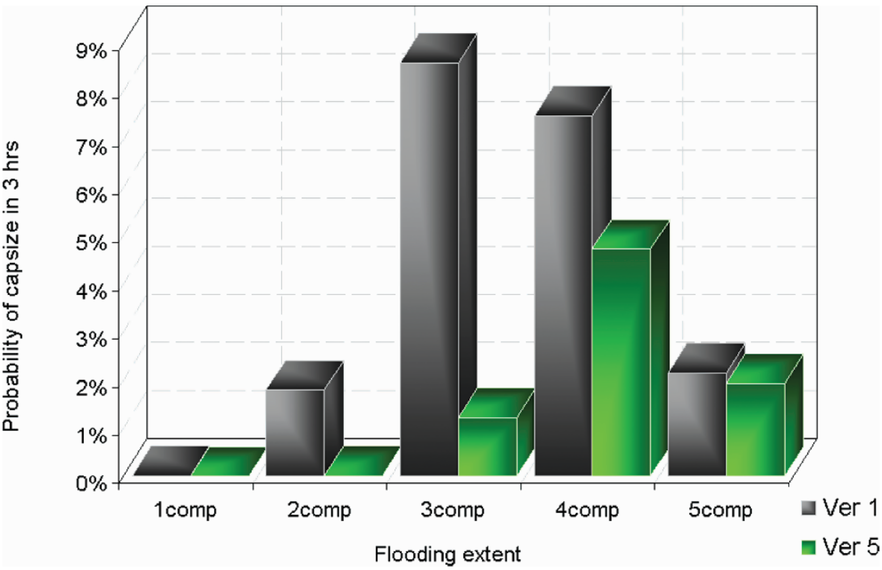

Fig. 2.71 Defining a damage threshold

with Index-A of 0.8 the risk contribution of 2-compartment damages is just over 2%, reducing to zero for Version 5 ($A = 0.92$). In the latter, even for 3-compartment damages the risk contribution falls below 2%.

At this stage of development, fire-related casualty threshold is much more clear cut, considering that the effect of fire is normally space specific and does not influence the whole ship in the way a flooding scenario might do.

Safe Return to Port

Having explored all issues pertinent to safe return to port, an attempt will be made here to synthesise these in accordance with the IMO framework, Fig. 2.15. Deriving from this, it will be helpful to classify flooding-related casualties as proposed in Table 2.5 below (covering the whole risk space of interest):

The functional requirements corresponding to the same categories can also be classified as shown in Table 2.6.

As a next step, quantifiable performance criteria would need to be developed that reflect the specific functional requirements but from the point of view of decision making in emergency situations, following a casualty, relevant criteria could readily be adopted as shown in Table 2.72.

Adopting the framework presented in Table 2.72 as a basis would reduce a complex and serious problem to manageable proportions, and this could be supplemented by additional information, specific to the casualty in question (actual extent of damage, sea state and so on). The proposed categorisation could be further fine-tuned, particularly concerning the more extensive damages (Categories III-4

Table 2.5 Flooding-related casualty classification

Casualty severity	Safety objectives
Category I (1-compartment damage)	Vessel remains upright and afloat and is *able to return to port under own power* (RTP)
Category II (2-compartment damage)	Vessel remains upright and afloat, but *unable to return to port under own power*/wait for assistance (WFA)
Category III-3 (3 or more-compartment damage)	*Vessel likely to capsize/sink*. Abandonment of the ship may be necessary (AS)

Table 2.6 Flooding-related functional requirements classification

Systems/functions availability	Functional requirements
Category I (Full)	All necessary habitability and transport functions available for (5) days
Category II (Partial)	All necessary habitability functions available for (5) days
Category III-3 (Basic)	Basic habitability functions and emergency systems availability for (3) hours.

Fig. 2.72 Decision making in flooding-related casualties

Casualty Severity	Design Criteria (Safety- and Functionality-related)	Outcome
Category I (1-compartment damage)	P[tc 3 hours] = 100% Heel, trim limits as per SOLAS Systems Availability → Full	RTP
Category II (2-compartment damage)	P[tc 3 hours] = 100% Heel, trim limits as per SOLAS Systems Availability → Full	RTP
	Systems Availability → Partial	WFA
Category III-3 (≥3-compartment damage)	P[tc 3 hours] = 100% Heel, trim limits as per SOLAS Systems Availability → Full	RTP
	Systems Availability → Partial	WFA
	P[tc 3 hours] < 100% Heel, trim limits as per SOLAS Systems Availability → Basic	AS

and III-5), based on results of purposely undertaken studies and on open discussion and debate at IMO.

Finally, as indicated in the foregoing, functions/systems availability at the "Basic" level is a requisite for all scenarios but what constitutes "Basic" as well as what is considered necessary at "Partial" or "Full" levels is primarily a decision of economics in need of full consideration in the design stage.

Similar developments with regard to fire-related casualties are already embedded in SOLAS.

2.2.2.2 Fire Safety Analysis

Similar to flooding survivability analysis, fire safety normally entails the following:

- Statutory fire protection (SOLAS Chapter II-2)
- Evaluation of vulnerability to fire (fire risk screening)
  - Each space onboard assumed to be a potential space of fire origin
  - Evaluation of the frequency of fire ignition
  - Evaluation of the probability of fire escalation beyond the space of fire origin

  – Evaluation of the risk to the ships' occupants in night and day case scenarios (FSS code)
  – Aggregation of the above for the whole ship (total values)

- Systems availability for each fire scenario
  – Geometrical and topological evaluation of main ship systems

- Evacuability assessment
  – Assembly and evacuation performance
  – Assessment of each untenable condition against total evacuation time

- Evaluation of casualty threshold/return to port capability
  – Probabilistic approach; link to system availability post-casualty

Generic results, pertinent to large passenger ships, are shown in Figs. 2.73, 2.73 and 2.74.

2.2.2.3 Safety Level

With all the elements in place, there is still one step to make, namely to estimate the safety level using the framework and risk model presented in "RBD Overview" and apply it to the example cruise vessel by considering flooding and fire hazards as outlined next.

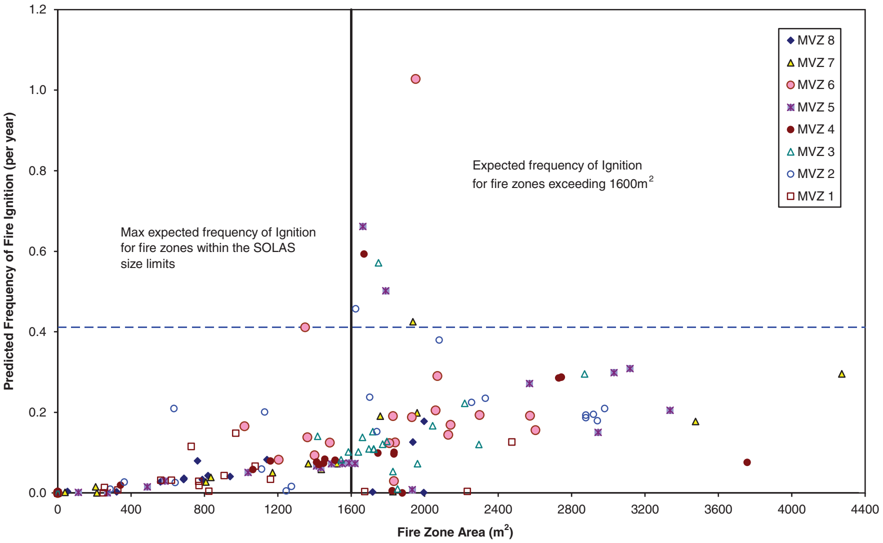

Fig. 2.73 Fire incidence – correlation between frequency of fire and fire zone size

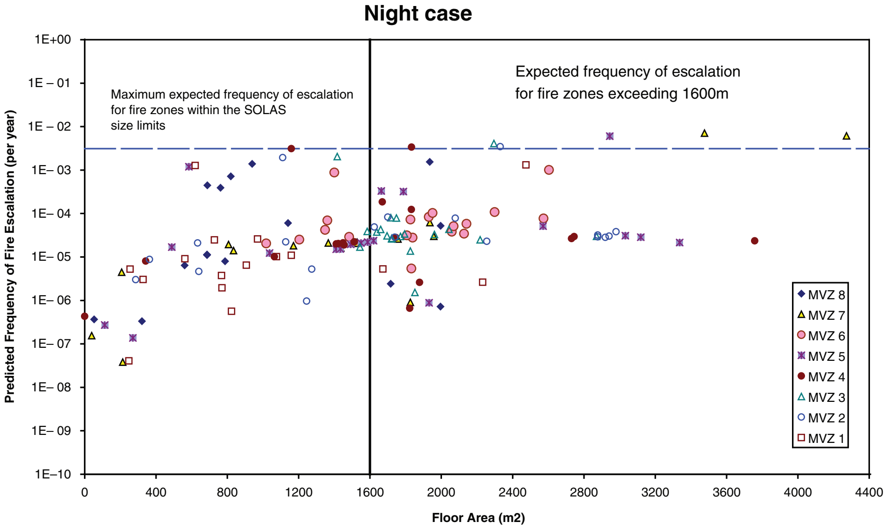

Fig. 2.74 Fire escalation – correlation between frequency of fire escalation and fire zone size

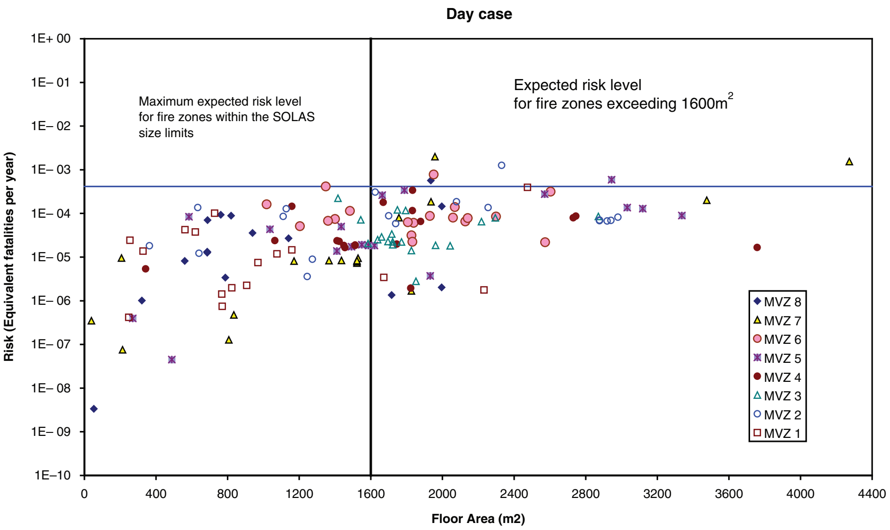

Fig. 2.75 Fire risk – correlation between risk and fire zone size

Flooding (Collision Only Events)

Using the formulation outlined earlier, the probability for N fatalities occurring due to $collision \cap flooding$ events can be expressed as shown in Eq. (2.4), where $pr_N(N|flooding) = pr_N(N|hz_1)$, with the probability mass function presented

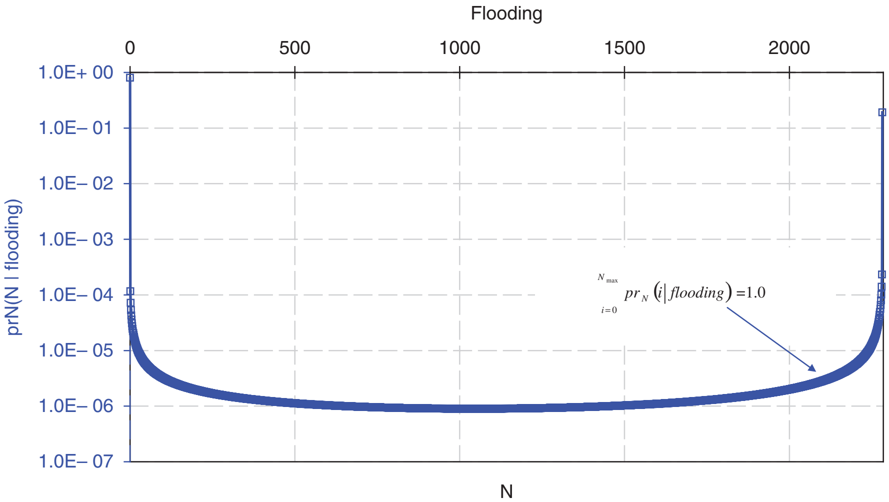

Fig. 2.76 Probability distribution for N fatalities o due to flooding for the example cruise vessel

here in Fig. 2.76. To estimate the contribution to risk from flooding loss scenarios, Eqs. (2.1), (2.2), and (2.3) are also used together with the statistical value for the frequency of occurrence of $collision \cap flooding$ events per cruise ship year (2.58E-03).

Figure 2.76 displays a numerical result (bimodal distribution) that makes sense readily on account of statistics. It emphasises the fact that $collision \cap flooding$ events result in relatively few fatalities or a very large number of fatalities rather than a mid-range value.

Fire

A heuristic argument is used here to estimate the fire risk contribution that accounts for available numerical results for a cabin case fire scenario using the example cruise vessel, namely assuming (seriously on the conservative side) that the sample distribution for N number of fatalities is representative of such distribution for the whole ship. Hence, similar to flooding, to assess the contribution to risk from fire loss scenarios, it is necessary to model both the frequency of fire occurrence per ship year, $fr_{hz}(hz_2 = fire)$, as well as the probability distribution, $p_N(N|fire)$, for N number of fatalities onboard the ship due to fire events.

The first of these, annual frequency of fire events, is given in from historical data as 1.2e-2 occurrences per cruise ship year. To derive the second term, use is made of first-principles tools available at SSRC as described in Sect. 3.1. Using these tools, prediction of the probability distribution for the number of fatalities due to fire at the cabin in question is done through Monte Carlo simulation for a range of parameters relevant to the specific location considered. An example of prediction of the $p_{N|fl_i}(N|fire \cap cabin)$ based on some 800 runs for one location

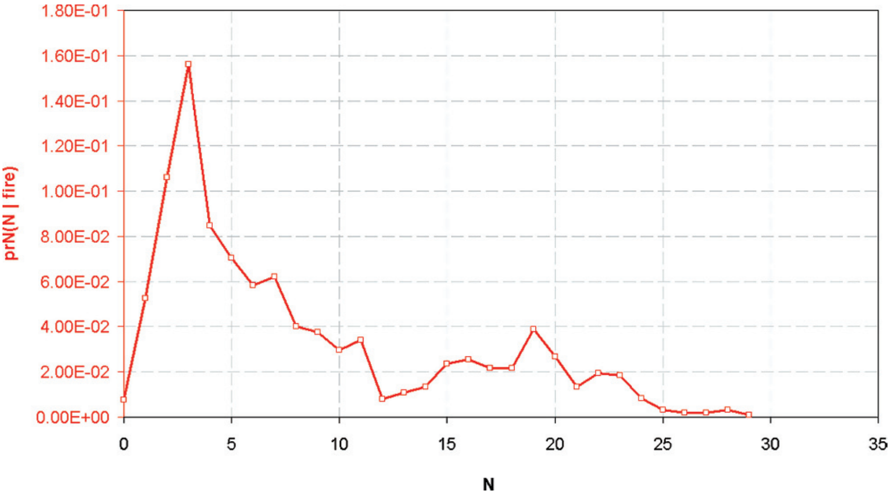

Fig. 2.77 Probability distribution for occurrence of N fatalities due to fire in accommodation spaces of the example cruise vessel

in accommodation spaces (day and night scenarios) is shown in Fig. 2.77. This is a noteworthy result, displaying the known fact that the number of fatalities in fire events is more frequently a small fraction of the passengers/crew onboard.

To allow for risk integration, it is further assumed, as indicated above that this sample distribution for N is representative of such distribution for the whole ship weighted according to fire statistics onboard passenger ships, as shown in Table 2.7 below.

Risk Integration (Equations Refer to Lecture on RBD Overview)

To illustrate the relative contributions of fire and flooding loss scenarios to the risk integral Eq. (2.1), the probability mass functions given by Eqs. (2.4) and (2.10) for flooding and fire, respectively, can be compared, as shown in Fig. 2.78.

Table 2.7 Probability distribution for occurrence of fire onboard passenger ships (1990–2003) – Germanisher Lloyd, FP49/3/1

i	fl_i	$p_{fl}(fl_i)$
1	Accommodation	0.14
2	Machinery A	0.54
3	Machinery other	0.10
4	Cargo spaces	0.08
5	Service spaces	0.12
6	Other	0.02

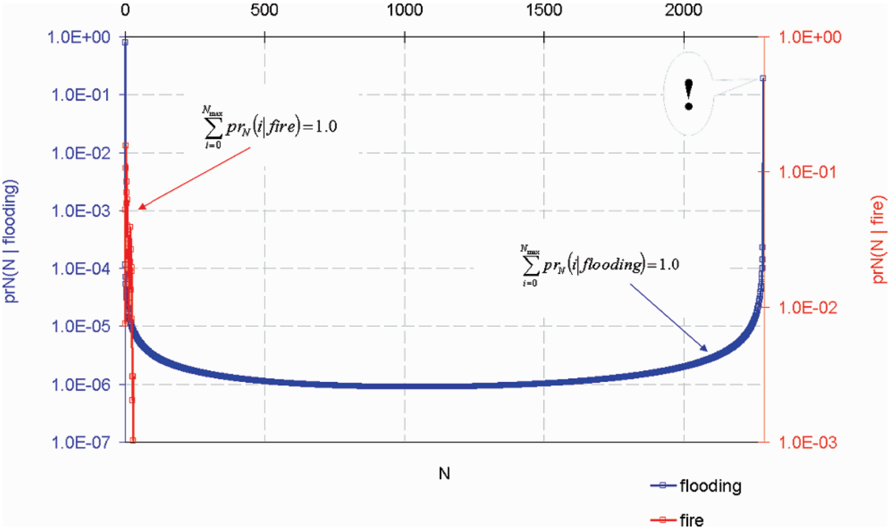

Fig. 2.78 Probability distribution for *N* number of fatalities occurring due to fire and flooding for the example cruise ship (version 1)

Alternatively, such comparison can be made using either of the models in Eqs. (2.1) and (2.2), being used separately or combined. Both results are shown in Fig. 2.79. Also drawn on Fig. 2.79 is the ALARP region using the societal risk evaluation criteria, recommended for cruise ships, (Skjong 2006).

Deriving from Fig. 2.79, the contribution to risk from flooding and fire as well as the risk as a summary statistic are now at hand. More specifically,

$$\begin{aligned} &\text{Risk}_{collision \cap flooding} &&= 1.14 \text{ fatalities per ship year} \\ &\text{Risk}_{fire} &&= 0.11 \text{ fatalities per ship year} \\ &\text{Total Risk} &&= 1.25 \text{ fatalities per ship year} \end{aligned}$$

On the basis of the foregoing the following remarks can be made:

- The “holly grail” is not really the absolute value of the risk numeral itself (for the uncertainty in its evaluation is too large for comfort) but the fact that this summary statistic derives from a comprehensive model that links all contributions to risk in a way that a bottom up approach will never be able to achieve in as complex a system as a large passenger ship. In other words, a truly holistic approach has to be linked to total risk estimation and as such address safety top down, leading to identification of design vulnerability and cost-effective risk reduction measures.
- Having said this, as much as an aggregate risk numeral can convey a lot of information, it could equally “hide” a lot of information; hence the need to apply safeguards at individual risk contributors, right down to individual scenario level of each hazard in question with performance criteria in place to ensure “fitness

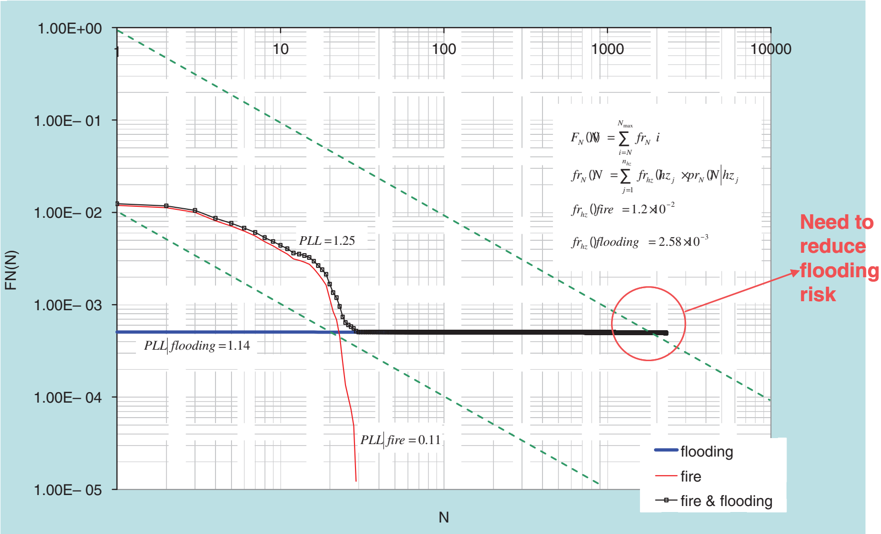

Fig. 2.79 The annual frequency of occurrence of N or more fatalities due to loss scenarios of fire and flooding for the example cruise ship (Version 1)

for purpose". This however, must be seen as the second step in targeting cost-effective safety.

- As can be seen in Figs. 2.76 and 2.77, the distinctive feature of the loss scenario involving hull breach and flooding is the high possibility of catastrophic scenarios involving very large number of fatalities. Although not entirely unexpected, this result demonstrates the importance that needs to be placed on ship stability deficiencies; the flooding risk contribution is an order of magnitude higher than that due to fire despite the fact that, according to statistical data, fire accidents are nearly 5 times more frequent than collision accidents. It is also to be noted that contributions to total risk from grounding-related flooding loss scenarios have not been accounted for; for large passenger ships, this is a large contribution according to (Skjong 2006).
- The derived F-N curve shows that with the example cruise ship used in this study, the likelihood for a catastrophic accident is unacceptably high; hence measures ought to be taken to reduce it irrespective of cost.

To demonstrate how this might be done, Version 5 of the example cruise ship (having an A-Index of 0.92) has been used as a first iteration. The outcome is rather interesting and is presented in Figs. 2.80 and 2.80, demonstrating emphatically the importance of targeting high Index-A values in cruise ship designs. Notably for a 15% increase in Index-A, total risk is reduced by 60%!

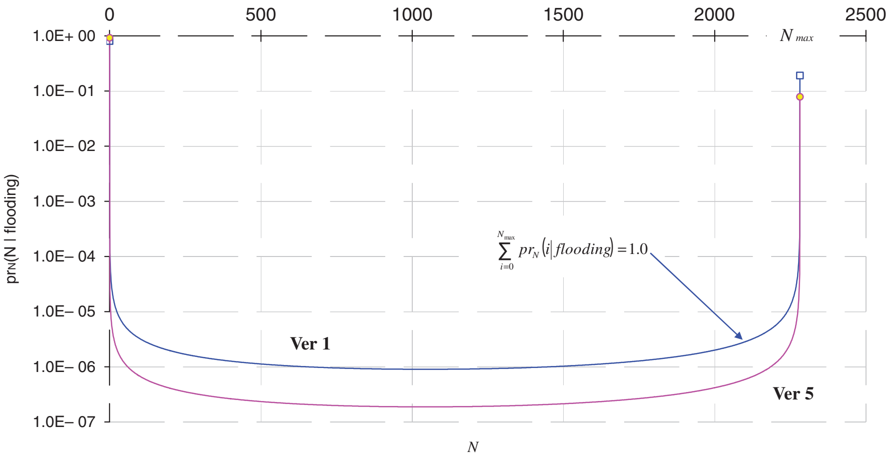

Fig. 2.80 Probability distribution for N number of fatalities occurring due to fire and flooding for the example cruise ship (versions 1 and 5)

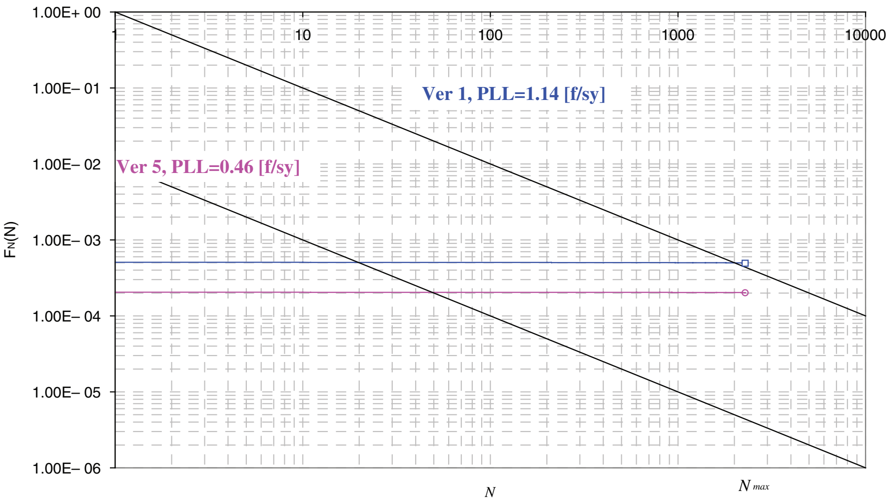

Fig. 2.81 The annual frequency of occurrence of N or more fatalities due to loss scenarios of fire and flooding for the example cruise ship (versions 1 and 5)

Acknowledgements This chapter represents the collective thinking permeating within SSRC with many colleagues contributing to building the emerging picture. Special thanks are due to all our colleagues in SAFEDOR, the UK Maritime and Coastguard Agency, the European Commission, Color Line, Royal Caribbean Cruise Lines and Deltamarin for their contribution in the development of the tools and concepts presented in this paper through funding, data and valuable discussions.

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Chapter 3
Regulatory Framework

Rolf Skjong

Abstract The present chapter is about ongoing activities and methodologies in use to gradually change the regulatory framework by systematic use of Formal Safety Assessment (FSA). This development is in the direction of a risk and goal based regulatory system. Risk based entails that the most important rules and regulations need to be justified on the basis of FSA, and goal based implies that the goals and functional requirements are formulated as long standing requirements without reference to specific technology or ways on how the goals should be achieved. The technology dependent rules and regulations are seen as standardized ways of achieving the goals for standard technical solutions. For innovative solutions, where detailed technology dependent rules and regulations do not exist, Risk Based Design (RBD) offers an alternative. RBD implies that the methods used to justify the rules and regulations are used directly for the development of each innovative concept. The chapter explains the related basic methodologies and frameworks and includes results of case studies from the gained experience with the development so far, in particular the experience from the use of FSA at the decision making process by the International Maritime Organization (IMO), including some experience from ongoing activities in the frame of developments of Goal Based standards (GBS)

3.1 Introduction

Many regulations in various industrial sectors internationally and within national boundaries are today based on some form of risk based analysis and justification. The term 'risk based' is not necessarily used. For example the nuclear safety regulations in the US are referred to as 'risk informed'. The distinction made by using the term 'risk informed' rather than 'risk based', is that the Nuclear Regulatory Commission (NRC) may make other considerations than those contained in a risk analysis when making decisions on regulatory actions. At the International Maritime Organisation (IMO), the UN body regulating maritime safety, the situation is similar and reflected in the fact that officially the traditional term 'risk acceptance

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criteria' is replaced by the term 'risk evaluation criteria'. At IMO this reflects the fact that Formal Safety Assessment (FSA), which is the term used for the risk assessment used to justify new or amended regulations, is not intended to be used to automate the decision process, but to inform the decision makers about risks, risk reduction and costs of taking a specific action in the form of implementing a specific Risk Control Option (RCO) that has been recommended by an FSA.

Today, the term 'Risk Based Regulation' implies the tendency to be used together with the term 'Goal Based Standard' (GBS), which is a more recent initiative also at IMO (and a popular term elsewhere, where a regulatory reform is debated). It is probably fair to say that the concept is not clearly defined at IMO and that IMO delegates may have different interpretations and understanding of what GBS is about. However, it is evident that GBS is intended to restructure the regulations based on a top down process, starting with a high level description of the (safety) objectives and functional requirements. The prescriptive requirements (in Codes, Rules and Regulations) are then in need of being verified to meet the goals and functional requirements and the ship herself is in the need of being verified to comply with the Codes, Rules and Regulations. The Regulatory system is therefore sometimes described as indirect, because the Goals and Functional Requirements are defining *Rules for Rules* that the Rules for Ships need to fulfil (sometimes referred to as an indirect goal based approach).

It should be noted in this context that FSA is also Rules for Rules. FSA is actually a rather detailed description of how a new regulation should be structured and justified, considering risks, risk reduction by implementing the regulation and costs associated with the implementation. This fits perfectly with the GBS ideas, as the FSA is also an analysis that may be verified, and there is already a verification process in place (IMO 2007).

The topics of this chapter are therefore: Formal Safety Assessment, Goal Based Standard, Risk Evaluation Criteria in FSA and Risk Based Design, together with a section on practical experience with FSA.

3.2 Formal Safety Assessment

3.2.1 Historical Background

The application of risk analysis techniques is generally well established in most industries, both as a means for the owner/operator to manage their own risks and for the regulator to prioritise work on the development of Rules and Regulations.

Most risk analysis techniques have their origin in the nuclear industry, for which risk analysis became an important tool in the 1960s, and has now developed into a Probabilistic Safety Assessment (PSA), (Freeman and Moir 1993). The focus here is on the probability of releases from nuclear containments. The PSA will be regularly updated, e.g. after upgrades, inspections, maintenance.

In the hazardous chemical industry, risk analysis techniques were adopted in the '70s. Within the EU and the European extended economic area, risk analysis was required by the *EU Seveso I* directive in 1982, which has later been replaced by the *Seveso II* directive.

In the offshore industry, the use of risk analysis has been required since 1986 in Norway and in the UK since 1992 as a consequence of the Piper Alpha disaster. The risk analysis is carried out on behalf of the owner of the plant, and has to be well documented. The document is called a *Safety Case* in the UK, which will be approved by the UK Health and Safety Executive. In Norway the authorities do not approve such documentation or any safety targets, but they are allow insight into the safety related decision making process of the individual enterprise, and act on situations which are not acceptable.

On a generic policy level, most OECD countries require risk analysis as the basis for regulation. For example, already according to the US President Executive Order no. 12866 on 'Regulatory Planning and Review' e.g. the US Coast Guard had to base their Rules and Regulation on Risk Analysis and Cost Benefit evaluation.

Finally, it should be noted that both ISO and CEN (Comité Européen de Normalisation/European Committee for Standardization) have their structural standards based on risk assessment, and the use of Structural Reliability Analysis.

In the shipping industry, most of the statutory regulations in the past have been developed as a reaction to major accidents and disasters. In 1992, the UK House of Lords Select Committee on Science and Technology recommended a Safety Case Regime for shipping, similar to that already adopted in the oil and gas industries. It also recommended a move towards performance standards in place of prescriptive rules (indicating that GBS was predicted – see below) and a concentration on the management of safety.

In 1993, during the 62nd session of the IMO Maritime Safety Committee (MSC), the UK Maritime and Coastguard Agency (MCA) (MSA at that time) proposed a standard five step risk based approach, which was called Formal Safety Assessment (FSA). In 1996 the IMO established a working group on FSA, and by 1997 a Circular on Interim Guidelines on the Application of FSA to the IMO Rule-making Process (IMO 1997) had been developed, which was adopted by the MSC and the Maritime Environmental Protection Committee (MEPC) in the same year. Since then, a number of FSA studies have been carried out and presented to the IMO. At MSC80, the FSA Guidelines were updated the second time. The last version is available (IMO 2007) now including such elements as risk evaluation criteria and an agreed process for reviewing FSAs.

3.2.2 Purpose of FSA

Formal Safety Assessment (FSA) is a structured and systematic methodology, aimed at enhancing maritime safety, including protection of life, health, the marine environment and property, by using risk analysis and cost benefit assessment.

FSA can be used as a tool to help in the evaluation of new regulations for maritime safety and protection of the marine environment or in making a comparison between existing and possibly improved regulations, with a view to achieving a balance between the various technical and operational issues, including the human element, and between maritime safety or protection of the marine environment and costs.

FSA is consistent with the current IMO decision-making process and provides a basis for making decisions in accordance with resolutions A.500(XII) 'Objectives of the Organization in the 1980s', A.777(18) 'Work methods and organization of work in committees and their subsidiary bodies' and A.900(21) 'Objectives of the Organization in the 2000s'.

The decision makers at IMO, through FSA, are able to appreciate the effect of proposed regulatory changes in terms of benefits (e.g. expected reduction of lives lost or of reduced pollution) and related costs incurred for the industry as a whole and for individual parties affected by the decision.

FSA should facilitate the development of regulatory changes equitable to the various parties thus aiding the achievement of consensus.

3.2.3 Application-General

In the FSA Guidelines it is stated that the FSA methodology can be applied by:

- a Member Government or an organization in consultative status with IMO, when proposing amendments to maritime safety, pollution prevention and response-related IMO instruments in order to analyse the implications of such proposals; or
- a Committee, or an instructed subsidiary body, to provide a balanced view of a framework of regulations, so as to identify priorities and areas of concern and to analyse the benefits and implications of proposed changes.

In practice, option 2 has proven unrealistic. It takes a project to run an FSA. This implies that option 1 has always been followed, with some intermediate reports to IMO. Usually a new project informs IMO by submitting the HazId Report (Step 1 of FSA). The full FSA Report may follow one or two committee meeting later.

It is *not* intended that FSA should be applied in all circumstances, but its application would be particularly relevant to proposals which may have far-reaching implications in terms of either costs (to society or the maritime industry), or the legislative and administrative burdens which may result. However, if a Goal Based Standard (GBS) is implemented, FSA may be made mandatory under agreed conditions at a later stage. This has been proposed, but so far not discussed in detail at IMO.

FSA may also be useful in those situations where there is a need for risk reduction but the required decisions regarding what to do are unclear, regardless of the scope of the project. In these circumstances, FSA will enable the benefits of proposed changes to be properly established, so as to give IMO Member Governments a clearer perception of the scope of the proposals and an improved basis on which they take decisions.

3.3 What is FSA?

FSA is a risk based approach consisting of five inter-related steps:

1. Identification of hazards
2. Assessment of the risks arising from the hazards identified
3. Identification of options to control the risks
4. Cost/benefit assessment of the risk control options
5. Recommendations for decision making, based upon the information derived in the previous steps (Fig. 3.1).

The safety of an aspect under consideration is assessed by evaluating the risk accompanied with this aspect, e.g. a specific operation. The decision upon the acceptability of that risk is done by employing risk acceptance criteria, as discussed below.

Compared to the previous safety assessment approach there are several differences to be observed. In the past, most decisions on regulatory changes at IMO were initiated as a reaction to an accident. The decision on safety requirements results from activities after the problem occurred, focusing on the question: What went wrong? The FSA approach is pro-active, by trying to find out before an accident occurs: What might go wrong?

In the previous safety assessment approach the risk was normally not explicitly evaluated. The FSA approach tries to find out the likelihood of scenarios, which may possibly develop from hazards, and the magnitude of their consequences in order to calculate the risk.

As the previous safety assessment process was mainly reactive to an accident rather than pro-active, decisions on how to improve matters were often carried out

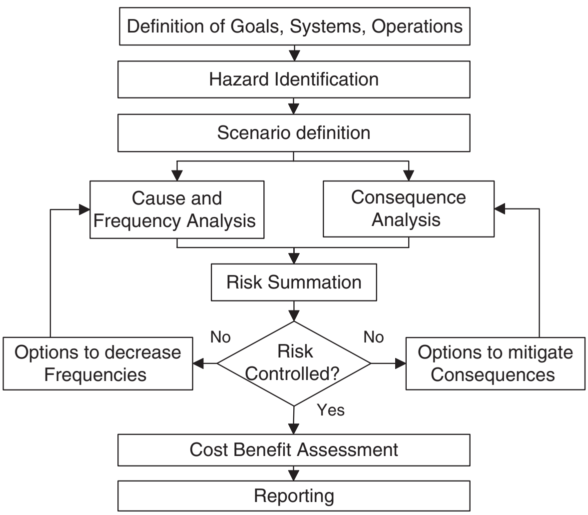

Fig. 3.1 Illustration of FSA process

on an ad-hoc basis, influenced by public and political pressure. Quick solutions were therefore preferred and an assessment of the costs and the benefits of such solutions were normally not performed. A case illustrating the point is the development of the International Ship and Port Security (ISPS) Code, which has developed fast and with little analysis, following the '*9.11*' attack. The FSA approach, on the other hand, systematically analyses the different options which are available to control the risk, and also assesses both the costs and the benefits of those options should they be implemented. The final decision on safety requirements can therefore be made on the basis of a thoroughly performed analysis.

The previous reactive approach has lead to a continuous amendment of already complex and sometimes inconsistent regulations. These regulations are often characterised as being prescriptive, leaving only limited room for other (technically equivalent) solutions to a safety problem than those "prescribed". Especially in periods of rapid technology developments the pace of regulatory developments is too slow to cope with industrial needs and the principle of technical equivalence an obstacle. Specific safety objectives and functional requirements (as developed following the GBS approach) would be more useful, requiring safety goals/performances to be met, encompassing both technical and operational aspects. This type of regulation is often called "performance or goal based regulation" (see below).

3.4 Development of Risk Assessment and FSA

The use of risk assessment also at IMO started prior to the development of the FSA guidelines. Actually the development of probabilistic design tools started already in the sixties, with the development of probabilistic damage stability.

About 30 years later, another step in the development of new probabilistic damage stability regulations started (the EU Commission funded research project HARDER, 2000–2003), which delivered an important input to the amendments to SOLAS approved by the International Maritime Organisation's Maritime Safety Committee in December 2004 and entering into force January 1, 2009.

However, this work can be traced back to the late 1960s, when Prof. Wendel of Hannover/Hamburg Universities outlined his ideas on the 'Subdivision of Ships' (Wendel 1968). Subsequent work by a specialist IMO group used his basic ideas to develop a new set of subdivision regulations. The outcome of this work was the 'Equivalent Passenger Ship Regulations', based on probabilistic analysis, and allowing freedom for the designer as long as the conditional probability of surviving a collision is acceptable. The marine industry has therefore had access to probabilistic design tools for very long. It is the more widespread use of risk based approaches for design and for justification of rules and regulations that is the more recent development.

3.4.1 Risk Assessment 'Solo Watch-keeping During Period of Darkness'

At the Maritime Safety Committee (MSC) meeting in May 1996 (MSC66), the first FSA working group met. DNV[1] had just carried out a risk assessment for Denmark related to the 'Solo Watch-keeping During Periods of Darkness' (Denmark 1996). For a period of about ten years ships with advanced bridge design had been exempted from the requirement of having a watch-keeper during periods of darkness as a trial. The DNV study indicated that a ship with such modern, high tech bridge systems design had a reduced risk of navigational accidents of about 50% as compared with a traditional bridge system. Denmark, Sweden, Norway, Germany, The Netherlands and UK had continued to operate these ships with solo watch-keeping, after an agreement had been reached to terminate the trials at MSC65 in May 1995, but without an agreement on the date of ending the trials. At the MSC66 meeting, an intense debate started between on the one side a group of nations supporting risk analysis and on the other side a group of nations favouring a political approach, without analysis of data. At MSC66 there was no final conclusion and a compromise was agreed between the countries active in the trials and those wishing them to end the trials. The compromise was to end the trials December 31, 1997, and ask the nations involved in the trials to report at MSC69, in 1998.[2]

At MSC69, the debate proved in many ways a repetition of MSC66. All reports from those involved in the trials concluded that the modern bridge that allowed for Solo Watch-keeping during period of darkness was as safe as or (much) safer than the traditional bridge. Also this time the arguments were substantiated with risk analyses. This time Denmark (1998) submitted a report where the Danish Technical University had carried out an FSA using Bayesian Network Modelling for Navigational Safety. The conclusions were similar to those submitted to MSC66 (Denmark 1996). Sweden (1998) submitted a more traditional analysis, with clear conclusion that the modern bridge without lookout during periods of darkness was as safe as or safer than the traditional bridge with lookout. Germany (1998) reported on simulator testing and risk assessment also with clear and similar conclusions. This did not prevent that the trials were ended. In the aftermath, it is probably fair to say that it is too late to inform IMO about a conducted risk assessment or any other analysis at a time when political decisions have already been made at national level, as IMO delegates are bound by political decisions in their home counties.

From FSA perspective, MSC69 was the first time a risk assessment based on Bayesian Networks had been presented at IMO. This method later gained popularity for modelling navigational safety in later studies (see below). The legal implication is also interesting: A flag state is allowed to accept equivalent solutions, following agreed reporting procedures.

[1] The author's role in this study was as internal verifier for DNV on the risk analysis part.

[2] A summary may be found in: The Journal of Commerce, 11/6-1996.

3.4.2 FSA – High Speed Craft

The first application of the FSA Guidelines, at that time referred to as the 'Interim Guidelines' (IMO 1997), and referring to the FSAs as 'Trial Applications', were the FSA on High Speed Crafts (HSC) carried out by UK. The first reports were submitted to MSC68 by UK (1997). These reports had been submitted without the consent of the members of the International Steering Board,[3] and the reports were also heavily criticized. For example the risk figures were unrealistically high, without a good explanation. Another controversy was that the risk models were not used for estimating the risk reduction. A rather unrelated model referred to as Regulatory Impact Diagram (RID) was used for this purpose. The references to RIDs were later removed from the IMO FSA Guidelines. Despite the heavy criticism, the reports were forwarded to the IMO DE committee, because DE was working on the revision of the HSC Code. However, UK updated the reports and submitted new versions to DE. Due to time constraints DE referred the issues back to MSC69, asking for a Review at MSC69 by FSA experts. As this FSA was never properly completed and reviewed, it ended up not being used for other decision-making than amending the FSA Guidelines.

3.4.3 FSA – Helicopter Landing Area on Cruise Ships as a Safety Measure

The idea of recommending a helicopter landing area (HLA) as a safety measure on passenger ships came from the Panel of Experts (PoE) working with improving passenger ship safety following the Estonia Accident (Estonia 1997). During the rescue operation, a HLA was cleared at the RoPax vessel coming to the scene of the accident, and during the extensive helicopter operations an air traffic coordinator was flown to the nearby ship SILJA EUROPA. The pilot on one of the two helicopters landing on the ship stated that 'landing on the ferries was the most difficult part of the whole rescue operation' (Estonia 1997, p. 107). When the proposals from the PoE came to IMO, the cruise industry was not represented, because the proposed safety measures were intended for use only on RoPax ships. It therefore came as a surprise to the industry when some of the suggested risk control options (RCOs) were made applicable also to non-Ro-Ro passenger ships.

The FSA/HLA was a response from the industry to extending the recommendation to all passenger ships, without considering the different modes of operation. It was carried out by DNV (Skjong et al. 1997) and submitted to the Design and Equipment Sub-Committee DE41 (Norway and the International Council of Cruise Lines (ICCL) 1997) and also to the Sub-Committee on Communication and Search and Rescue (COMSAR). Paragraph §6 of Norway and ICCL, (1997) is summing up how the FSA was carried out, namely: '*The FSA was carried out with mod-*

[3] The author was member of the International Steering Board.

elling assumptions valid for non Ro-Ro passenger ships. The recommendations are primarily based on considerations of costs and benefits of installing an HLA. The implied costs of averting a statistical fatality (ICAF) have been estimated to be a factor of 20–100 higher (less cost effective) than for safety measures commonly recommended for implementation in OECD countries. Requiring helicopter landing areas on non-Ro-Ro passenger ships is therefore not recommended. This conclusion has been further substantiated by a comprehensive review of historical data and by a statistical model. The two models are quite different, and it is reassuring that the two independent analyses lead to the same conclusion'.

The study by Norway and ICCL, and the later supporting submission by Italy were all reviewed by the intersessional working group (WG) on FSA, working between MSC69 and MSC70. The results are reported in UK (1998a). The review concluded that the studies very generally making assumptions that would favour HLA (§18), indicating that the recommendation would be robust. In addition, the group observed that HLA could encourage the use of HLA for other purposes and that this other use could increase the risk (§29.3). As this was the first FSA that could result in a conclusion the WG FSA at MSC70 also reviewed the report of the Correspondence Group (CG) and reached a final recommendation. IMO (1998) §14.14 reads '*The Committee noted that the cost-effectiveness of a helicopter landing area, in terms of the cost of implementation divided by the expected number of additional lives saved (i.e. ICAF,*[4] *the implied cost of averting a fatality) is US$37 million and that, acknowledging the uncertainties in the evaluation of both risk benefit and cost, the group agreed that the ICAF may range from about US$12 to 73,000 million*.' Based on the recommendation of the WG, MSC concluded (IMO 1998) §14.15 *In the light of the above considerations, the Committee noted the group's conclusion that the requirement for helicopter landing areas on non Ro-Ro passenger ships cannot be justified in terms of the cost-effectiveness of the measure in reducing risk. In reaching this conclusion the group had in mind that previous assumptions in the evaluation of both risk benefit and implementation costs were generally favourable to the HLA solution. Additionally, even at the most optimistic end of the range, the ICAF value exceeds the suggested criteria value*.

For the first time, IMO had made a decision based on FSA, including assessment of costs and benefits. The credibility of FSA was established, §14.19 *The majority of the delegations who spoke were, however, of the view that the thorough study carried out firstly by the Correspondence Group on Application of FSA and by the working group at this session vindicates the usefulness of the FSA concept in the rule-making process of the Organization*. The remaining problem was to implement the conclusion, as a '*regulation cannot be amended until it has been enforced*' according to the internal IMO internal procedures. This formal problem was resolved at MSC71. It should be observed that many ships, including non-Ro-Ro passenger ships, have in the meantime an HLA installed. This is not mandatory, and HLA is not installed as a safety measure. Actually, strict requirements apply to HLA operations, because of the risk it represents.

[4] In current terminology ICAF is replaced by GCAF, Gross Cost of Averting A Fatality.

3.4.4 FSA for Bulk Carriers

3.4.4.1 Initial Studies

The first FSA study on bulk carriers was carried out by DNV in 1997, and a paper was distributed to both the working group on Bulk Carrier Safety and the working group on FSA during the MSC68 meeting (DNV 1997a). The study represented DNV's justification for supporting the IACS decision to strengthen the bulkhead between No.1 and 2 cargo holds on existing bulk carriers. The justification was based on Net Costs of Averting a Fatality (NCAF) between \$0.5 million and \$1.5 million for the various types of bulk carriers analyzed. This decision is therefore consistent with later decisions at IMO and was based on criteria of cost effectiveness submitted by Norway (2000). The study was based on extensive analysis of casualty data and rather simple risk modeling. As the paper was widely referenced it is believed to have highly contributed to the understanding of FSA by the maritime industry.

3.4.4.2 Bulk Carrier FSA Studies at IMO

An FSA on bulk carrier safety was proposed by UK (1998b). The proposal was generally supported, although many delegates expressed concerns that the scope of the study was too broad. In the aftermath it may be noted that this concern was justified. Most of the risk control options adopted during MSC 76 in December 2002 related to the fore-end watertight integrity – an issue put on the agenda prior to MSC 70 for urgent review. On this issue, IACS submitted a hazard identification (HAZID) report to MSC 71 (IACS 1999) and a full FSA to MSC 74 (IACS 2001). The study took about a year. The study uses standard risk assessment techniques involving fault and event trees and extensive analysis of accident data. In addition, to be able to quantify some of the risk reduction effects (e.g. strengthening of hatch covers), structural reliability methods (see Skjong et al. 1995) were developed based on detailed probabilistic modelling of strength, structural response and the marine environmental loads.

Norway initiated the study on life saving appliances by preparing a document on risk acceptance criteria, as this was viewed as a preparatory step to an FSA. This document was submitted to MSC 72 (Norway 2000). Individual and Societal risk for bulk carriers and other ship types, given in Figs. 3.2 and 3.3, are taken from this document.

The FSA study was reported to MSC 74 (Norway and ICFTU 2001). This study took less than a year, though it is very detailed in the risk modelling as compared to other FSA submissions. The level of detail reflected the need to quantify risk control measures that affected probabilities at a detailed level (use of different types of rafts, lifeboats and survival suits in different accidents scenarios). The study had to use human reliability data from other industries, as similar data did not exist for the maritime industry. The study was carried out independently of the UK International study.

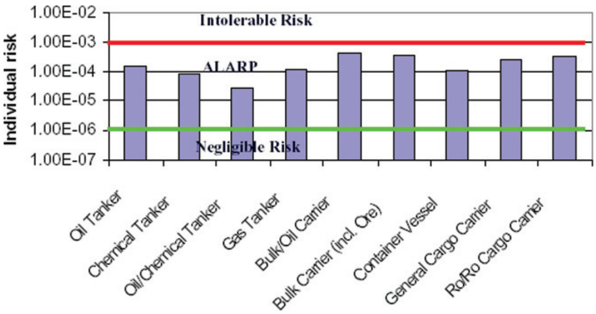

Fig. 3.2 Individual (annual) risk per ship-type

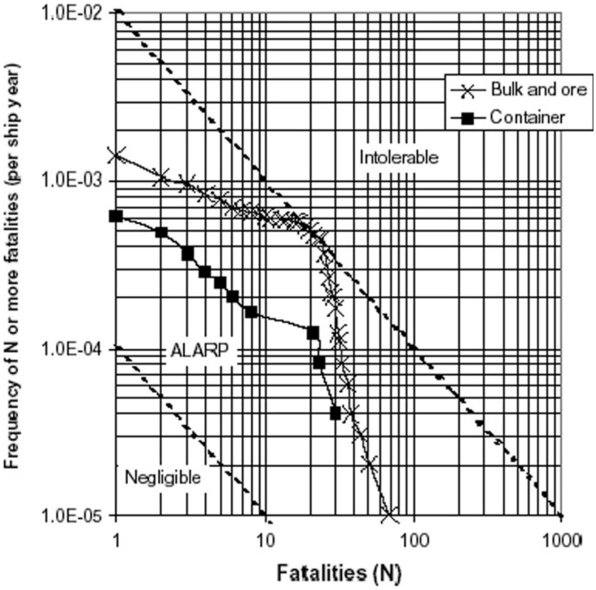

Fig. 3.3 Societal risk of bulk carrier and container vessel accidents

Japan also delivered an FSA after the completion of a one year project (Japan 2001), but decided to update the study to MSC 75 (Japan 2002a). The Japan study, much like the IACS study, is based on comprehensive assessment of accident statistics and rather limited risk modelling. Still, the study is sufficiently detailed for the decision making and relatively easy to follow.

The international study was coordinated by UK based on terms of reference agreed during MSC 71 (IMO 1999). Up to MSC 76 only progress reports were received by IMO. An implication was that during MSC 75 in May 2002, the committee short-listed the recommendations from all studies including the UK recommendation, but without any reported FSA study from UK. The main study was subsequently reported to MSC76 (UK 2002a). UK also submitted a large number of other papers on bulk carrier safety that were independent of the main FSA report, including a complete FSA carried out at Strathclyde (UK 2002b) on the IACS unified requirement for hatch cover strength.

3.4.4.3 Decision Making

The final decision making based on the FSA studies on bulk carrier safety was scheduled for MSC 76 (December 2002). As previously stated, the risk control options had already been short-listed at MSC 75, and the working group tried to structure the order in which decisions were made. The reason is that decisions to implement one risk control option would affect the cost effectiveness of other risk control options as there would be ‘fewer to save’. Both Japan (2002a) and the International Association of Dry Cargo Shipowners (INTERCARGO 2002) submitted papers discussing this final decision making process. For a risk analyst it may be difficult to understand the problem as such recalculations are rather trivial, and the whole idea of waiting to make all decisions relating to bulk carrier safety at the same time was that such dependencies between risk control options were unavoidable, given that the many studies were carried out independently.

3.4.4.4 The Risk Control Options and the Decisions

The first and most important risk control option related to the side shell failures. These failures had been demonstrated by all studies to be a major contributor to bulk carrier casualties. The most comprehensive risk control option considered was to require a *double side skin*. The quantification of costs and benefits were carried out by IACS (2001). The key data, from IACS, are given in Table 3.1. The decision parameters are now defined in the FSA guidelines as Gross and Net Cost of Averting a Fatality, Eqs. (3.1) and (3.2):

$$\mathrm{GCAF} = \Delta\mathrm{Cost}/\Delta\mathrm{PLL} \tag{3.1}$$

$$\mathrm{NCAF} = (\Delta\mathrm{Cost} - \Delta\mathrm{Benefit})/\Delta\mathrm{PLL} \tag{3.2}$$

Table 3.1 Double side skin for new bulk carriers (IACS 2001)

	Cost $	Risk reduction	GCAF $ million	NCAF $ million
Double Side Skin, new bulk carriers	131,000–182,000	41%	0.8–1.1	0.1–0.4

PLL is the Potential Loss of Life, ΔCost is the additional cost of the RCO, and ΔBenefit is the economic benefits resulting from implementing the risk control option.

The clear recommendation for double side skin, given an acceptance criterion of $3 million for CAF was later confirmed by UK (2002a). This study claimed many commercial benefits of double side skin in addition to the safety benefits which resulted in negative NCAF values. Although the IACS study was conclusive, IACS did wait for MSC76 to take the decision, and promised to develop the necessary IACS Unified Requirements (UR) for double side skin bulk carriers (IMO 2002a). IACS could have decided to mandate double side skin for bulk carriers classified by the IACS member societies, but finally decided that such decisions should be made at IMO level.

IACS (2002) and UK (2002a) both had included *coating* in their assessment, and both studies produced negative NCAFs. IACS summarized the situation in the working group by stating that the analysis confirmed that it is always in the owner's best interest to properly coat his ships and to maintain coating. However, as explained by INTERCARGO, coating of cargo holds can not be easily be regulated, as appropriate coating depends on the cargo. However, MSC noted that SOLAS regulation II-1/3-2 made the coating of dedicated ballast tanks mandatory for oil tankers and bulk carriers but extending that requirement to cargo holds could introduce serious problems, bearing in mind that cargos can react distinctly to different coatings. Therefore, MSC agreed that new ships should be required to have their dedicated seawater ballast tanks and void spaces within double hull spaces coated according to current SOLAS requirements for ballast spaces. The MSC instructed the Design and Equipment (DE) Sub-Committee to develop international performance standards for coatings. With respect to existing ships, the Committee acknowledged that at present there was sufficient control over the condition of coatings through the enhanced survey programme and agreed that this risk control option should also be addressed by class and the ship owner.

Control standards of steel repair carried out at terminals, was proposed by UK (2002a), and presented with negative NCAFs, but very small risk reducing effects, actually an indication that this was mainly of commercial interest. The discussion disclosed that the problem could be associated with repair carried out without notifying the class society. The discussion was inspired by a detailed casualty investigation presented by Marshall Island (2002), where this problem was clearly identified. MSC agreed to request the DE Sub-Committee to prepare a draft MSC circular to remind ship owners and operators of their obligations and responsibilities under SOLAS regulation II-1/3-1, concerning the provision that ships shall be maintained in accordance with the structural requirements of recognized classification societies, and other related management obligations under the ISM Code. It is clear from the discussion that the FSA was not used as a significant contributor to this decision.

IACS did propose the fitting of a *forecastle* and presented this as marginally cost effective for new building; see Table 11 of IACS (2001) and Table 3.2.

MSC noted the information provided by IACS on the on-going development of Unified Requirement S28, requiring the fitting of a forecastle on bulk carriers

Table 3.2 Forecastle for new bulk carriers

	Cost $	Risk reduction	NCAF $ million	GCAF $ million
Capesize	54,000–102,000	0.0211	2.2–4.5	2.6–4.8
Panamax	29,100–54,000	0.0493	0.2–0.7	0.6–1.1
Handymax	15,600–51,000	0.0933	−4.9 to −2.0	0.2–0.3

contracted for construction on or after 1 January 2004 with the purpose of protecting foredeck fittings against green sea loads and minimizing the impact of such loads on fore hatch covers. The Committee also noted that, while the fitting of a forecastle as such was not an IMO requirement, draft Load Lines Protocol regulation 39 – 'Minimum bow height and reserve buoyancy' would require additional reserve buoyancy forward consistent with the provision of some sheer and/or a forecastle. This demonstrated the advantage of use of common and agreed risk acceptance criteria by IMO and IACS.

The MSC recognized that *replacing hatch covers* in existing ships would not be cost-effective, but agreed that more attention should be paid to hatch cover securing mechanisms and the issue of horizontal loads, especially with regard to maintenance and frequency of inspection. The Committee agreed that ship owners and operators should be made aware of the need to implement regular maintenance and inspection procedures for closing mechanisms in existing bulk carriers in order to ensure proper operation and efficiency at all times, and instructed the DE Sub-Committee to develop standards for hatch cover securing arrangements for existing ships. The decision of not strengthening hatch covers on existing ships is not well documented. It may be noted that IACS (2001), in Table 12, lists this risk control option as cost effective. UK (2002b) also lists this as cost-effective. The reason for not implementing this risk control option may be found in Japan (2002c), Table 3.1. This table shows that UK classified too many accidents as hatch cover related. A scrutiny of the data, which was made possible by the exchange of information between UK and Japan, resulted in an agreement to reduce the frequency of hatch cover failures in the models. This resulted in the conclusion that this risk control option was no longer cost effective. This demonstrates the lack of consistency in the approach followed at IMO. When such changes in assumptions are made, this should be recorded. Retrospectively, it is practically impossible to identify from the documents what considerations were finally made.[5]

Hold, ballast and dry space *water level detectors* were already scheduled for implementation in the new SOLAS regulation XII/12, both for new and existing bulk carriers. Both Norway and ICFTU (2001) and IACS (2001) demonstrated this risk control option to be cost effective, using very different risk models. After the decision was made, also UK (2002a) confirmed this. Close comparisons of the FSA studies show that all risk models are different – still giving the same result. Earlier, at IMO, many delegates had expressed scepticism on FSA by referring to undoc-

[5] The author's knowledge is as a member of the International Steering Board of the UK/International study.

umented experience that an FSA can produce ‘any answer’. The case of the water level detectors is clear evidence of the opposite.

3.4.4.5 Note on the Decision-Making Related to Double Side Skin for Bulk Carriers

The review of the FSAs and the main decision were made at MSC 76, agreeing to implement double side skin for bulk carrier larger than 150 meters. Further discussions and drafting of the SOLAS text was carried out at MSC 77, with a plan to adopt the regulation at MSC 78. However, at MSC 78, Greece (2004) submitted a document ‘Comparative Study of Single and Double Side Skin Bulk Carriers’.

This report was presented as a review of the previous FSA studies, which had been reviewed and formed the basis for the agreement in the working group and by the committee at MSC 76. At MSC 78 (during adoption), the IMO procedure was to finally decide to adopt the new regulation. During adoption there is actually no working group that can review and discuss the new evidence that may have been contained in a new submission. The only possibility is a debate in plenary. In this case, Greece had succeeded in raising concerns about mandating double side skin bulk carriers, and in the voting about adopting the new regulation 32 delegations preferred not to make double-side skin construction mandatory, but to offer it as an optional alternative (at the time some owners were already ordering double side skin bulk carriers); 22 delegations voted in favour of making double-side skin construction mandatory; and 15 delegations abstained. With this, the mandating of double side skin bulk carriers was abandoned, and for many delegates the decision confirmed their scepticism towards FSA.

It appears now that if this report had been reviewed it would not have been accepted as basis for decision-making. In retrospective, it is probably most relevant to discuss the decision processes at IMO in general. As was indicated by the old case of ‘*solo watch- keeping during period of darkness*’ it is always regretted by the analyst that any analysis may be ignored in the final political decision process. The protection against such political overruling of FSA recommendations could for example be a better documentation of which considerations were made during the original decision process (in this case at MSC76). As a matter of fact, the problems with the current decision process was predicted by the WG/FSA at MSC76, when the delegation of Liberia had expressed concern *regarding the need for better background discussion of risk control options (RCOs) prior to recommending adoption by the Committee and had brought the group’s attention to Step 5 of the FSA approach: the decision-making process. Decision-making was based upon the results of the FSA and other factors that may influence the decision. In order for decision makers to properly consider an RCO assumption, uncertainties, methodologies and any other important factors that may influence the decisions should be properly summarized and communicated both verbally and in writing. The delegation of Liberia would hope that this issue will be properly considered in future FSAs to allow for greater* *transparency and facilitate the decision-making process* (Quote from (IMO 2002b) §5.19, author's underlining.)

3.4.5 Ongoing FSA on Electronic Chart Display and Information System

There have been many other FSAs submitted to IMO, and many studies have been carried out in national or international research projects. But, as these studies have not contained recommendations for decision making they have not been reviewed and the content and quality of these studies are not generally known.

One exception is the studies of navigational safety for large passenger ships and a number of follow up studies on the mandatory carriage requirements of Electronic Chart Display and Information System (ECDIS). This can be traced back to the IMO Chairman's initiative at MSC72 (IMO Secretary General 1999) that puts large passenger ships on the agenda of MSC. Norway, responded to this by suggesting that FSA studies should be carried out, and volunteered to carry out an FSA on large passenger ship safety, hoping that other flag states could carry out FSAs on other functions. Unfortunately, Norway ended up as the only flag state that carried out a related FSA. This was reported as Norway (2004), and recommended the following RCOs:

- Electronic Chart Display and Information System
- Track Control System
- Automatic Identification System integration with radar
- Improved bridge design
- Improved navigator training

The recommendations were not followed by IMO, but largely followed up by the industry. However, the study resulted in a new study, looking into Electronic Chart Display and Information System for practically all ship types. This study was initiated by Denmark and Norway (2005), and submitted by Denmark and Norway (2006). The study had been carried out by DNV, and this time a Bayesian Network model had been used as modelling technique. This very detailed and comprehensive study concluded that ECDIS should be made mandatory for most ships, for details see Denmark and Norway (2005). The study was confirmed by Japan (2006). The following debate has focused on the coverage of Electronic Nautical Charts. These questions were answered by very detailed studies by DNV and submitted as Denmark et al. (2007). By programming and counting the likelihood that a ship that needed ENC to avoid grounding actually had access to ENC was establishes as about 90% (Norway 2008). The coverage is improving rather fast. ECDIS is thus expected to reduce the frequencies of groundings by about 1/3 as compared to the standard paper nautical charts. The Sub-Committee on Safety of Navigation, NAV54

(July 2008) recommend that MSC mandate ECDIS based on these studies. The subcommittee made clear recommendations and prepared the relevant amendments to SOLAS Chapter V.

3.4.6 Other Ongoing FSA Studies

The partially EU funded SAFEDOR project has submitted a series of so called 'high level FSAs'. These studies are quite standard FSAs, focusing on developing detailed accident scenarios and estimating the likelihood (using event trees) of the most relevant accident scenarios. At MSC86, May 2009, MSC is expected to have the following FSA studies from SAFEDOR on the agenda.

- FSA: LNG ships, Denmark (2007a)
- FSA: Container Ships, Denmark (2007b)
- FSA: Tankers for Oil, Denmark (2008a)
- FSA: Cruise Ships, Denmark (2008b)
- FSA: Ro-Pax, Denmark (2008c)
- FSA: Dangerous Good in Containers (not yet submitted)

With all these FSAs on the table, it is expected that FSA is re-established as an important method for developing Rules and Regulations at IMO level.

3.5 Discussion on FSA

3.5.1 FSA Work

Generally IACS, Japan and Norway/ICFTU demonstrated that rather extensive FSA studies may be carried out in about a year's time. If well coordinated a comprehensive FSA study of a ship type may take two to three years, as was the case for some of the FSAs in SAFEDOR. The reason is that many ship types are more complicated to analyse, more modelling work and search into reliability and incident data may therefore be required. Bulk carriers and oil tankers are particularly simple designs, there are large fleets of these ships, and there have been (too) many accidents that make up the experience/casualties base. Thus, FSA studies may be carried out within the time span that is normally available at IMO for such tasks, namely two to three years if a dedicated working team is in place to complete the tasks.

3.5.2 FSA Methods

Most FSA studies presented at IMO have used standard risk models using fault and event trees. *Fault trees* have not been until now very detailed. When detailed fault trees have been prepared, e.g. by France (2002) as part of the UK/International project on bulk carrier safety, then the analysts have sometimes given up on populating the fault trees with relevant data. This happened also with the UK/International study, which ended up without using fault trees for the risk modelling except for splitting up the initiating events into causes. The result of this was that the UK/International study had no models for quantifying risk reduction, but resorted to expert judgement of risk reducing effects for each event tree scenario.

Both IACS (2001) and Japan (2002b) used rather detailed structural reliability models to be able to quantify risk reducing effects; Norway and ICFTU (2001) used also detailed fault and event trees populated by data from many sources also from outside shipping; the FSAs on navigation safety have used Bayesian Networks as the modelling tool.

3.5.3 Open Issues

There are some issues that are still unresolved and subject to debate. For example there seems to be two different views on the use of NCAFs and GCAFs. When risk reduction is small and economic benefits are large, this may result in a large negative NCAF. Some seem to conclude that such risk control options should be implemented in mandatory instruments, whilst others are of the opinion that there is no need to regulate, as it is reasonable to assume that the owner can take care of his own economic interest. At MSC76, various questions relating to coating came in this category. All studies showed that it is in the owner's best interest to coat and maintain coating, and that this also have safety implications. Still it was decided to regulate this at IMO level.

There are also controversies on how FSA studies should be verified. The verification of the FSA on helicopter landing areas (HLA) for non-Ro-Ro passenger ships was a case of detailed verification. The international FSA on bulk carrier safety was not verified. The study was open to anyone, but there are no records of any independent verification. Following a proposal by IACS (2004), there is now an agreed review procedure.

Finally, the risk acceptance criteria will be an issue of future discussions. The criteria on safety have been agreed, but on environmental risks there have so far only been a few proposals on how to deal with this issue.

3.5.4 Risk Acceptance Criteria

The FSA guidelines are sufficiently specific on the format of the risk acceptance criteria for safety relating to loss of life. Individual risk and societal risks are supposed to be analyzed, and societal risk should be presented as FN diagrams. The ALARP criterion is referred to and criteria have been given for intolerable risk or negligible risk. In reality the proposal by Norway (2000) has been adopted. However, the numbers used for the cost-effectiveness analysis need to be updated. For example all cost/benefit ratios have been given in US$, a currency that has lost more than 1/3 of its value against other currencies since year 2000. Norway (2000) concluded that most ship types (including bulk carriers) are in the ALARP area, and that cost effectiveness criteria should be used to reach a final recommendation. In the decision making process at IMO, this criterion was referred to and all risk control options were implemented with a cost of averting a fatality less than $3 million. This is the criterion suggested by Norway (2000) in cases where a fatality is used as an indicator; which in addition to representing the fatality risk also represents a mix of severe and serious injuries.

3.5.5 The FSA Process

Most risk analysts see the FSA process as a method to coordinate all activities relating to the decision making process. This is still not a widespread view in the maritime industry. A number of risk issues with large cost implications have been put on the agenda during the last couples of years, without considering FSA studies. For example, both security issues and large passenger ship safety issues have been considered without FSA.

Even during the decision making process for bulk carriers, there were a number of risk control options implemented without FSA, for example issues relating to the revision of the Load Line Conventions or the UK proposal to strengthen all bulkheads on existing bulk carriers (UK 2002c). Furthermore a large number of separate studies, e.g. results from model tests were never integrated into the FSA studies, although some studies used structural reliability models that could easily include e.g. new hatch cover load distributions in the risk estimation and estimation of risk reduction.

3.6 Conclusions on FSA

It took the maritime industry seven years from the completion of the first version of the FSA guidelines before the first major decisions were made based on the new decision making tool. There have been some failures with using the new tool, but the industry is learning relatively fast. Attempts to make FSA something different from a standard risk based decision making method have failed, and focus seems now to be shifting towards educating more people to use the new tools, rather than 'inventing the wheel' again.

There is still a lot to be done relating to verification, risk acceptance, data collection and methods for integrating all relevant knowledge. This is probably going to take many more years.

3.7 Goal Based Standards

The new item on the agenda for the International Maritime Organisation's (IMO) Maritime Safety Committee (MSC) – 'Goal-Based New Ships Construction Standards' – was introduced at the MSC78 in May 2004 and it has been an MSC agenda item ever since, with a dedicated Working Group in place. GBS is expected to stay on the IMO agenda for the next years. This agenda item was introduced by the Bahamas and Greece in a paper to the IMO Council (Bahamas and Greece 2002). In this paper, the Bahamas and Greece argue that the IMO should play a greater role in determining the construction standards to which new ships are built, a role traditionally delegated to the classification societies, and that this should be incorporated into the IMO Strategic Plan. Many flag states opposed the proposal as they did not see any compelling need for it. However, the Bahamas and Greece prevailed.

The initiative was also surprising, as FSA also will tend to result in goal based standards, as the goal (or the safety objective of a regulation) is made explicit. By making the goal explicit it is also easier to deal with innovative and risk based design, as the prescriptive rules are seen as a means to achieve the goal (for standard design solutions), but in principle the goal may be achieved by any other design solution that can be documented to meet the goal (the risk acceptance criteria). This would open opportunities for risk based design. Some classification societies had already started to use the FSA guidelines as basis for own rule development, and saw clear benefits of having more well-defined criteria to relate to.

There are also new elements introduced in the regulatory process, by formalizing a Goal Based Approach. This relates to the style of writing regulations: Rather than stating in prescriptive form how ships should be built and equipped, the regulations focus on the goals, the purpose of the regulation, what should be achieved, rather than how to achieve it. This affects the structure of the regulations, and helps keeping a well-defined structure to the regulation. This is an attractive idea, as the current regulatory system is extremely complicated, and is becoming ever more complicated due to a continuous amendment process.

The structure of the goal based regulatory system as tentatively agreed at MSC84 (May 2008) is shown in Fig. 3.4. It is noted that Tiers I, II and III represents the GBS to be maintained at IMO level, and includes a verification process that e.g. classification rules, being an example of Tier IV, should be verified to meet the goals for one or more functional requirements.

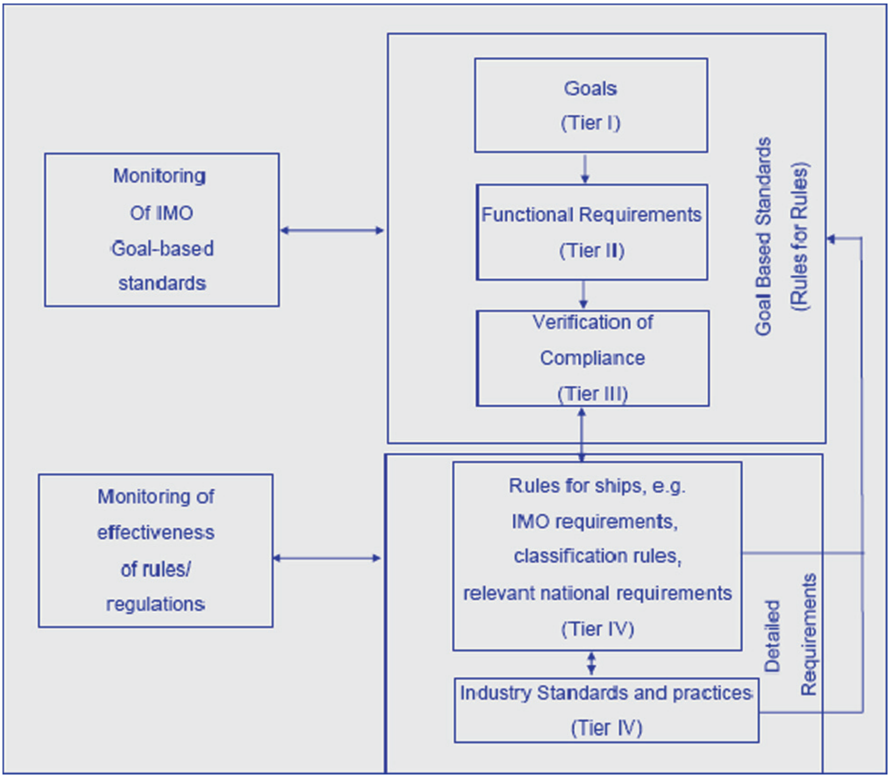

Fig. 3.4 Goal based standards framework

3.7.1 Definition of GBS

According to the current definition, IMO goal-based standards are:

1. broad, over-arching safety, environmental and/or security standards that ships are required to meet during their lifecycle;
2. the required level to be achieved by the requirements applied by class societies and other recognized organizations, Administrations and IMO;
3. clear, demonstrable, verifiable, long standing, implementable and achievable, irrespective of ship design and technology; and
4. specific enough in order not to be open to differing interpretations.

3.7.2 Tier I: Goals

Currently a draft text is available only for ship construction and the goals (Tier I) are expressed as follows:

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.

1. Safe and environmentally friendly means the ship shall have adequate strength, integrity and stability to minimize the risk of loss of the ship or pollution to the marine environment due to structural failure, including collapse, resulting in flooding or loss of watertight integrity.
2. Environmentally friendly also includes the ship being constructed of materials for environmentally acceptable dismantling and recycling.
3. Safety also includes the ship's structure being arranged to provide for safe access, escape, inspection and proper maintenance.
4. Specified operating and environmental conditions are defined by the operating area for the ship throughout its life and cover the conditions, including intermediate conditions, arising from cargo and ballast operations in port, waterways and at sea.
5. Specified design life is the nominal period that the ship is assumed to be exposed to operating and/or environmental conditions and/or the corrosive environment and is used for selecting appropriate ship design parameters. However, the ship's actual service life may be longer or shorter depending on the actual operating conditions and maintenance of the ship throughout its life cycle (End quote).

Many have proposed to simply add a reference to the ALARP principle, and the FSA Guidelines to make these goals risk based (and possible to understand in practical application to rule development). Since the FSA Guidelines already contains the risk evaluation criteria this would be sufficiently clear to a rule developer.

3.7.3 Tier II: Functional Requirements

The first three of the so-called functional requirements, are given below:

Tier II (Functional Requirements)

(Applicable to new oil tankers and bulk carriers in unrestricted navigation)

Design

II.1 Design life

The specified design life is not to be less than 25 years.

II.2 Environmental conditions

Ships should be designed in accordance with North Atlantic environmental conditions and relevant long-term sea state scatter diagrams.

II.3 Structural strength

Ships should be designed with suitable safety margins:

1. to withstand, at net scantlings, in the intact condition, the environmental conditions anticipated for the ship' 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; and

2. 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.

The structural strength should be assessed against excess deformation and failure modes, including but not limited to buckling, yielding and fatigue. Ultimate strength calculations should include ultimate hull girder capacity and ultimate strength of plates and stiffeners. The ship's structural members should be of a design that is compatible with the purpose of the space and ensures a degree of structural continuity. The structural members of ships should be designed to facilitate load/discharge for all contemplated cargoes to avoid damage by loading/discharging equipment which may compromise the safety of the structure.

II.4 Fatigue life

The design fatigue life should not be less than the ship's design life and should be based on the environmental conditions in II.2 (end quote).

Already at this stage, there are many challenges, as seen from a risk perspective.

1. *25 years design life*. In practice this is strongly dependent on maintenance, and outside control of the regulator; but in any case most ships are designed to have an economic life of 25 years. But the actual life depends on many commercial issues, like e.g. the market situation: At times with high day-rates there is no scrapping. The term 'design life' does not play any important role in classification rules. The 25 years used in classification rules rather refers to the return period for extreme loads (which is a different concept than the design life).
2. *Bulk Carriers and Tankers* are today designed to 20 years North Atlantic extremes loads. To change this to 25 years has almost no effect.
3. *Suitable safety margin*? This is where a risk based approach becomes useful, as Structural Reliability Analysis could be used to calibrate the Rules to the reliability level defined.
4. *Fatigue life equal to design life*. This statement must be based on a non-standard definition of fatigue life (corresponding to about 2.27% probability of failure for each 'hot spot'). With hundreds of hot spots this probability appears too high.

These few examples demonstrate that rules today should be better based on a risk based approach. It is not possible to seriously discuss safety, without using risk concepts. The example relating to hull girder ultimate strength was prepared based on work of Hørte et al. (2007) and internal work in DNV for IACS (2006).

The role of FSA and Structural Reliability Analysis in the GBS Framework is a rational way for the justification of the rules and regulations. These analyses can be subject to verification. The final formulation of the rules and regulations is, however, usually not possible to be verified. The tendency for those supporting a prescriptive approach to GBS is to write detailed verification requirements (in Tier III), rather than leaving it to the developer of the rules/regulation to justify their development.

3.8 Risk Acceptance

3.8.1 Methods to Justify Criteria

There are many methods to establish risk acceptance criteria, and this is a continuing debate in the scientific community; but there are, also, intense political and public debates on these issues. New ways of reasoning may still appear and gain support. For example the new method described in Skjong and Ronold (1998) is regarded as a breakthrough for setting target reliabilities in structural reliability applications by Rackwitz (2001), as compared to the more classical approach used in DNV (1992) and Skjong et al. (1995). For a discussion, see Skjong (2002), Ronold and Skjong (2002) and Skjong and Bitner-Gregersen (2002). Currently, the main methods for defining criteria are:

Compare with other hazards. This implies that a comparison is made with relevant criteria of other industries that are felt to represent a reasonable target, and where the documentation is good. This approach may lead to some learning from other industries, which could add benefits. However, the method must be used competently. For example, ships may compare unfavourably on a passenger-kilometre scale and well on a ton-kilometre scale if compared to airplanes. The aircraft industry seldom presents FN diagrams, as in plane accidents the result is often no survivors in many accidents.

Shipping should be as safe as road transport

Compare with natural hazards. The idea is to compare things we do to ourselves with things done to us by Nature (God). It is generally a goal in using this approach that what we do to ourselves should be a small portion on what we can blame on Nature (God). The problem with this is that the distinction is not very clear. If a ship is designed to survive the twenty year North Atlantic extreme wave, and than meet an even higher wave resulting in structural failure, that is hardly an act of God, although the insurance company accept it as such.

Risks posed by human activity should be smaller than those posed by nature

Compare with risks we normally take. We do a number of things that are hazardous, like crossing the street, driving cars, repairing the roof, and sport activities. We do not consider these activities dangerous, but in reality they are more risky than a number of individual work related risks. This is usually phrased as ‘The most dangerous place to be is at home’. This statement is largely verified by statistics for most white-collar workers.

Risk that are smaller than staying at home may be accepted

Compare with previous decisions. An acceptable risk is always implicit in any building code, road standard, train safety standard etc. It is possible through analysis of data or by risk models to find the implicit risk. By comparing to standards that are accepted as 'high quality', we may arrive at an evaluation criterion. As building codes are calibrated according to ISO/CEN structural reliability standards, the implicit criteria will be replaced by explicit and known criteria.

Risks that are smaller than in current building codes may be accepted

Compare with well informed decisions made in democratic forums. From time to time risk assessment is carried out and presented to national parliaments and is subject to extensive review and public debate. When a decision is finally made the value judgement on 'barely acceptable' or 'barely unacceptable' is disclosed in risk terms. This may be used as evaluation criteria in later risk studies.

Risk associated with the construction of the National Natural Gas Power Station is barely acceptable

3.9 Decision Parameters

In principle, different decision parameters may be used, and will be used unless some standardisation effort is undertaken. The advantage of standardisation is e.g. that

– the FSA team knows what to document,
– the decision makers know what to ask for,
– information are collected from many analyses in the same format,
– previous decisions may be compared to current and future decisions,
– *risk based design may be based on the same criteria*,
– the high level goal in a GBS is defined

The risk evaluation criteria are normative statements or value judgements, as opposed to a statement about risk, which ideally should be objective statements of probabilities and consequences. Applications of FSA have disclosed such value judgements, and in Skjong et al. (2005) there is an extensive list of RCOs implemented and not-implemented with associated cost effectiveness. If evaluation criteria are not made explicit, the FSA may be used to disclose the value judgement. In this chapter generic risk results for the common ship types are shown together with the evaluation criteria to indicate the effect of the criteria proposed and used at IMO.

To make a well-informed decision about the possible implementation of a new regulation, a new risk control option, or possible deletion of an obsolete regulation, many different decision parameters may be necessary. In the FSA Guidelines the following decision parameters may be identified, or are suggested:

– Individual risk for a crew member (individual risk is risk of death, injury and ill health)

– Individual risk for a passenger (if relevant)
– Individual risk to third parties (as appropriate)
– Societal risk in terms of FN[6] diagrams for crew members
– Societal risk in terms of FN diagrams for passenger (if relevant)
– Societal risk in terms of FN diagrams for third parties (as appropriate)
– Costs of each risk control options should be presented together with the effect on the six items above.
– The Gross Costs of Averting a statistical Fatality (GCAF) should be presented.
– The cost of reducing risk of injuries and ill health, should be presented (see discussion below)
– In cases where the risk control options can not be justified purely for safety reasons, the net economic benefit may be subtracted from the costs, and the Net Cost of Averting a Fatality (NCAF) should be presented[7].

The risks and risk control options should fulfil *all* the criteria associated with the decision parameters above.

Further criteria for environmental protection needs to be developed. Alternatively, all environmental consequences could be transferred to monetary units, and included in a cost benefit assessment, but this also requires an agreed way of converting pollution averted into monetary units. The only criteria presented to IMO are cost effectiveness criteria for evaluating measures to reduce oil-outflow. The criterion is presented below. At IMO there are no agreed criteria.

For each type of the *individual* risks (i.e. the risk to an individual person) the risk of death, injury and ill health should be presented separately. An integrated indicator may also be presented as Equivalent Fatalities or the Disability Adjusted Life Year (DALY), see below. As different integrated indicators exist, the presentation of separate results should always be made. In case only fatality rates are presented it must be made clear if this implies that risk of injury and ill health are implicit in the numbers or explicitly excluded from the analysis. This will affect the risk evaluation criterion used (see below).

In evaluation of a specific risk control option, results before and after implementing the risk control options should be presented. For each of the *societal* risk evaluation criteria, results should be presented separately and added together.

3.10 Risk Evaluation Criteria

The standard term used for risk evaluation criteria is ‘risk acceptance criteria’. The term is well established in many industries and regulations. In shipping, IMO has, however, decided to use the term risk evaluation criteria to indicate that the criteria

[6] FN diagrams are plots of frequency (F) of N or more fatalities. FN diagrams are displayed in log-log scale.

[7] If the net benefit is large, it may be recommended not to regulate, as the market will regulate this.

will not be used as the only decision criteria. Other considerations may also be appropriate.

In general risk evaluation criteria may be implicit or explicit, and they may be of high-level or low-level. The technical equivalency in Regulation 5 of SOLAS Chapter I is an example of a low-level implicit criterion (technical equivalency without knowing the safety). Acceptance of equivalency may also be given based on safety equivalency. This would be a high-level implicit criterion. As the safety is not known in current regulations, i.e. is implicit, safety should first be established by analysis of previously accepted ships designs, i.e. made explicit. Thereafter safety equivalency may be demonstrated for a new solution.

It should be noted that without explicit safety objectives, it is not obvious what safety equivalency should imply. E.g. should the probability of a catastrophic accident vary with the ship size, number of passengers etc.? Does safety equivalency relate to individual risk or societal risk? In general, a number of interpretations may be possible.

3.11 Explicit Risk Evaluation Criteria – Individual Risk of Death, Injury and Ill Health for Passengers, Crew and Third Parties

3.11.1 Purpose

The purpose of *individual* risk evaluation criteria is to limit the risks to people onboard the ship or to individuals who may be affected by accidents. The criteria should define the term 'intolerable and negligible level of risk' in terms of the *individual* risks of death, injury and ill health.

3.11.2 Background

Modern risk assessment practice is to use an *individual* risk criterion that defines the intolerable and the negligible (broadly acceptable) risk. These criteria are limits to the area where cost-effectiveness assessment may be applied, as intolerable risks must be reduced irrespectively of costs. The area where cost-effectiveness assessment may be applied are commonly referred to as the As Low As Reasonably Practicable (ALARP) area. *In this area risks should be reduced as long as the risk reduction is not disproportionate to the costs*. To reduce risks beyond where risk reduction is disproportionate to the costs is not reasonable. The cost-effectiveness criteria therefore define what is reasonable (in terms of R in ALARP, see section about Cost-Effectiveness below).

There is no single universal level of acceptable *individual* risk. People are prepared to accept a wide variety of risks depending on their own perception of the risks and benefits from the activity. In general, higher risks are accepted if the risk is voluntary, ordinary, natural, the effects are delayed and the individual consider that they have control. These factors may explain why high risks are commonly accepted in some sports, in driving cars and motorbikes, and in certain hazardous occupations where risk control depends on the individual's own skill (e.g. flying, diving).

When people are exposed to risks over which they have little or no control, they rightly expect that the appropriate authorities impose control on their behalf. It is these 'involuntary' risks which risk evaluation criteria are developed to control. An appropriate level for the risk evaluation criteria would then be substantially below the total accident risks experienced in daily life, but might be similar to risks that are accepted from other involuntary sources.

Individual risk criteria for hazardous activities are often set using the risk levels that have been accepted from other industrial activities. This involves a judgement that the acceptability of *individual* risks is similar for all activities over whose safety the person exposed has little or no control. Thus, risk criteria for ship's crew could be similar to those for land-based industries e.g. manufacturing and offshore industries. This implies that risk criteria that have already been developed in other industries can be applied to ships.

In principle there are many different methods that may be used to set the limit of tolerable risk as mentioned previously. By comparing to other industries Tables 3.3 and 3.4 are relevant. Comparing to natural hazards a risk evaluation criterion of 10^{-3} per ship-year for crew may be suggested. The number can be traced back to a time when the annual fatality rate (for all reasons) in the period of life when this is at its lowest (4–15 years of age) was about 10^{-3} in OECD member countries. Today this figure is down to $2 \cdot 10^{-4}$ in some countries. This was used by many regulators as an intolerable limit. For passengers it is common to use a stricter criterion, because the passengers are less informed about the risks, they are not compensated (but pay), and are less in control. A negligible or 'broadly acceptable' criterion of 10^{-6} should be understood as a very small number representing an insignificant risk to an individual. If exposed to only such risks an individual would live in the order of a million years.

Crew-members on a ship should have more influence over the risks and should be better informed than passengers or members of the public near the port. It is therefore common to treat occupational risk (crew) differently than transport related risk (passengers).

3.11.3 Individual Risk Criteria

Based on the considerations above *individual* risk criteria were proposed Norway (2000) for ships, based on those published by the UK Health & Safety Executive (HSE 1999). This was agreed at IMO.

Maximum tolerable risk for crew members	10^{-3} annually
Maximum tolerable risk for passengers	10^{-4} annually
Maximum tolerable risk for public ashore	10^{-4} annually
Negligible risk	10^{-6} annually

Table 3.3 Individual risk criteria

Authority	Description	Criterion (annual)
HSE (1999)	Maximum tolerable risk to workers	10^{-3}
	Maximum tolerable risk to the public	10^{-4}
	Negligible risk	10^{-6}
Netherlands (Bottelberghs 1995)	Maximum tolerable for existing situations	10^{-5}
	Maximum tolerable risk for new situations	10^{-6}
New South Wales, Australia (DUAP 1997)	Sensitive developments (hospitals, schools etc.)	$5 \cdot 10^{-7}$
	Residential, hotels, motels, tourist resorts etc.	$1 \cdot 10^{-6}$
	Commercial, retail, offices etc	$1 \cdot 10^{-5}$
	Sporting complexes, active open space	$1 \cdot 10^{-5}$
	Industrial	$5 \cdot 10^{-5}$
Western Australia (EPA 1998)	Sensitive developments (hospitals, schools etc.)	$5 \cdot 10^{-7}$
	Residential zones	$1 \cdot 10^{-6}$
	Non-industrial (commercial, sporting etc.)	$1 \cdot 10^{-5}$
	Industrial	$5 \cdot 10^{-5}$

Table 3.4 Individual risk in various industries and activities, Mathiesen (1997)

Industry	Annual individual risk ($\times 10^{-5}$)
Oil and gas production	100.0
Agriculture	7.9
Forestry	15.0
Deep sea fishing	84.0
Energy production	2.5
Metal manufacturing	5.5
Chemical industry	2.1
Mechanical engineering	1.9
Electrical engineering	0.8

Risks below the tolerable risk but above the negligible level should be made ALARP by adopting cost-effective risk reduction measures. Other regulators use similar or slightly different criteria.

The maximum tolerable criteria specified above are not particularly strict, and it may be required that all ships should meet them. When a comprehensive FSA is carried out for new ships, it may be appropriate to have a more demanding target, which should be met.

These may be indicated as follows (proposed by Norway (2000) and agreed at IMO):

Target individual risk for crew members	10^{-4} annually
Target individual risk for passengers	10^{-5} annually
Target individual risk for public ashore	10^{-5} annually

Although it is not necessarily essential to have risks below these targets, failure to meet them would suggest that cost-effective risk control options might be available. New regulations based on an FSA should demonstrate that the new ships meet these targets, and that risks are ALARP.

Regarding the *individual* risk evaluation criteria for public ashore, indications of risk levels are given above. However, the responsible national authorities should decide on the *individual* risk evaluation criteria for public ashore.

3.11.4 Comparison with Historical Data

Figure 3.5 shows the estimated average *individual* risk for crews from different ship types in the period from 1978 to 1998 (Eknes and Kvien 1999). The data source is the LMIS casualty database, representing the *ship* accidents, and excluding personal accidents. The figures indicate that, unless personal accidents dominate, the individual fatality risk levels in the maritime industry, according to the proposed criteria, fall in the ALARP region, where risk control options should be introduced if they are cost effective. Indications are that the number of personal accidents account for a similar risk as the ship accidents. This being the case, the total individual risk may be close to intolerable for some ship types. There may be exceptions among subgroups of ship types investigated or ship types that have not been investigated, such as tug boats and fishing vessels.

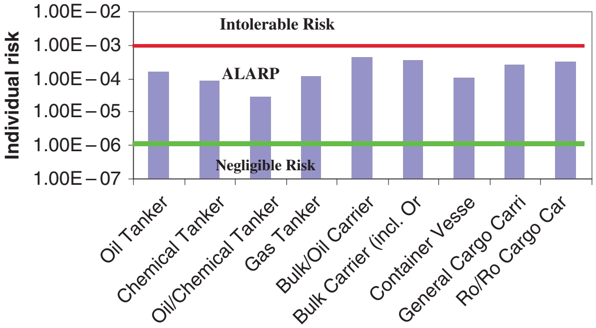

Fig. 3.5 Individual fatality risk (annual) for crew of different ship types, shown together with the proposed individual risk evaluation criterion (data from 1978 to 1998, data source: LMIS/Ship accidents). As the data is from LMIS the personal accidents are not included

For *individual* risks of injury and ill health similar evaluation criteria may be developed by comparing to other industries and transport. For example, if a significant proportion of the crew is injured or develops similar health problems, this should be regarded intolerable. What is significant may be judged by comparing to statistics representing larger populations. No explicit criteria have been proposed.

Further, for an explicit treatment of risk of injuries and ill health more explicit criteria should be based on cost-effectiveness considerations (see the section about cost-effectiveness below). Except for such obviously intolerable cases a criterion based on cost effectiveness is more appropriate for explicit studies of risks of injuries and ill health, see below.

3.12 Explicit Risk Evaluation Criteria – Societal Risk to Life for Passengers, Crew and third Parties

3.12.1 Purpose

The purpose of *societal* risk evaluation criteria is to limit the risks from ships to whole crews, groups of passengers or the society as a whole, and to local communities (such as ports) which may be affected by ship activities. As the term is used at IMO, other regulators might use the term *group risk*. In particular, societal risk evaluation criteria are used to limit the risks of catastrophes affecting many people at the same time, since society is particularly concerned with such events. In effect, the criteria define the term ‘acceptable level of risk’ in terms of the overall *societal* risks of fatalities.

3.12.2 Background

In general, *societal* risk evaluation criteria, and the societies’ risk aversion against large or catastrophic accidents may be considered as lacking an explicit rationale. Some risk analysts would count the risk aversion against large accidents as one of the ‘risk conversion factors’ representing and defined as the bias ‘perceived risk’ divided by ‘actual risk’. E.g. Litai (1980) is listing the following factors affecting this bias: Volition, *Severity*, Origin, Effect Manifestation, Exposure Pattern, Controllability, Familiarity, Benefit and Necessity. The factors are found to be similar to factors addressed by Rowe (1977), Starr (1969), Kinchin (1978), Otway and Cohen (1975) and Green et al. (1998). Although the rationality may be debated, societal risk criteria are used by a large number of regulators. The problems of inconsistency are, however, often seen and debated.

FN diagrams may be established in similar ways as *individual* risk criteria. However, comparison with other industries may result in unpredictable and illogical results. The *societal* risk evaluation criteria should reflect the importance of the activity to society. For example, the evaluation criteria used for a single fishing vessel should be different from the whole transport sector in a country. To formalise such observations an FN evaluation criterion may be established by considering the economic activity represented by the different ship types. This may vary by orders of magnitude. The examples given for some ship types show that when the importance to the society is accounted for, the established FN evaluation curves vary within 1–2 orders of magnitude. The outlined method (Skjong and Eknes 2001, 2002) may be used for any type of activity above a certain size. An obvious limitation of the principle is represented by activities of high economic value with low labour intensity in remote places, e.g. offshore oil production. It should be the added value by the activity that is included.

The objective of the outlined method is to establish transparent FN risk evaluation criteria with a more rational foundation, which may be established from factual and available information. This way the criteria would be transparent as required in IMO (1997, 2001).

3.12.3 Method

The evaluation criteria may be associated with the economic importance of the activity in question, and calibrated against the average fatality rate per unit economic production. The importance of an activity may be measured most adequately in economic terms, assuming that what is paid in an open market on average represents the importance. Similarly, Gross National Product (GNP[8]) is an aggregated indicator of the economic activity. *Societal* risk associated with an activity may be accepted according to the importance to society of the activity.

For occupational accidents the aggregated indicator q, may be defined as the average fatality rate per unit GNP. For transport related accidents a similar aggregated indicator, r may be defined.

$q = \frac{\text{Number of occupational fatalities}}{\text{GNP}}$	crew
$r = \frac{\text{Number of fatalities due to transportation}}{\text{Contribution to GNP from transportation}}$	passengers

By using data from US and Norway on occupational fatalities $q = 1.0$ *fatalities/\$ billion* may be estimated for the occupational fatalities and $r = 5.73$ *fatalities/\$ billion* may be estimated from statistics for scheduled air traffic (ICAO 1995; Skjong and Eknes 2000, 2001). These numbers are in need for regular updates based on new statistics, both with respect to airplane accidents and economic values. Air traffic

[8] GNP = An estimate of the total money value of all the final goods and services produced in a given one-year period by the factor of production owned by a particular country's residents.

is selected for comparison because of the availability of good statistics, and the generally high safety standards.

For a specific activity (e.g. a ship), an *average* acceptable Potential Loss of Life (PLL_A) may be based on the Economic Value (EV) of the activity.

$$\begin{aligned} PLL_A &= q \cdot EV \ \text{ for crew/workers} \\ PLL_A &= r \cdot EV \ \text{ for passengers} \end{aligned} \tag{3.3}$$

This states that largely the total occupational risk should be distributed between the different activities accounting for their contribution to GNP, and that large deviations from this should be assessed. A similar criterion should be established for a transport activity. For activities and trades, which are of less importance to the society, the society may not be willing to accept a high accidental fatality risk. For activities and trades of minor significance, and with minor contribution to the service production, only minor risks should be accepted. As the ultimate solution the fatality risk may be eliminated, by eliminating the activity itself. This way a safety budget would be established. E.g. a low economic importance corresponds to a low PLL_A.

FN curves are commonly regarded as useful tools. An FN curve with inclination *b on log-log scale* may be fitted to the resulting PLL_A by:

$$PLL_A = \sum_{N=1}^{N_u} N f_N = F_1 \left(\frac{1}{N_u^{b-1}} + \sum_{N=1}^{N_u-1} \frac{(N+1)^b - N^b}{N^{b-1}(N+1)^b} \right) \tag{3.4}$$

Here N_u is the upper limit of the number of fatalities that may occur in one accident. For a ship this is well defined as the maximum number of crew/passengers

f_N frequency of occurrence of an accident involving N fatalities
F_1 frequency of accidents involving one or more fatalities

Following the recommendation by HSC (1991), HCGPD (1983) and Statoil (1995), $b = 1$ is chosen, and the above simplifies to:

$$PLL_A = F_1 \left(1 + \sum_{N=1}^{N_u-1} \frac{1}{N+1} \right) = F_1 \sum_{N=1}^{N_u} \frac{1}{N} \tag{3.5}$$

Some risk analysis practitioners are of the opinion that $b = 1$ is not risk averse. This is wrong, as explained in details in HSE (1991). The risk aversion may be understood by observing that small contributions to PLL come from large N. Since these small contributions are as 'intolerable' as the comparable large contributions from small N, the $b = 1$ is risk averse.

If solved with respect to F_1, Eq. (3.5) gives

$$F_1 = \frac{PLL_A}{\sum_{N=1}^{N_u} \frac{1}{N}} \tag{3.6}$$

The ALARP region is introduced by assuming that the risk is intolerable if more than one order of magnitude above the average acceptable and negligible (broadly acceptable) if more than one order of magnitude below the average acceptable. This implies that the region where risks should be reduced to As Low As Reasonably Practicable (ALARP) ranges over two orders of magnitude, in agreement with many published FN evaluation criteria, e.g. HSE (1999), HKGPD (1983) and Statoil (1995).

3.12.4 Examples of Criteria and Comparison with Data for Some Ship Types

Figures 3.6, 3.7 and 3.8 below show FN data for different types of ships, tankers, bulk carriers, container vessels, and passenger Ro/Ro vessels. The FN curves are based on data from LMIS (1999). The figures also show the *societal* risk evaluation criteria established by the method outlined above. The tankers, bulk carriers and container vessels were all assumed to have an average crew size of 20. Based on data from Clarkson Research Studies (1999) the average annual turnover for the different tankers was estimated to approximately \$5 million, while the average annual turnover for bulk carriers and container vessels was estimated to approximately \$2.5 million. For the passenger Ro/Ro vessels, the evaluation criteria are based on data

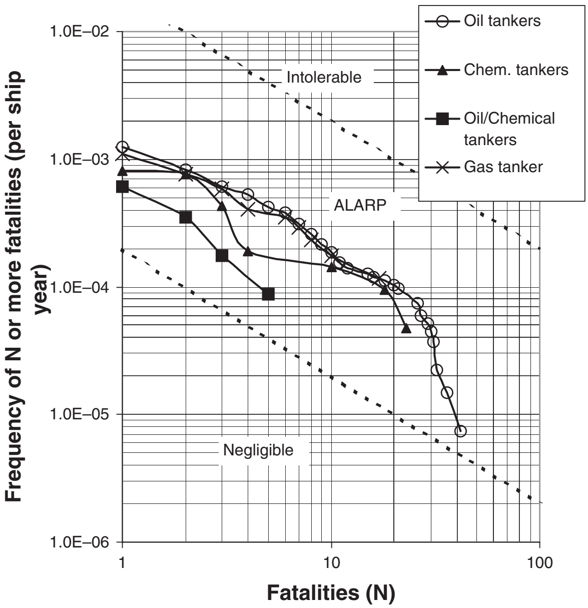

Fig. 3.6 FN curves for different tankers, shown together with established risk evaluation curves. Data from 1978 to 1998. (Data source: LMIS)

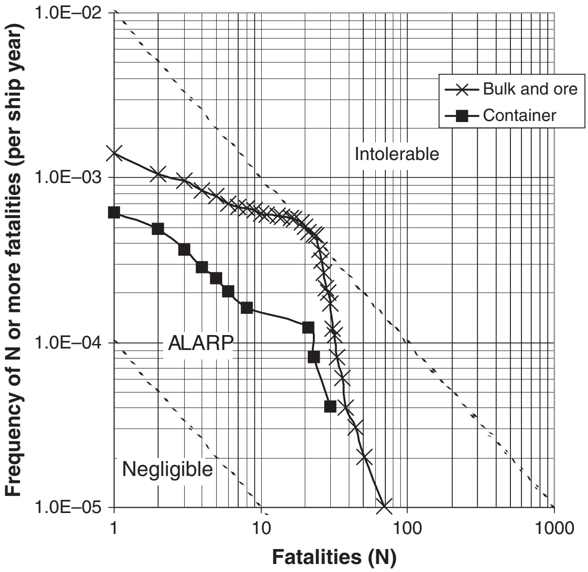

Fig. 3.7 FN curves for bulk and ore carriers, and container vessels, shown together with risk evaluation criteria established by the above outlined method. Data from 1978 to 1998. (Data source: LMIS)

for a fleet of only 7 vessels. A passenger Ro/Ro vessel with a crew size of 140 and annual turnover of $50 million gives a *societal* risk evaluation criterion for crew as shown in Fig. 3.8. A *societal* risk evaluation criterion for passengers as shown in Fig. 3.8 results when considering a vessel carrying 1,900 passengers at annual operating revenue from tickets of $16 million. In an FSA all data above must be updated to current figures, but avoiding to use e.g. figures from time periods with extremely high profits.

The historical data appears to give FN curves in the ALARP region for most of the examined ship types. The bulk carriers are different, apparently touching the borderline between the ALARP and the intolerable risk region. This may be observed to be in agreement with the concern behind the attention that has been given to bulk carriers' safety in recent years that calumniated with the many decisions to improve bulk carrier safety (described above), where the impression has been that the number of losses of these ships involving many fatalities has been judged as intolerable. For bulk carriers, the FN curve above is now outdated. For bulk carriers the curve is in agreement with the previous published FN curve by Mathiesen (1997) which was derived by other methods. For Passenger Ro/Ro Vessels the curve presented is in agreement with the FN diagram published by the North West European Project on Passenger Ro/Ro Vessels (DNV 1997b).

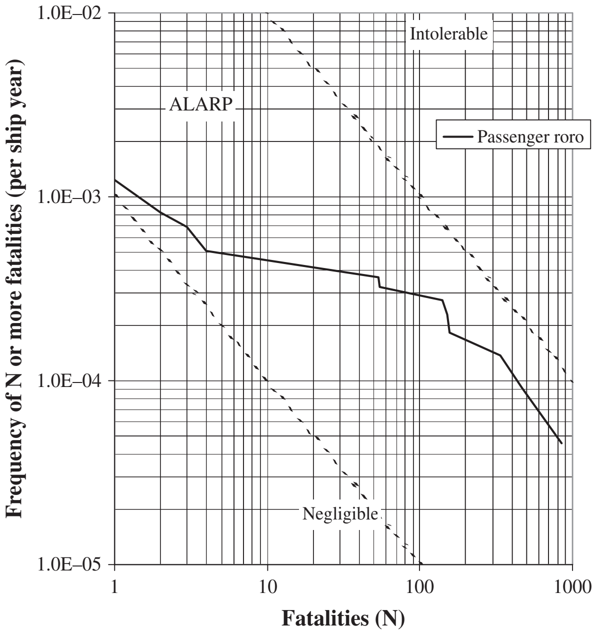

Fig. 3.8 FN curve for passenger Ro/Ro ships, shown together with risk evaluation criteria established by the above outlined method. Data from 1989 to 1998. (Data source: LMIS)

3.12.5 Third Parties

On safety issues there will always be a conflict between the interests of third parties and industries, as the third parties will be involuntarily exposed to the risks from the industry. The shipping industry is not an exception. It should be the national authorities' responsibility to define maximum tolerable and negligible third party risk, to protect the citizens.

3.12.6 Cost Benefit and Cost Effectiveness Assessment

3.12.6.1 Purpose

The type of risk criteria proposed above may define a range within which the risks should be reduced to a level 'as low as reasonably practicable' (ALARP). Within this range cost effectiveness assessment is recommended used to select reasonably practicable risk reduction measures.

The purpose of the cost effectiveness criterion will be to provide a basis for decision-making about risk control options resulting from FSA Step 3, see FSA Guidelines.

3.12.6.2 Background

Currently many IMO decisions and other decisions have been made within the maritime industry based on FSA. Early versions of these decisions are listed in Table 3.5, a comprehensive list may be found in Skjong et al. (2005). When a decision is made to implement a risk control option the '>' is used to indicate that 'a statistical fatality averted is worth more than $10 million'. It is seen that there are no inconsistencies at IMO level, and based on early well-founded decisions the criterion is in the range $1.5 million to $5 million.

Initially IMO decided to require Helicopter Landing Area (HLA) on all passenger ships. The Formal Safety Assessment that was prepared by DNV, for Norway and ICCL, showed that this requirement could not be justified as the cost were in great disproportion to the benefits for non-Ro/Ro passenger ships. The cost of averting a fatality was about $37 million. A decision was therefore made to repeal the requirement (see also Sect. 4.3 of this chapter).

Society spends large sums (up to 20% of Gross Domestic Product (GDP[9]) in some countries) on safety. Such use of resources cannot easily be justified in order to optimise economic production or the well-being in the population. Resources are limited and society in practice put some limit to how much resources could be used for safety, and thus a cost effectiveness criterion may be applied.

The evaluation of fatality risks is a critical step in this process, and modern risk assessment practice is to highlight this issue by expressing the results in the form of a Gross Cost of Averting a Fatality (GCAF) if a risk control option were to be adopted, i.e. by cost effectiveness assessment.

Table 3.5 Cost of averting fatalities in actual decisions

Decision	Decision maker	Value($ million)
Strengthening bulkheads on existing bulk carriers	IACS and IMO (1)	> 1.5
Helicopter landing area on non-Ro/Ro passenger ships	IMO(2)	< 37 (12–73,000)
3 bulkheads on car deck	IMO(3)	< 5
3 bulkheads on car deck	NMD(3)	> 5
3 bulkheads + sponsons	IMO(3)	< 7.8
Extended sponsons only	IMO(3)	< 11
Collision avoidance training	Owner(3)	> 0.7
Extra deck officer	IMO(3)	< 5.5

Re: (1) Mathiesen (1997), (2) Skjong et al. (1997), (3) DNV (1997b).

[9] GDP = An estimate of the total money value of all the final goods and services produced in a given one-year period using the factor of production located within a particular country's borders. The differences between GDP and GNP arise from the facts that there may be foreign-owned companies engaged in production within the country's borders and there may be companies owned by the country's residents that are engaged in production in some other country but provide income to residents.

$$GCAF = \frac{\Delta \text{Cost}}{\Delta \text{Risk}} \tag{3.7}$$

ΔCost is the marginal (additional) cost of the risk control option, whilst ΔRisk is the reduced risk in terms of fatalities averted.

An alternative cost-effectiveness measure is given by Net Cost of Averting a Fatality (NCAF), where the economic benefits of the investigated risk control options are accounted for. Economic benefits (or risk reduction) may also include the economic value of reduced pollution. The consequence of pollution may be established from clean-up costs and environmental costs or from previous decisions, see below

$$NCAF = \frac{\Delta \text{Cost} - \Delta \text{EconomicBenefis}}{\Delta \text{Risk}} = GCAF - \frac{\Delta \text{EconomicBenefis}}{\Delta \text{Risk}} \tag{3.8}$$

This approach then requires criteria to define the NCAF values at which measures are considered just cost-effective. Again, there are many methods to identify an evaluation criterion. Alternatives are such methods as willingness to pay studies by public surveys, willingness to pay in actual decisions, studies of risk control options implemented and not implemented. If regulators could avoid implementing risk control options with high NCAFs and implement those with low NCAFs, more lives would be saved for the same budget (Condition of Pareto optimality), see e.g. Tengs et al. (1995) and Ramberg and Sjøberg (1997).

Table 3.6 gives values of CAF used by some authorities.

Large studies in other industries have revealed large inconsistencies in safety policy. The most well known and largest study is that of Tengs et al. (1995) carried out in the US. Table 3.7 presents the average values from this study. These figures represent willingness to pay in actual decisions. Assuming that a fatality correspond to 35 lost life-years, the median value corresponds to \$1.470.000.

Table 3.6 Published CAFs in use as evaluation criteria

Organisation	Subject	CAF	Source
US Federal Highway Administration	Road transport	\$ 2.5 million	FHWA (1994)
UK Department of Transport	Road transport	£1.0m (1998, up-rated with GDP per capita)	DETR (1998)
UK Health & Safety Executive	Industrial safety	As above or higher	HSE (1999)
Railtrack (UK rail infrastructure controller)	Over-ground railways	As above to £2.65m	Railtrack (1998)
London Underground Ltd	Underground railways	£2million	Rose (1994)
EU	Road transport	€1 million	Evans (1998)
Norway	All hazards	NOK 10m	Norway (1996)

Table 3.7 Results from Tengs et al. (1995)

Five hundred life-saving interventions and their cost effectiveness	
Number of measures studied	587
Range of cost effectiveness	Negative to $10 billion/life year saved
Median value	$42.000/life year
Median for medical interventions	$19.000/life year
Median for injury prevention	$48.000/life year
Median for toxic control	$2.8 million/life year

It is also possible to derive evaluation criteria expressed as NCAF from compound aggregated social indicators, see UNDP (1990) and Lind (1996). The Life Quality Index Criterion for acceptable risk implies that an option is preferred or accepted as long as the change in the Life Quality Index owing to the implementation of the option is positive. The Life Quality Index contains such indicators as GDP/capita and life expectancy at birth. As a risk control option changes these two values, an optimum acceptable NCAF may be derived, and as GDP and life expectancy varies between countries there are variations in the evaluation criteria. Within OECD member countries (representing some 95% of the global GDP and presumably a similar share of the maritime transport), the variation is not very large, see Fig. 3.9.

Based on the above Fig. 3.9, a NCAF criterion of $3 million was proposed for use by IMO, in cases where fatalities in addition to representing fatality risk also represent an indicator of risk of injuries and ill health. The NCAF criterion is proposed to

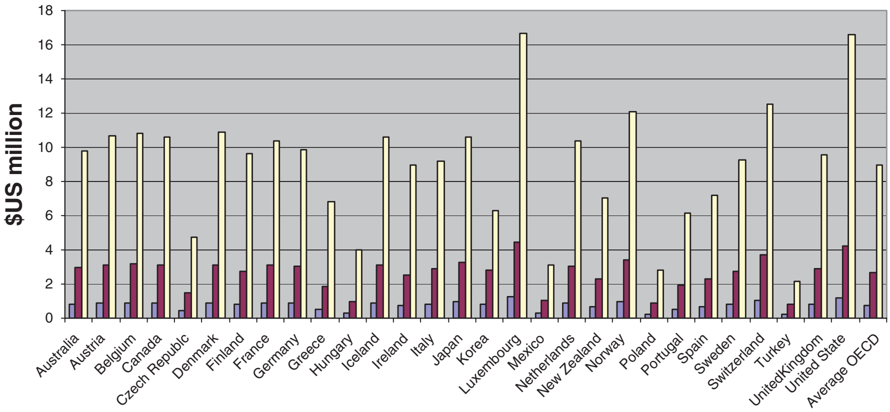

Fig. 3.9 The net cost of averting fatality criteria for OECD member countries. The *blue* (*left*) columns would be defendable by purely economic considerations (production value of man), the *red* (*middle*) columns represent the societal value (derived from the societal indicators), the *yellow* (*right*) columns represent the limit where no regulation should be implemented as individuals would use the resources better on life saving. The OECD average numbers are 0.76, 2.65 and US$8.93 million (Skjong and Ronold 2002)

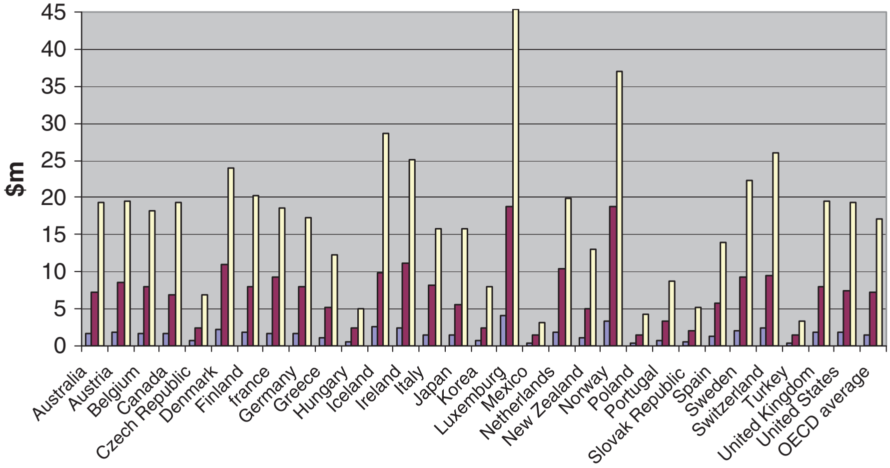

Fig. 3.10 The cost of averting fatality (CAF) criteria for OECD member countries. The OECD average numbers for 2007 are 1.57, 7.23 and \$17.2 million. From 2001 to 2007 the recommended criteria is up from 2.65 to \$7.23 million. Most of the effect is due to the decreased value of the US\$, but there is also an effect of economic growth and reduced hours of work

be updated every year according to the average risk free rate of return (some 5%), or if data are available by use of the formula derived on the basis of societal indicators, see Skjong and Ronold (1998). Higher values may be justified for risks that are just tolerable, and a range of \$2–5 million may be indicated.

By using the same procedure as above, but input data from 2007, Fig. 3.9, should be replaced by Fig. 3.10. Data are collected CIA fact book, the International Monetary Fund (IMF) and the World Bank (WB), all referenced from e.g. Wikipedia. In developing the updated numbers, the actual value for w (the part of time in economic production) has been estimated based on real statistics for 2007 for each country, rather than a common value of $w = 1/8$, as used in Skjong and Eknes (2002), a number estimated by Natwani et al. (1997).

3.12.7 Risk of Injuries and Ill Health

As indicated above risk of injuries and ill health may be dealt with implicitly or explicitly in the FSA. In the societal indicator approach the indicator is life-year (life expectancy at birth), and may be interpreted as an indicator of life expectancy as well as life quality. The NCAF criterion may therefore implicitly be assumed to account for risk of injuries and ill health. In separate studies of risk of injuries and ill health, the NCAF criterion is therefore initially of no use. It may, therefore, be suggested to use the NCAF criterion and split it into contributions covering risk of death, injuries and ill health separately.

According to the UK Department of Transport, (DETR 1998), the willingness to pay for slight injuries is 0.9% of the value of prevention of a statistical fatality. The number of injuries to crew on UK registered merchant vessels during 1993–1997 was 1886 compared to 15 fatalities (MAIB. 1998). The ratio of approximately 130 injuries to 1 fatality can be applied to the estimated personal accident rate above. The severity of these injuries is not defined, but they are assumed to be equivalent to lost-time injuries, as they do not necessarily involve medical evacuation. It is not clear how comprehensively they are reported. This suggests that the overall cost of injuries could be approximately equal to the loss value of fatalities (0.9% of 130 = 1.17). Similar results have previously been reported in UK (1997). By defining serious injuries as 1/10 equivalent fatalities, and minor injuries as 1/100 equivalent fatality the data suggested a 1:1 correspondence (or actually 14:14.89). These results are highly uncertain, and for comparison, fatalities on Norwegian roads are estimated to contribute with approximately 14% of the total costs of fatalities and injuries, whereas the injuries are estimated to contribute the remaining 86% (Elvik 1993). The relatively large difference between these estimates may be explained by minor injuries in traffic on average being more severe than minor injuries for crew members. It is thus initially, in the lack of better statistics, proposed to split the NCAF criterion equally between the two contributors, one applying for fatalities and one for risk of injuries and ill health. As more knowledge is gained, this should be revised.

A criterion based on the Disability Adjusted Life Years (DALYs) gained may be used for risk control options affecting injury and health. This would be similar to the equivalent fatality approach suggested in UK (1997). An evaluation criterion may be established based on the NCAF criterion, see below.

Attempts to measure and value quality of life are a more recent innovation, with a number of approaches being used. The DALY is advocated as a measure for health effects by the World Health Organisation (WHO 2000). Particular efforts have been invested in researching ways in which an overall health index might be constructed to locate a specific health state on a continuum between 0 (= death) and 1 (= perfect health). Obviously the portrayal of health like this is far from ideal, since, for example, the definition of perfect health is subjective and some individuals have argued that some health states are worse than death. In any case it seems better for the regulator of maritime safety to use concepts developed by specialized organisations like WHO.

The DALYs are presently crude numerals, but may be sufficient in prioritising risk control options, which is their use in a risk assessment. It is necessary to be aware of their limitations, and more research may make the process better documented, justified and useful.

DALYs may provide an indication of the benefits gained from a variety of RCOs in terms of quality of life and survival. An example is shown in the Fig. 3.11. The RCO could be e.g. the use of protective shoes. The benefit of the RCO is illustrated in the Figure in terms of DALYs gained by one person.

Some sources of information on DALY and similar indicators may be referenced.

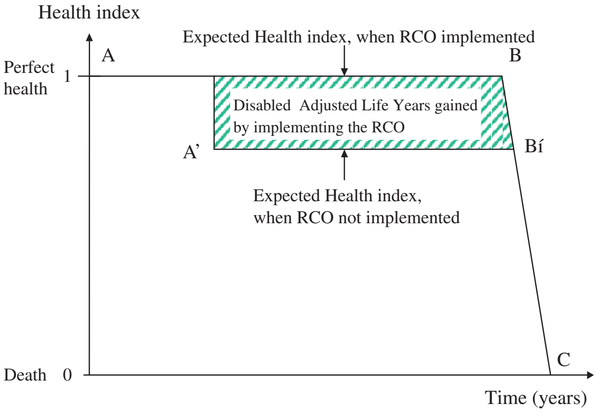

Fig. 3.11 Example of disability adjusted life years gained by one person by implementing a risk control option

- The Quality of Well Being Scale (Kaplan and Anderson 1988)
- The McMaster Health Classification System (Drummond et al. 1987)
- The Rosser and Kind Index (Kind et al. 1982)
- The EuroQol Instrument (EuroQol Group 1990; Nord 1991)
- The World Health Organization

If it is assumed that on average one prevented fatality implies 35 Disability Adjusted Life Years gained, a DALY criterion may be based on the NCAF criterion as follows:

$$\mathrm{DALY}_{\mathrm{criterion}} = \frac{\mathrm{NCAF}_{\mathrm{criterion}}/2}{\Delta e} = \frac{\$3\ \mathrm{million}/2}{35} = \$42{,}000 \text{ per DALY gained}$$

This figure is very close to the figure used for decisions in the health care area, where e.g. Gafni (1999) refer to a DALY of $35,000. The average value for life saving interventions in the US in Tengs et al. (1995) is also $42.000 per life-year, see Table 3.7. It is actually surprising how such criteria derived by different techniques produce the same or very similar results.

If it is accepted that the ship type analysed is already in the ALARP area, only the cost effectiveness criteria apply. This simplifies considerably and FSA reduces to a Pareto optimisation, a method that may easily be implemented as a method for risk based design, and that fits nicely into a concurrent engineering approach.

3.13 Environmental Risk Evaluation Criteria

In addition to fulfilling requirements on individual and societal risk to people, activities that introduce additional risks to the environment need to meet acceptance criteria for environmental risk as well. Damage to the environment can be expressed at different levels such as organism level, population level, habitat level complete ecosystem level, or global level (as for CO_2) and several environmental components can be damaged. Environmental risk assessment is about making estimates of harm to plant and animal life and to the ecosystem integrity that can later be compared to previously agreed risk acceptance criteria. However, due to practicality, environmental risk analysis for a complete ecosystem is normally not performed, in particular not to decide on an RCO to be implemented on a ship, which in general is allowed to trade globally. The risk is rather assessed for vulnerable single components within the environment, e.g. stock of specific species or habitats. These serve as risk indicators and this is normally considered to be sufficient in order to estimate the environmental risk.

In a report published by GESAMP in 2001 it was made clear that the major threats to the marine environment came from activities on land. In comparison, the environmental pressure on the oceans due to shipping was believed to have decreased over the past decade. Nevertheless, the environmental risk stemming from shipping activities should not be trivialized, and the following sections of this chapter will discuss issues related to environmental risk and shipping.

Environmental impacts from shipping activities may be caused by regular (both legal and illegal) and accidental releases. The regular releases (of e.g. CO_2, NO_X, sewage or garbage) are not considered here in a risk context, as the estimation of quantities of regular releases may be done without involving the use of risk assessment, and the estimation of consequence is no different from releases from other sources. Risk assessment for regular releases is only relevant if the system is not defined as the ship, and the analysis go into analysing short and long term effects on the environment, habitat, biodiversity etc. For accidental releases, however, risk assessment is as relevant as for accidents threatening safety of crew and passenger. Figure 3.12 illustrates the most important emissions and discharges from tanker ships in operation.

At IMO there has so far not been any application of FSA for environmental consequences. Therefore there has not been any detailed discussion on environmental risk criteria based on real analysis.

Early on there were some debate in the Joint MSC MEPC working group on FSA on environmental risk criteria and it seems that the tendency has been to favour the use of some cost effectiveness criteria for the risk control options that are considered. For oil-spills this would imply that the criterion would be for example a $/tonnes of accidental release of oil (and other pollutants) prevented. Information could be the cleanup and compensation costs from spills in the past, or it could be based on willingness to pay studies. Both methods were suggested in Mathiesen and Skjong (1996).

An example of willingness to pay for preventive measures may be identified by studying the cost and benefits of OPA 90 and other risk control options that have been implemented in the past. For OPA 90 this has been done by US Coastguard, (Speares 1991). The total costs has been estimated to $11 billion and the reduction

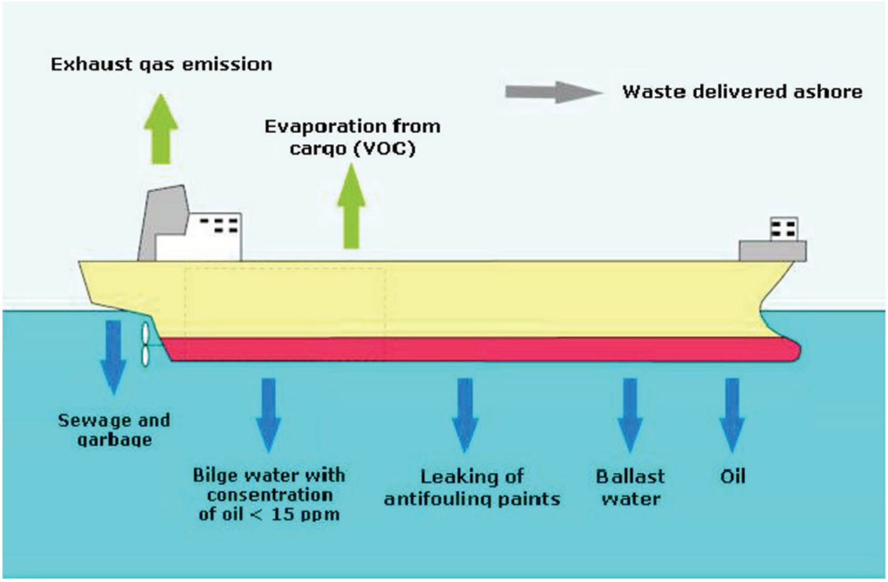

Fig. 3.12 Emissions and discharges from ships in service (tankers)

of accidental release was estimated to 1.2 million barrels, 9,167 \$/barrel or about 57,660 \$/tonnes.

Based on a review of cleanup costs, estimates of environmental damages, and applying an insurance factors of 1.5 (reflecting the willingness to pay more for prevention than paying for the cleanup and living with the environmental consequences), Skjong et al. (2005) proposed a Cost of Averting a Tonne of oil Spill (CATS) of \$60.000.

Of this the average cost of cleanup is \$16.000, the average environmental costs is \$24.000 based on review of available literature. The sum is thus \$40.000. With an insurance factor of 1.5 (from insurance statistics), this results in a CATS of \$60.000. This is close to the willingness to pay in line with OPA90.

The debate on which criteria to use has not come yet to a conclusion. However, there are already a number of FSAs that have used the suggested CATS value. The debate seems now to go in two different directions, complicating the use of one single CATS number to multiple values, namely:

- Dependent on spill size
- Dependent on accident type (grounding, collision etc.)
- A combination

At time of writing this section, it is not clear what will be the end result.

Societal risk acceptance of environmental damages from shipping is not yet proposed. And, to effectively apply a cost-effectiveness criterion related to environmental protection, societal risk acceptance and the associated ALARP area need to be defined. Risk evaluation criteria related to the protection of the environment are not yet agreed at IMO. Thus, no proposal concerning the acceptability of the societal risk of environmental damages from oil transport by tankers exists.

McGregor (2007) suggested an ALARP region for oil spills of tankers based on information from US pipeline requirements. He presented an ALARP area using historical data relating to oil spills of AFRAMAX tankers. His assessment is based on a consequence function which is linearly dependent on oil spill size, thus, viewing large spills as relatively less important. This is based on the recommendation from the US Marine Board (2001) which indicated that the relationship between spill size and environmental consequence is nonlinear. Introducing the relationship of consequences and oil spill size ($C = 1$ equals 1892 m^3 of oil), McGregor presented his proposal using oil outflow as parameter and the newly proposed criterion has a much gentler slope than the usual slope of -1. This reflects the opinion that large spills are relatively less severe than smaller spills.

Sames and Hamann (2008) explored how an ALARP area could be fitted to existing oil-spill data under the assumption that current maritime oil transport by tankers – defined by 1990–2006 data – is JUST acceptable and cost-effective risk control options should be implemented. By fitting the ALARP boundaries to larger spills, spills smaller than 20 tonnes are considered negligible, i.e., no design or rule changes should be targeting these spills. The second approach considered ratio of CAF and CATS is used to translate the ALARP boundaries for oil tankers from the FN-diagram. The resulting ALARP boundaries render maritime oil transport effectively unacceptable as spills larger than 1000 tonnes are in the intolerable area. Only by introducing a spill-size dependent value of CATS, this second approach was shown to deliver a meaningful result. They concluded that that the presently available historic data are not sufficient to evaluate the environmental risk of oil tankers or to demonstrate the appropriateness of the proposed ALARP area.

3.14 Environmental Risk Criteria – CO_2

The same approach may be used to prioritising reduction in emissions. Actually, most of the high level analysis that is needed was carried out by Intergovernmental Panel on Climate Change (IPCC), and is reported in the Fourth Assessment Report form, Contributions from Working Group III. The report contains estimates of the risk reduction at different carbon price levels, both based on top-down and bottom-up studies and for two different scenarios. This is given in IPCC (2007), Table SPM.1 and 2. Reproduced here as Tables 3.8 and 3.9.

The economic potential for emission reduction estimates is surprisingly consistent at all carbon price levels. The two scenarios are defined as follows:

The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita

Table 3.8 Global economic mitigation potential in 2030 estimated from bottom-up studies

Carbon price (US\$/tCO_2–eq)	Economic potential ($GtCO_2$–eq/yr)	Reduction relative to SPES A1 B (68 $GtCO_2$–eq/yr) (%)	Reduction relative to SPES B2 (49 $GtCO_2$–eq/yr) (%)
0	5–7	7–10	10–14
20	9–17	14–25	19–35
50	13–26	20–38	27–52
100	16–31	23–46	32–63

Table 3.9 Global economic mitigation potential in 2030 estimated from top-down studies

Carbon price (US\$/tCO_2–eq)	Economic potential ($GtCO_2$–eq/yr)	Reduction relative to SPES A1 B (68 $GtCO_2$–eq/yr) (%)	Reduction relative to SPES B2 (49 $GtCO_2$–eq/yr) (%)
20	9–18	13–27	18–37
50	14–23	21–34	29–47
100	17–26	24–38	35–53

income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

Assuming that the politically expressed wish to reduce the emission by 80%, compared to the current level B2 scenario at 2030, and ignoring the uncertainties, this indicates that all measures that can avert a tonne of CO_2–eq emission for \$50 should be implemented now or in the near future. This is higher but not that far from the current price of about €25/tonne in the EU market, considering that all economic models predict an increased price. At IMO this way of deciding to implement RCOs would be consistent with current decision making processes and FSA, e.g.

$$\text{Cost of Averting a Tonne } CO_2 - \text{eq Heating effect (CATCH)} = \$50$$

It may obviously also be argued that due to the uncertainty in the estimates, and the long term irreversible effect of climate change, a safety factor should be introduced too. For a discussion on this topic, see Nordhaus (2008).

3.15 Risk Criteria for Use in Risk Based Design

Risk Based Design has always been an option, in the sense that all regulations contain possibilities for proving safety equivalency. It may actually be against both WTO and EU regulations (on free trade), to develop regulations that do not allow for equivalent solutions. Viewed from a free trade's standpoint, it is frequently observed that safety and environmental regulations are used to distort competition. However, in shipping, no court case is known where trade treaties are used to challenge safety/environmental protection regulations.

In the project SAFEDOR the long term objective is to develop a risk based regulatory regime, and it is clear from the work program that this has a dual purpose: The Rules and Regulations should be risk based, but the ultimate goal is also to develop the necessary methods, tools and understanding to allow for risk based design – or direct use of risk analysis techniques in designing and approving innovative ship designs. Actually, when FSA was first proposed, it was presented as a Safety Case Regime for ships. This was soon realised to be unrealistic as a general approach to maritime regulations.

In the following an attempt is made to define clearly what is meant by a risk based regulatory regime – this is done by defining a long term goal, disregarding a number of practical and implementation problems.

A risk based regulatory regime implies that regulations have been developed and justified based on well defined approaches to reduce risk in the most cost effective manner until further risk reduction involves excessive costs. A risk based regulatory regime is also open to direct use of risk assessment in design and design approval, thereby being open for innovation in cases where the prescriptive regulations are prepared with applicability to specific technologies. A risk based regulatory regime, is characterized by rationality, objectivity, transparency, auditability, openness for innovation, etc. The aim of a risk based regulatory regime is also to optimise investments in safety and environmental protection.

In this chapter the term *regulatory regime* is limited to regulations related to safety and environmental protection, and also limited to shipping activities. There are other uses of the term risk based regulatory regimes, both outside shipping and not related to safety and environmental protection.

Risk based implies that regulations are justified by risk analysis (FSA), usually by referring to agreed risk acceptance criteria. In the maritime sector, 'risk based' rules and regulations therefore usually refer to adherence the FSA process in the development and justifications for rules and regulations. Whilst the risk analysis estimates probabilities and consequences of accident scenarios, the regulations themselves may be simple requirements, which are prescriptive and do not refer to risk (Tier IV in the GBS Structure). There is therefore no contradiction in referring to a rule or regulation as risk based and prescriptive. The risk analysis has the status of a commentary (GBS terminology), justifying the regulations and thereby explaining the reasons the regulation is in place. This analysis is therefore auditable, and may be subjected to review.

The risk based regime is rational in many meanings of the term. For example, the analysis is based on reason and logic, by explicitly using logical diagrams like fault and event trees and other scientific tools. The risk model may however, as all models also be based on simplifications and assumptions that should be verified.

A risk based regime is objective in its dealing with facts or conditions as observed and analysed, without distortion by personal feelings, prejudices, or interpretations. There may be subjectivity involved in the analysis, stemming from use of experts (Skjong and Wentworth 2001), for example to estimate probabilities or consequences, or risk reducing effects. Subjectivity should in such cases be reduced as far as possible by using appropriate expert elicitation techniques.

There may also be discussions on the objectivity of risk criteria. For example, the justification for the amount of money invested to reduce the risk to human life is today considered objective by many, and the literature based on rational approaches are growing very fast, whilst others claim such decision parameters are based on subjectivity and should be based on political decisions. This being the situation, it is important that such issues are agreed in open and transparent deliberative processes.

The risk based rules and regulations should represent an optimum solution to the regulatory issues, in the sense that the marginal return of investing in further safety and environmental protection should not be achievable without violating the acceptance criteria. I.e. increased investments in one risk control option compensated by reduced investments (of the same size) in another risk control option would result in reduces safety and/or environmental protection. This is usually referred to as Pareto optimality.

In the description of the risk based regulatory regime within the maritime sector, reference is made to the IMO Guidelines for Formal Safety Assessment. If all regulations with impact on safety and environmental protection had been justified by FSA studies, that had also been subjected to review, and that was based on agreed risk criteria, the resulting rules and regulation would been termed risk based. A regulatory system based on FSAs will inevitably become goal based, because the safety goals will be stated in terms of the risk evaluation criteria.

Use of FSA also disclose implicit safety levels in current regulations and disclose the cost effectiveness of risk control options required by existing regulations as well as in new and proposed regulations, contributing to transparency.

There have already for a long time been developments at IMO in the direction of risk and goal based regulations. For example, the new damage stability regulations have defined a probabilistic design procedure, estimating the conditional probability of surviving a collision with water ingress: A; where the requirement is defined as a minimum probability level: R. The design is accepted if $A > R$. This regulation is clearly both risk based (probabilistic) and goal based. However, the required survivability was, at the time of that regulation's development, not based on the risk acceptance criteria, but rather on a harmonisation of existing requirements.

In SOLAS Chapter II-2 Regulation 17, there are provisions for basing the fire risk assessment on a formalised risk based analysis. The goal is that new designs should be as safe as or safer than what is required by the current prescriptive regulations. Each time such a design analysis is carried out, the implicit safety in the current prescriptive regulations will be disclosed. This regulation is therefore also risk based, although IMO has not formulated a goal based standard, e.g. by specifying the acceptable risk level. The individual functional requirements are also formulated in each regulation, each of which can be linked to a fault tree (fire safety concept tree). This demonstrates that FSA may be used also to structure a risk based and goal based regulation.

3.16 Risk-Based Approaches in the Context of the Regulatory Regime

Throughout the history of maritime regulation ship owners, designers and builders have had to adhere to prescriptive rules; rules stating which configurations, installations and dimensions a ship must have. It has always been possible, in cases of innovative design solutions, to approve the design based on some sort of risk analysis and equivalency with the prescriptive design. This, of course, provided that the innovative design is safer than or as safe as the prescriptive design. This approach is resulting from SOLAS Part A, Regulation 5: 'Equivalents'. Though this route to approval is possible, it is unpredictable and may involve high (economic) risk for the owner in a new-building project. The main reason for this is a lack of agreed standards for accepting equivalent solutions – the approval process is unpredictable.

A step forward with respect to such standards is regulation 17 of SOLAS Chapter 2-II, which follows standard risk assessment procedures closely. Regulation 17 describes functional requirements to be met concerning fire safety, and prescriptive regulations for standard designs. The envisioned future risk based regulatory framework will in a similar (but improved) manner describe all aspects of a ships design.

In the process of approving an innovative design solution the aim is to quantify the risk through what is generally called a quantitative risk assessment method (QRA). However, knowing the risk level is not of much value without a reference value that can be referred to in the approval process. With the exception of the risk acceptance criteria at ship level as described above, currently, the only reference value is the risk level associated with the prescriptive design solution, which all innovative solutions will have to be compared to. This means that both the innovative and the prescriptive designs will undergo a QRA, and the two risk levels will be compared. One weakness inherent in this approach is that the current prescriptive rules may be the product of an opaque and unknown process and the priorities of the recourses (the allocation RCOs) may be far from optimum, and the associated risk levels have not been scrutinised and may be far from optimal. The comparison with such a risk level may therefore not be desirable.

Within a risk based regulatory regime the objective is to provide knowledge of risk levels that are acceptable and with which comparison is desirable and practicable, ensuring that innovative designs undergoing a QRA may be measured against agreed sensible criteria. Within the risk based framework a tiered system of safety goals/requirements/objectives is developed where the low level goals are consistent

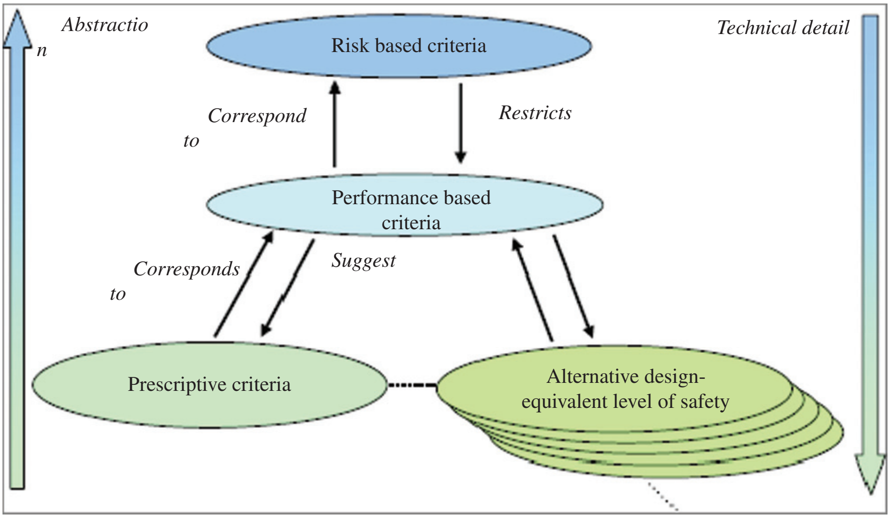

Fig. 3.13 Emissions Relationship between risk-based, performance based and prescriptive design criteria (Skjong et al. 2005)

with the high level goals. The envisioned relationship between risk based, performance based and prescriptive goals is illustrated in Fig. 3.13.

Such a risk based and goal based approach may be applied at any level from the overall ship safety level downwards. This makes it possible for a designer to evaluate the innovative solution against the most practicable level of goals, minimizing the work required and streamlining the approval process. The goals will be explicit, and the process of demonstrating compliance will be described in detail, providing a process for approval of innovative designs which is transparent, predictable and rational. Figure 3.13 illustrates this point.

The ideal situation for the designer is, in principle, represented by the new damage stability regulations (IMO 2005). These regulations require the calculation of the attained index A, which value must be higher than the required index R; such that $A > R$. Here A is a conditional probability of the ship sinking following a collision with water ingress. Both A and R are therefore probabilities that can easily be associated with a risk model of the collision scenario. The drawback with the approach used to derive R was that this was done based on harmonisation In the FSAs on Cruise and RoPax an attempt is made to derive a new R requirement based on the FSA approach and the IMO risk evaluation criteria. This results in a stricter requirement for R (Denmark 2008b, 2008c).

The envisioned future regulatory regime will facilitate the approval of innovative ship designs which deviate from prescriptive rules. The approval of such designs must be predictable, transparent and consistent. The amount of work involved in obtaining such an approval should be kept at a minimum to ensure an effective process. The approval of innovative designs will depend on the design's safety level. To ensure efficiency the verification of safety should be done according to current rules and regulations as far as possible. Only those elements that are affected by the innovative element should be subjected to risk based approval, and at the lowest possible level, where the top level is overall ship safety, and the bottom level is system component level (nuts and bolts). Figure 3.13 illustrates this.

3.17 General Procedure for Establishing Risk Criteria at Lower Level

Skjong et al. (2005) describes various possible procedures for developing risk acceptance criteria at ship function (or lower) levels, and also includes some examples of how this procedure works. Two worked examples are publicly available. One relates to hull girder strength, IACS (2006), and the other to systems, Rude and Hamann (2008). However, the only new element as compared to the literature on use of Structural Reliability Analysis for ship safety is the use of the FSA risk acceptance criteria in SRA. As a general procedure this may be described as follows:

Step 1: Develop a risk model, including all scenarios that are affected by the function in question.
Step 2: Use the decision criteria relating to cost effectiveness described above, for the function
Step 3: Derive the target reliability (or availability) by cost effectiveness criteria
Step 4: Use this 'optimum' as reliability (availability) as target for the function analysed.

It is seen that in Step 3, there is an implicit assumption that the risk is in the ALARP area, and that cost effectiveness criteria can be applied. It is also seen that this procedure is a simplified FSA, limited to the relevant function.

When risk based acceptance criteria are derived from previous FSA studies this procedure is followed, because an FSA study should, in principle, include all relevant functions and scenarios.

It should be noted that the risk acceptance criteria derived this way for the purpose of regulation, may not be dimensioning for the function in question, as e.g. purely commercial considerations may result in more strict requirements. If this is the case, and can be proven to be the case under a variety of conditions, the regulator may decide not to regulate.

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Chapter 4
Risk-Based Approval

Jeppe Skovbakke Juhl

Abstract Due to an increase in the number of novel and risk-based ship designs over the past years, there is a growing need within the maritime industry for a formal approval process allowing for innovation. The scope of this chapter is to give an overview of the expected levels and requirements related to the approval of the risk-based designed ship e.g. to the required documentation, as they are assessed from the current standpoint of development; it is expected that this will establish in due time the necessary confidence in risk based approaches and their fundamental role in ensuring safety. A matrix with explanatory comments has been developed to facilitate the development of guidance to the client as well as for the approval authority with regard to the depth of analysis and examination requirements affecting the various levels in the approval process.

4.1 Introduction

Risk-based ship design and approval is envisioned to satisfy the maritime industries' need to deliver ever more innovative transport solutions to their customers. Risk-based ship design and approval will – at the same time – motivate, but also satisfy the society's need to have increasingly safer transport. The motivation is thus twofold; to improve the competitiveness of those organisations, which drive innovation and are able to exploit the new opportunities as well as to increase safety by increasing the knowledge and understanding of risk issues relating to ship design and operation.

Risk-based approaches in the shipping industry started with the concept of probabilistic damage stability in the early 1960s, and risk-based design was later widely applied within the offshore sector and is now being adapted, extended and increasingly utilised within the shipping sector. Risk-based ship design introduces risk analysis into the traditional design process aiming to meet safety objectives

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cost effectively. This is facilitated by use of advanced computational tools to quantify the risk level of particular candidate designs. Risk is used to measure the safety performance. With safety becoming measurable, the design optimisation can effectively be expanded and a new objective – to minimise risk – is addressed alongside commercial design objectives relating to earning potential, speed and cargo carrying capacity. It is expected that with the introduction of safety as an objective into the design optimisation process, rather than treating it as a constraint, new technical solutions can be explored: the design solution space becomes larger.

The number of novel and risk-based designs appears to be increasing. There may be a number of reasons for this, but the most important ones are:

- Economic motivation for new designs,
- Needs for new or modified designs to fulfill new operational requirements,
- Recent regulatory developments opening up for more risk-based designs (e.g. SOLAS-II.2/17).

Today the development in all industries, including the maritime, is subject to rapid and often radical technological changes. These changes now take place more frequently at ever shorter time intervals. Changes and eventually actual breakthrough solutions appear at a much faster pace than our experience is gained. Therefore, the established method of basing any development on empirical data at best displays severe limitation. For advanced and sophisticated ships the traditional method is by no means adequate.

The present regulatory system is, confronted with a novel risk-based design, often inadequately suited to a ship owner's motivation for exploiting the full market potential. This is mainly due to the fact that new developments concerning rules and requirements will frequently not be in place when these ship owner needs appears.

The existing regulatory system for the maritime industry consists primarily of international regulations developed by the IMO and enforced by the Flag States. In addition the classification societies have developed their own rules covering the safety of hull, machinery and electrical systems. Furthermore there are regional rules, national rules and even rules for specific ports. These rules are the result of a continuous amendment process.

The existing regulatory system is of a very complex nature and the initiating event for any given development is rarely easily identified. At times a development may address safety deficiencies – developed as a result of a specific accident. In that respect the regulation reveals itself to be re-active rather than pro-active – in other words: the regulation focuses on avoiding similar situations to arise as opposed to pro-active accident prevention.

Throughout maritime history, a major motivating factor in devising new regulation has been based on analysis of marine incidents of the past, enforcing regulations aiming at preventing identical or similar incidents and accidents to occur again.

Legislating in this manner has advantages. Arguing the necessity of any new measure largely consists of acknowledging a failure of equipment, design, management system etc. which may have lead to a marine accident or incident, a consensus is built on a desire for loss prevention in the future. Such prescriptive regulation is "commercially safe", in terms of providing a relatively high degree of assurance in any given design to be approved. It is simple to evaluate.

It may, though, also constitute a limiting factor, as very few commercial operators will engage in challenging the current state of the art, if the perspectives of having anything novel approved are futile.

Utilizing a novel piece of equipment and breaking the ground for new approaches may often appear as a win-all or lose-all deal to the operator, as insights gained from the (presumably cost intensive) research- and trial period may well come to the benefit of other less daring operators, waiting for others to make the mistakes for them.

When developing requirements dealing with a new approval process to perform safety verification in an efficient and responsible manner, it should initially be recognized, that existing prescriptive requirements are not necessarily as objective and "safe" as one could assume. This is not to say that any existing figures, numbers or measures have been chosen at random. As previously stated, they will usually be a reaction to one or more marine incidents.

This, though, also bears within a potentially longer reaction time throughout the industry, when novel designs or systems are at hand which – at least at the time suggested – have no precedent historical record. Obstacles to innovative solutions which may potentially enhance maritime safety, though, can indisputably not be regarded as an advantage by any means.

Also, one argument in favour of applying alternative approval methods is the widely neglected fact, that in principle, the sheer dimensioning of vessels as they are currently being constructed may cause prescriptive rules to fall short, to put it bluntly, in that particular respect, the future may already be here.

As vessels are growing in size, as well as through general progress in research dealing with e.g. the environmental loads (such as freak waves etc.) which ocean going vessels may be subjected to, it becomes increasingly questionable whether the prevailing requirements for strength and stability are in fact even living up to the present situation and state of knowledge.

Alternative approval methods for alternative designs and systems should serve as a motivating factor to venture into new and previously less explored fields, even to the less daring.

Given the above considerations, this is not only beneficial in terms of constituting a competitive advantage, but may in fact be crucial to maintain a high level of safety while keeping abreast of future developments and discoveries.

4.1.1 Why Do We Need an Approval Procedure Related to Risk-Based Design

From a ship owner's perspective there could be various elements which drive the motivation to introduce safety objectives explicitly in the design process:

First, it is the realisation of an idea for a new transport solution which challenges (possibly outdated) rules – meaning that the new solution cannot be approved. Risk-based design and approval are then used to identify the issues and prove that the new solution is at least as safe as required. A requirement from the Approval Authority can be either based on references to a specific vessel (equal level of safety) or by specified risk acceptance criteria. This approach is exemplified within the regulation 17 of SOLAS-II.2 on fire safety, as explained later in this chapter. This first variant of risk-based ship design has become widely known as "safety equivalence." It may also be called "rule-challenge" as existing rules and regulations are challenged. It is noted that when rule-challenging solutions are approved again and again, guidelines may be created to standardise the approach, and to make its application more cost-effective.

Second, it is the optimisation of a rule-compliant vessel aiming to increase the level of safety at the same costs or to increase earning potential at the same level of safety. For this second variant of risk-based ship design application, the approval is only needed if the existing rules and regulations are challenged, but the design optimisation could well be within current rule and regulation limits. An example for this variant is optimisation within the new probabilistic damage stability regulations, SOLAS (2009). This second variant of risk-based ship design may be called "risk-based design optimisation" to differentiate this variant from the first.

Both types of the risk-based design philosophy as mentioned above require the same technology and framework which reflects and derives from the introduction of safety as an objective in the design process as illustrated in the figure below. The design philosophy is divided into two horizontal levels:

1. a design methodology needs to be developed, aligned with the traditional design process, which includes safety as objective and preferably integrate any associated computational tools to quantify pertinent risks.
2. the regulatory framework must be in place to facilitate the risk-based design – core elements of this are risk acceptance and evaluation criteria which preferably should be agreed at the International Maritime Organisation (IMO) (Fig. 4.1).

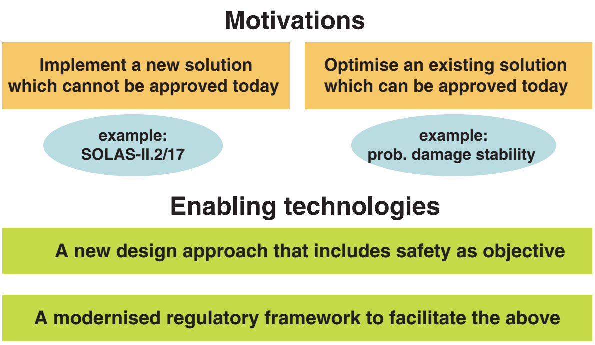


Fig. 4.1 Motivation and enabling technologies for risk-based ships design and approval

From a historical perspective this process is not new to the maritime industry, even though the implementation has only been progressing slowly.

A comprehension of the balance between safety of the ship and earning potential has for the last 5–10 years slowly started in modern passenger ferry designs. For example with regard to most of the existing North West European passenger Ro-Ro ferries fleet, which have been upgraded to meet enhanced damage stability requirements by using design solutions achieved through a risk-based design optimisation process aimed to maximise cargo capacity and safety at minimum cost.

Re-introduction of the atrium arcades on board cruise ships in the late Eighties paved the way for accepting novel design features beyond rule limits, and thus, performance-based design criteria provide the designer with increased freedom that can be exploited in the design and construction of new ships. As mentioned, the openings to alternative design in SOLAS have repeatedly been utilized in novel designs of passenger ships, such as the interior layout of public spaces and big atria that exceed the prescribed maximum size of a main fire zone (not greater than 48 m in length or $1,600\,\mathrm{m}^2$ in area according to the prescriptive regulations). The specific need for rule development related to this issue resulted in the repeatedly quoted regulation 17.

The freedom in design introduced by alternative regulations facilitates optimisation of various design parameters, and a number of tools have been developed for corresponding design optimisation applications.

One example, are the commercially available tools for analysing evacuation performance of passenger ships, that can be used to optimise the escape route layout and the evacuation arrangements.

Broadening the design envelope, giving the owner a wider selection of possible design concepts enhances the motivation for innovation (Fig. 4.2).

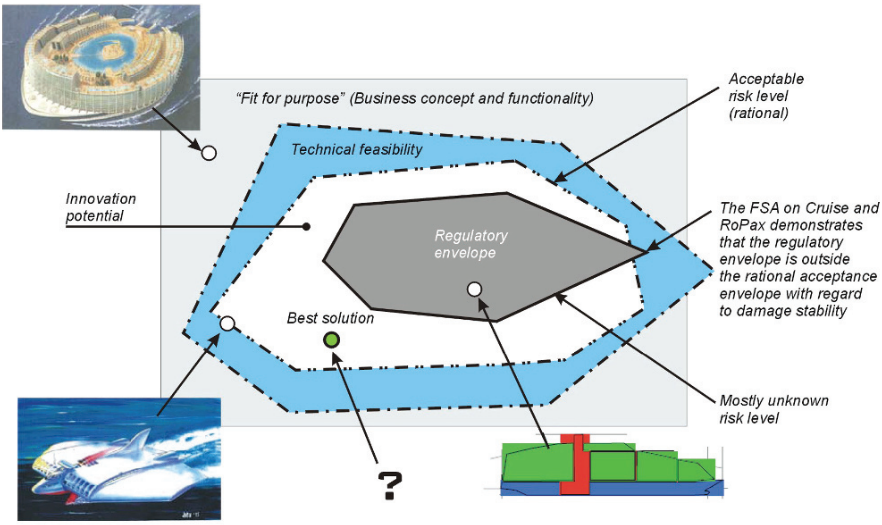


Fig. 4.2 Design envelope (reference to Guarin et al. (2005))

4.1.2 Present Approval Process – A Prescriptive Procedure

Conventional ship design aims to satisfy requirements whilst achieving a balance between performance, costs and earnings.

The ship owner has a main interest in ship performance, including elements such as payload, speed and safe operation; costs include building and operating costs; earnings include all items related to income potential; a requirement might include minimum environmental impact, class rule-based safety beyond regulatory compliance (voluntary notations) etc. But at the same time he must fulfill the regulatory safety regulations – but these are treated as post-design compliance issues.

If both the ship owners and the regulatory criteria are fulfilled; the design is a viable candidate (Fig. 4.3).

From the regulatory point of view, the presently established approval process proceeds along the lines of verifying compliance with international, regional and national regulation together with rules from the Classification societies (Fig. 4.4).

As the regulatory regime at present is by and large prescriptive (with few exemptions), proof of compliance is hence achieved by means of accounting for, measuring and comparing the presented design with the applicable set of requirements, rules and standards.

Should any particular feature deviate from the prescribed, the Approval Authority (normally the Flag Administration and/or a Classification Society) will be requested to consider the equivalence of the feature compared to the prescribed feature.

Considerations on equivalence have up to this time mainly taken place on subsystems (including human element issues, such as safe manning), subsidiary features (such as emergency exits) or specific types of equipment (such as alternative LSA) – however rarely on a full scale ship project.

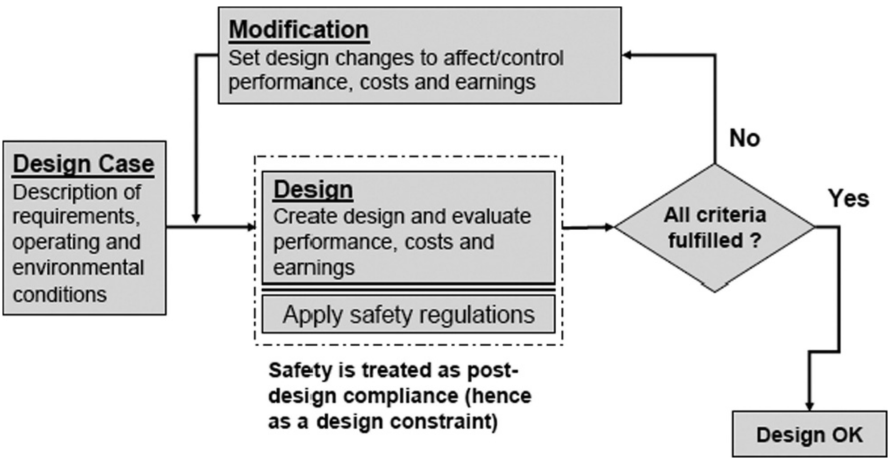


Fig. 4.3 Approval flow diagram for the "conventional" design

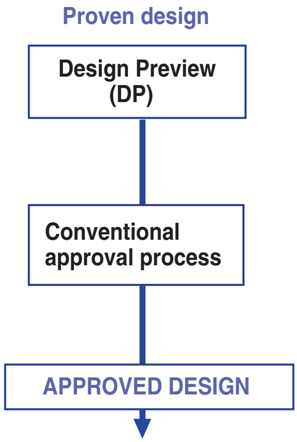


Fig. 4.4 Present approval process

Verification of compliance rests with the Flag Administration, however elements of the work is delegated to the classification society as recognised organisation or nominated body. Subjects like working environment issues, stability requirements on passenger vessels, fire protection subjects etc. are verified by the Flag State Auditors and not by the recognised organisation.

Decision making on equivalence also rests with the Administration. Accepting the equivalent feature is usually based on safety equivalence and is in many cases evaluated qualitatively, or through consequence assessment, mainly due to the relatively minor volume and scale of cases where equivalence is sought documented.

In principle, considerations on equivalence will usually move along the lines of evaluating the inherent impact in risk reduction (or aggravation) based on qualitative evaluation by competent parties, supported by statistics, analysis, drawings and reviews.

Applications will be evaluated by individuals having operational knowledge of the issue in question as well as by experts on the topic, and any decisions should be well found and soundly backed by statistical, historical or operational experience from credible sources.

4.1.3 Risk-Based Approval Process – The Future Procedure

The risk-based approval process is different from the conventional, as risk-based ship design adds another set of criteria to the final selection of the design, also aiming to achieve required safety standards cost-effectively (safety of life and protection of property and environment). An optimum design solution that includes safety is possible only through risk-based design, because safety is treated as a design objective concurrently with the commercial objectives (Fig. 4.5).

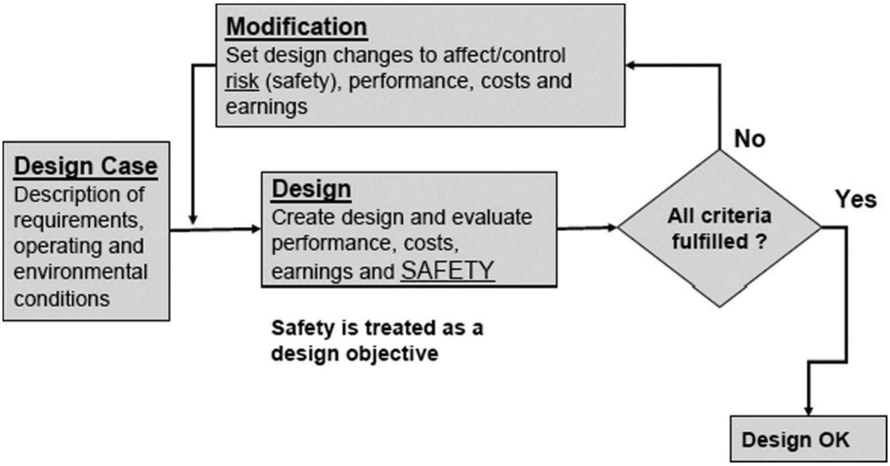


Fig. 4.5 Approval flow diagram for the risk-based design

As mentioned previously, one of the chapters within SOLAS that has driven the development of the risk-based approval concept to a usable extent is the chapter on fire protection, SOLAS Chapter II-2, regulation 17.

Currently, SOLAS has two accepted methods for approving designs and arrangements for fire safety.

1. The common prescriptive regulation set out in the parts B, C, D, E or G referring to specific topics such as prevention of fire and explosion, suppression of fire, escape, operational requirements and special requirements.
2. The new part F regulation 17, referring to alternative design and arrangements, applying to a specific fire safety system, design or arrangement for which the approval of an alternative design deviating from the prescriptive requirements of SOLAS Chapter II-2 is sought.

Today both methods are equally acceptable by the administrations. But due to the novelty of regulation 17, this procedure has only been used in few cases. Hence only few Administrations have developed standard rules and procedures for this risk-based approach. As the use of alternative designs has been dominated until now by cruise ship cases, and due to the fact that the dominating Flag states delegate this work to recognised organisations, there may be more experience in some major Classification societies (e.g. DNV, GL etc.)

As with the present approval process, compliance with class rules, international and flag state regulation is part of the foundation or basis for a design.

By evaluating compliance step by step, any rules challenged can be identified, thence following a path similar to what is described in the paragraphs on equivalence in the present approval process.

However more risk-based requirements are being adopted within SOLAS, even though still not in force:

The new Regulations II-1/55 and III/38 that will enter into force on 1 July 2010. This requirement will give future steps for approval of alternative design. MSC/Circ.1212 (IMO 2006) that outlines a methodology for the development of the required engineering analysis will support these two regulations.

Resolutions 239(83) and 240(83) which will enter into force on 1 July 2009 define the new format of Ship Safety Certificate with the purpose of stating the risk-based nature of a ship.

Finally the Goal Based Standards being discussed at the IMO introduce the Ship Construction File (SCF) concept that may become independent mandatory requirements under SOLAS Chapter II-1.

The SCF, which contains drawings and information on materials/construction of hull, machinery and equipment, remains with the ship through changes of ownership, classification and flag.

Within SAFEDOR thoughts and considerations on how to develop a new approval procedure have been developed. The purpose is to define and describe a high-level process for novel and risk-based ship types providing a sound and harmonized approval process to be used by the Approval Authority in order to ensure that novel and risk-based designs are handled safely and efficiently. Furthermore the work serves to make the approval process more transparent and logic to understand which should ease the process for clients seeking approval.

The following figure illustrates the novel approval process (Fig. 4.6).

The task pending with the Administration throughout the transitional period, largely consist of verifying the quality of the documentation submitted.

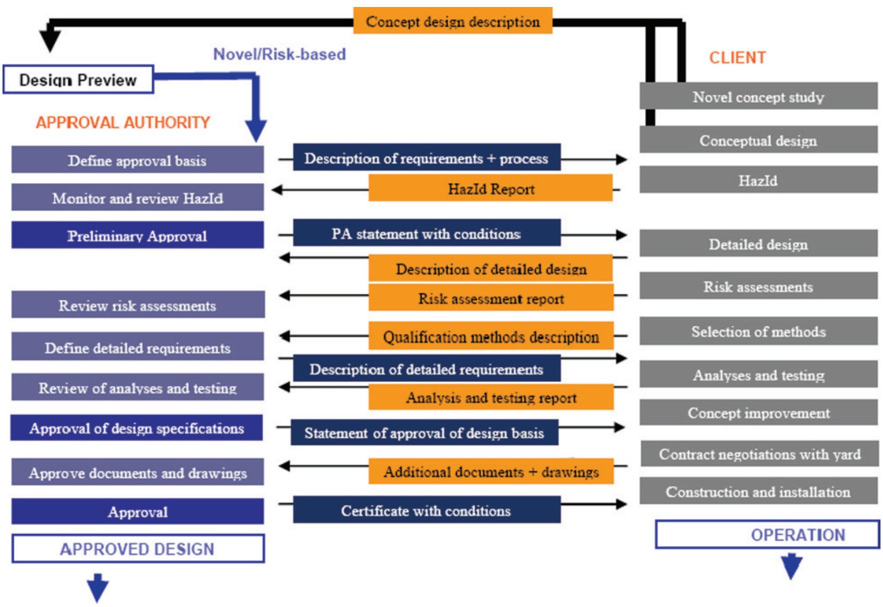


Fig. 4.6 Novel approval process developed in SAFEDOR (Wentworth et al. 2005)

As such, the Administration has a supervisory function, in terms of ensuring the soundness of the sources of information applied, whether approvable methodology is utilised, monitoring for proper generation of acceptance criteria and ensuring that the group of experts is indeed covering all relevant fields of knowledge, at least to the satisfaction of any minimum criteria set out in advance of the actual approval process.

Rendering explicit the safety levels of the existing prescriptive regulation is a task which is presently being addressed. This may eventually pave the way for comparison with new and untested principles, along with predictions by means of probabilistic tools e.g. as described in various deliverables within SAFEDOR concerning the risk-based design.

When new design projects bearing alternative features are submitted for approval, the Administration may utilise a number of tools already provided for to ensure a sound approval basis. One of these is the Formal Safety Assessment (FSA) procedure.

In the IMO guidelines for FSA, a number of "tools" to eventually achieve a concise evaluation of inherent risk and safety levels in any given project, design, operation or regulation are described, the result eventually being a "Safety study" (in principle equivalent to the Offshore sector "safety case" documenting all reviews, analyses and evaluations that may have taken place for the particular project). In most cases the FSA is a safety case for the Rules and Regulations.

The methodology, as per below (concisely described in the circular) may to some extent be applied at any given approval process level, as it contains core elements of the considerations which would in any case have to be investigated by the Authority to render any alternative approval process safety-wise acceptable (Fig. 4.7).

In this manner, evidently – provided of course, the safety study is devised with care and all due regard to sound scientific principle – the regulating body has a sound

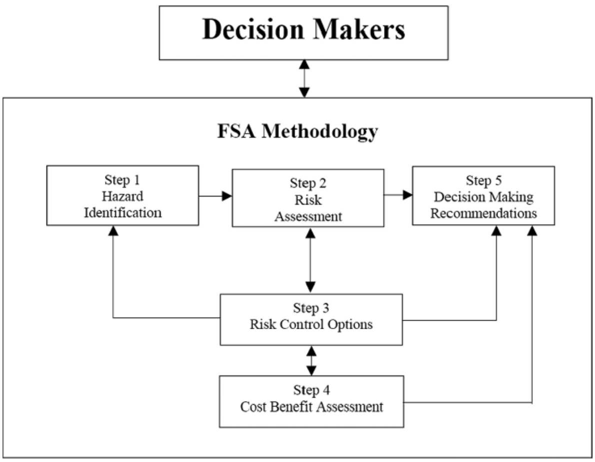


Fig. 4.7 FSA process excerpt from MSC/Circ.1023 Annex (IMO 2002b)

tool to evaluate compliance by comparing risk and safety, querying for mitigating measures (Risk Control Options) where any risk may not have been reduced to what is reasonably possible at the design stage.

From the *approval in principle*, through the safety assessment in its integrity to the *notification of compliance in principle*, it should at all times be verifiable whether the sources of data used are sound, reliable and unbiased. To facilitate the process of approval, it may be relevant for the Administration to develop guidelines of its own on acceptable data sources, approval and audit methodology, accepted industry standards (- or minimum standards) as well as paving the way for database material on alternative approval cases, which might, if relevant, be shared selectively within the Community to build common ground.

4.2 Acceptance of the Alternative Design

As mentioned previously, risk-based ship design is expected to focus on selected elements or aspects of ship design. The overwhelming part of the ship will still be using prescriptive rules, but at some point of novelty of design the risk based design process will be taking over as directing the process, whilst prescriptive rules may still play a considerable part in detail design. A complete risk-based ship design is expected only in relatively rare cases. Based on this, three design categories may be distinguished:

- Partial risk-based design using safety equivalence for one selected function
- Partial risk-based design using safety equivalence and safety balance addressing several functions
- Complete risk-based design

Following from the above, decision-making in risk-based design depends on the complexity of the attempted design and the expected proof of compliance. Hence it is difficult to develop one single procedure on how to accept the alternative design. In the following, relevant elements of SOLAS are referred:

4.2.1 Safety Equivalent Provisions in SOLAS 74, ICLL 66 and STCW 95

The international maritime safety convention has always contained provisions, which make it possible to deviate from the prescribed requirement. Even if theses provisions do not assume the use of a risk based approach, they should, when it comes to complying with the requirement in the international safety conventions, be considered in these contexts, as “the equivalent provisions” in many cases will be the formal basis for the use of a risk based approach in the maritime industry. When “the equivalent provision” is used, the owner has, in accordance with the conventions, to satisfy the Approval Authority that the equivalent fitting, material, appliance or apparatus, or type thereof is at least as effective/safe as that required by the present regulations.

The cause for this provision is to allow the shipbuilder and the owner some flexibility and also to make it possible to take advantage of the technological development in the maritime industry. It has always been feared, that this possibility was bound to open the door to a very wide diversions from standards, but experience has shown, that such fear is uncalled for. Experience does also show, however, that shipbuilders and owners rarely make use of theses provisions, as they fear, possibly with some justification, that an equivalent measure approved by one flag state, would not necessarily be approved by another flag state, having potentially severe consequences for the operation and second hand value of the ship. Furthermore, port state control has made it even more risky for the owner to use “equivalence provisions”, as an owner could find himself in a situation where it is difficult to convince a port state inspector that the equivalent measure is in every respect at least as effective as that required by the regulations.

Another hindrance to the use of “equivalence provisions” is, that there is no internationally accepted way to prove and document that the equivalent measure is sufficiently effective, and instructions on how all the various parties involved in the approval and the control of the ship, such as flag state, port state, classification, charter, insurance and finance, shall deal with such documentation.

4.2.2 SOLAS II-2/17 Related to Fire Safety

In July 2002, the new SOLAS Chapter II-2 on fire safety entered into force. It contains the previously mentioned new regulation 17 on alternative design and arrangement. It explicitly states that fire safety designs and arrangements may deviate from prescriptive requirements provided that fire safety objectives and functional requirements are met. An engineering analysis based on the guidelines (MSC/Circ.1002, IMO (2001)) is required to prove the case.

Only alternative designs and arrangements that are suitable to satisfy the fire safety objectives and functional requirements can be considered. This, however, includes a wide range of measures, including alternative shipboard structures and systems based on novel or unique designs, as well as traditional shipboard structures and systems that are installed in alternative arrangements or configurations.

The case requires analysis of the original (prescriptive) design and of the alternative design for the purpose of comparing safety levels. This means that a relative and not an absolute level of fire safety is documented or achieved. It also require two analyses, one for an existing standard design (to find the implicit level of safety) and an analysis of the proposed design (do demonstrate equivalence).

Fortunately, in due time, many such analyses will improve the knowledge of the implicit safety levels. FSA studies will have the same effect. Today we already see many ship designs with alternative arrangements related to fire safety, following SOLAS-II.2/17 and the process as outlined in MSC/Circ.1002.

At MSC82, a broadening of the safety equivalence for systems was agreed and this is documented in MSC/Circ.1212. Unfortunately, MSC/Circ.1212 only partly reflects on MSC/Circ.1002 and the FSA guidelines. Another obstacle is that it is set to enter into force only in 2010, effectively blocking any changes until then, because regulations can only be amended after they enter into force. Collectively however, FSA guidelines, MSC/Circ.1002 and MSC/Circ.1212 constitute a good part of a modern regulatory framework that is needed to facilitate risk-based design and approval.

4.2.3 Future Regulations Allowing for Alternative Designs

Future steps for approval and operation of alternative design will be introduced when the two new regulations of SOLAS will enter into force in 1 July 2010. Regulation II-1/55 will allow alternative designs and arrangements for machinery and electrical installations, as well as the Regulation III/38 will allow the approval of alternative design and arrangements for Life-saving appliances and arrangements.

As for current Regulation II-2/17, Regulations II-1/55 and III/38 also require an engineering analysis to be submitted to the Administration in order to provide technical justification for alternative design and arrangements.

As for the MSC.1/Circ.1002, the MSC.1/Circ.1212 contains the engineering analysis methodology and the forms of the "document of approval" and "report of the approval" of the alternative design to be carried on board the ship.

4.2.4 SOLAS II-1 Related to Damage Stability

Well aware that the SOLAS requirements to damage stability are about to be changed (1 January 2009) it is relevant to mention the SOLAS 90, Chapter II-1, regulation 25 requirements in this context too. The requirements indicate that alternative arrangements are acceptable, if at least the same degree of safety as represented by the regulation is achieved. However, each case must be reported to IMO individually. Resolution A.265 (VIII) defines subdivision and stability equivalent to regulation 25 of SOLAS.

The rules require that the attained subdivision index A is larger than or equal to the required subdivision index R. The subdivision index R is prescriptive in nature as it depends on ship length and persons onboard including life boat capacity. No other operational aspects are included into R. The attained subdivision index A summarizes the probability of flooding for each compartment multiplied with the consequences this flooding may have.

Although the determination of A is of a prescriptive nature, the concept generally enables probabilistic elements. Indeed, the HARDER (1999) project investigated all elements of the existing approach and proposed new formulations taking into account probabilistic data.

4.2.5 SOLAS 2009 Will Replace SOLAS 90

The SOLAS 90 damage stability requirements did have three alternative approaches to evaluate the damage stability of a ship for approval: For cargo ships, subdivision and damage stability should comply with regulations contained in part B-1 of SOLAS Chapter II-1, whereas passenger ships should comply with either part B of SOLAS Chapter II-1 or be in accordance with the requirements in resolution A.265 (VIII) (MSC/Circ.574 (IMO 1991)). Part B of SOLAS Chapters II-1 contains deterministic rules for subdivision and stability for passenger ships.

Both part B-1 of SOLAS Chapter II-1 and the requirements according to resolution A.265 (VIII), however, describe probabilistic standards for subdivision and damage stability. Both the prevailing probabilistic standards for damage stability are based on subdivision indices, i.e. a required subdivision index and an attained subdivision index. The attained subdivision index, A, is associated with the survivability of a specific ship, i.e. the probability of surviving conditional on flooding of one or more compartments. The required subdivision index, R, determines the degree of subdivision to be provided and is thus intended to make sure that all ships meet a minimum standard of subdivision. Mathematically, the probabilistic standards of damage stability can be expressed as follows:

$$A \geq R$$

and

$$A = \Sigma p_i \, s_i$$

where i denotes each compartment or group of compartments under consideration, p_i denotes the probability that only the compartment or group of compartments i is being flooded and s_i denotes the probability of survival given flooding of the compartment or group of compartments i. The required subdivision index can be assigned an appropriate value and is thus a damage stability performance criterion that can be applied for comparison to when evaluating the damage stability of a given ship.

The two different probabilistic standards for damage stability in part B-1 of SOLAS Chapter II-1 and A.265 use different methods to calculate the attained and required subdivision indices. Regardless of the method applied for calculation of the indices, the fundamental approach remains to apply the indices as evaluation criteria for subdivision and damage stability.

If criteria based on the required subdivision index should be regarded as valid within a risk based regulatory context, the damage stability standards should be related to some general risk model, i.e. the impact of damage stability on the overall risk level should be modeled. This was done in the FSA Cruise (Denmark 2008a) and FSA RoPax (Denmark 2008b) demonstrating that the required R was not in agreement with the high level criteria and therefore the requirements needs to be raised.

Resolution A.265 (VIII) restrictively prescribes several other aspects related to damage stability, including machinery bulkheads, double bottoms, openings in watertight bulkheads, openings in shell plating below immersion line and watertight integrity above bulkheads. Here, no deviation from rules appears possible without referring to Regulation 5 of SOLAS Chapter 1 (concerning equivalences).

4.2.6 High-Speed-Craft Code Requirements for Selected Systems

Annex 4 of the High-Speed Craft (HSC 2000) code details the procedures for failure mode and effects analysis (FMEA) for selected systems such as directional control systems, machinery systems and their associated controls, electrical system, taking into account the effects of electrical failure on the systems being supplied, and the stabilization system.

It states that analysis of failure performance may be used to assist in safety assessments. This indicates that FMEAs are only considered part of a broader safety assessment. It is also important to understand that the required FMEAs are not integrated into a ship-wide analysis. Each system is analyzed as a stand-alone system.

The procedure include a system definition, block diagrams, identification of potential failures, evaluation of possible effects, identification of detection methods and corrective actions, assessment of probabilities of failures with catastrophic or hazardous consequences, development of a test program and documentation.

A test program is required to support the conclusions from the FMEAs. It is proposed to include all systems where failures would lead to major or more severe effects, restricted operations or any other corrective actions. Test shall also include investigations into layout of control stations and the existence and quality of the operational documentation with due regard to the pre-voyage checklists.

4.2.7 Different Acceptance Criterion Philosophies

SOLAS provides the possibility of using alternative designs. Often, however, it is left to “the satisfaction of the Administration”, whether a design is acceptable or not – and various philosophies behind the accept criteria can be applied.

4.2.7.1 Risk Evaluation Criteria at IMO

Risk evaluations criteria normally place the risk in one of three categories; intolerable/unacceptable, tolerable and negligible/broadly acceptable. Risks that are assessed to lie between the boundaries for intolerable and negligible will normally be required to be kept “As Low As Reasonably Practicable” or “ALARP”. Additional criteria for what is reasonably practicable are thus needed and for safety this is often given in terms of the Cost of Averting a Fatality, e.g. CAF.

Similar cost effectiveness criteria for environmental risks related to accidental oil spills are the Cost of Averting a Ton of oil Spilt, e.g., CATS. The currently available risk evaluation criteria are summarized in Chap. 3.

Available risk acceptance criteria are related to safety of human life. Both individual and societal criteria are documented and their use is promoted by the FSA guidelines.

Risk acceptance criteria related to the protection of the environment beyond the CATS criteria are not yet documented but work is being conducted to develop a societal acceptance criterion related to oil spills.

This issue is described in detail in Chap. 3 of this handbook.

4.2.7.2 Risk Acceptance Criteria for Main Ship Functions

Setting acceptance criteria for ship functions requires that the functions are defined first. Among these functions are structural integrity, watertight integrity, stability, the capabilities for propulsion, power supply, communication, navigation, manoeuvrability, sea-keeping, emergency control, habitability and cargo handling. Work reported in Chap. 3 addresses acceptance criteria for these functions and concluded that additional work needs to be done to establish acceptance criteria.

It was underlined that for several ship functions and systems, safety is not be the dimensioning issue for acceptance criteria may therefore be irrelevant. Instead, reliability or availability dimensioned by commercial considerations is expected to be the more important requirements for functions such as propulsion availability and capability.

Based on work related to target reliabilities for structures the SAFEDOR report proposed as general procedure to determine acceptance criteria for main ship functions and systems the following four steps:

- Develop a risk model that include the function in question–all scenarios that are affected
- Use Cost-Effectiveness criteria
- Derive the requirement (availability, target reliability etc.)
- Use this as target in Risk Based Design.

This issue is described in some detail in other Chap. 3 of the handbook.

4.2.7.3 Cost-Effectiveness

Current decision-making with relation to safety at IMO and classification societies employs cost effectiveness as central decision-making criterion. It is well rooted and used within the ALARP principle. Main advantages are that existing criteria (CAF, CATS) can be used and easy integration into the traditional design framework. However, only design changes can be assessed. Note that this apparent disadvantage is not considered a true disadvantage, since most ship designs are not completely new but are almost always adaptations of existing designs. It is therefore clearly recommended to use cost-effectiveness for decision-making in risk-based design.

To find an adequate balance, we need to be able to draw on qualified personnel, acquainted with the process, the philosophy and the techniques of risk based approval.

This issue is described in detail in other chapters of this book.

4.2.7.4 Risk Balance

In principle, safety equivalency can be used for all functions, systems, sub-systems and components. Based on the same philosophy as for the damage stability requirements, each function could be treated the same way, imposing similar requirements. This is illustrated in the figure below, using the symbols from the approved new damage stability regulations (The attained index (A), which is an estimate of the probability of surviving a collision with water ingress, is required to be larger than the R; R is then a risk-based acceptance criterion for damage stability).

This concept may be illustrative as it is intuitive. This is, however, a simplification that will not be generally valid. The condition for using this approach is that the innovative design solutions do only affect one of the functions or systems. In most cases an innovative solution may affect multiple function and accident scenarios. In such cases this description may be too simplistic.

The second route would need explicit safety levels against which to design. This second route probably is necessary for future trade-offs between several aspects of ship design (e.g., damage stability and life saving). Safety levels and acceptance criteria are key elements of the future regulatory framework and the next section discusses these in more detail.

In the short- and medium-term, only partially risk-based designed ships are expected. Thus, prescriptive and probabilistic rules need to be applied together. This coexistence certainly is a challenge for the regulator as elements from one design aspect (e.g., bulkhead positions related to damage stability) frequently influence other design aspects (e.g., cargo capacity, strength and outflow of fluids, to name a few).

For each element in ship design challenging current rules in isolation, safety equivalency appears to be the best way ahead for the time being. It offers the designer freedom for alternative arrangements and/or equipment and offers to the regulator a method for approval which closely follows the SOLAS-II.2/17 approach.

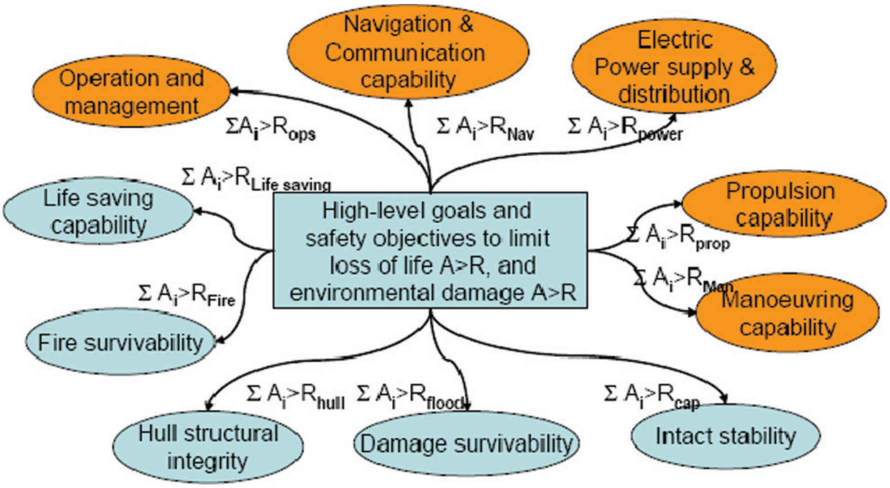


Fig. 4.8 Risk balanced acceptance criteria

The challenge, however, is to define the equivalent design and designing a second ship just for reference purpose is certainly not cost-effective.

The regulatory framework of the future has to facilitate full optimization of safety which is expected to become visible when two or more aspects or functions of ship safety are becoming traded off against each other. It is well known that many ship functions contribute to the overall safety of the vessel. What is not known explicitly is the share each function actually contributes (Fig. 4.8).

A collection of ship functions that contribute to safety are presented in the figure with elements marked in Blue indicating that requirements Rxy are set by IMO and/or class, and with orange-marked elements indicating those requirements which are probably specified by the owner, i.e., owner's requirements are stricter than IMO requirements. Note that for each function, an individual R will have to be specified together with a procedure to determine A.

4.3 Stakeholders in the Approval Process – How Do They Work Together?

Assessment and approval of risk-based ship design is a special branch of knowledge, and special qualification needs and experience become necessary to carry out such projects. Also, the operation and inspection may require new skills, or a modification of existing methods of work.

Risk based design has for many years been used in other sectors, such as nuclear, offshore, hazardous, and the aerospace industries.

Existing knowledge and experience from other sectors has, however, only to a very limited extent been used in the maritime sector, and thus, there is merit in phrasing guidelines on qualification upgrades to the key personnel responsible for design, assessment, approval and operation, to facilitate an adaptation to the maritime industry.

The challenge in defining which qualifications are required through a process of designing, building, approving, operating and inspecting a risk based vessel is not only to define an adequate level of knowledge, but also to differentiate between the knowledge levels required from the various stakeholders.

However it is also necessary to define base line requirements, starting from a level of knowledge required to perform duties, involving risk based designs, where these duties only differ marginally from such being performed on a traditional design, up to a level of knowledge required to analyse on the design itself and on the involved systems.

Also, an attempt is made to identify key subjects, of which it will be necessary to attain knowledge, depending on the work the concerned individual is tasked to perform.

When determining the requirements to key personnel involved in the assessment and approval process, it is useful to categorize the various stakeholders by mapping their contribution to the process including the interests they represent.

The following maps cover different stakeholders contributing to the various phases in the design and operation:

- The documentation sequence starts with the "Production map". This map addresses stakeholder involvement in the sequence from the Concept design description up to submission of documents for approval to the authorities.
- The next sequence is the "Process map", which covers the stakeholder involvement in the process up to the granting of approval to the Owner from the Authority.
- The "Retention map" describes the stakeholder involvement with documents required to be kept available after approval as working documents, or as a basis for further developments.
- The "Control map" describes the stakeholder involvement with documents required to be inspected upon request if the vessel is subject to survey, Port State or class inspectors.

The maps are categorized in several parts referring to the various elements of documentation and information throughout the life of the vessel.

4.3.1 Design and Construction Phase

Concept design description, drawings and documents is the preliminarily available description, drawings and any obtainable further descriptive documentation, which may serve to inform on, how the design meets its measures of efficiency.

Hazid investigation refers directly to the IMO formal safety assessment methodology.

Approval in principle statement is a statement from Administration/Approval authority, that the design/the project are conditionally acceptable, subject to re-evaluation as the construction entails.

Risk assessment, analysis and detailed documentation The engineering analyses and test are used to verify that the design is feasible with respect to intentions and overall safety in all phases of operation. The analyses and test will ensure that the novel or risk-based design will meet expectations from a functional and safety point of view.

Approval of the design the approval of the design indicates to the owner of the project, that the risk based vessel or system lives up to the level of safety required by the approval authority.

Certificates documentation on the compliance of a vessel or system with regulation or the stated intent of regulation.

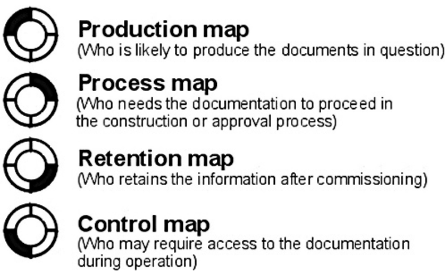
Ship Construction File, SCF, is a document suggested to contain all information relevant for a risk based design. Whether the analyses and the risk model originally applied should be part of the file is still debated internationally. Presently the SCF is undertaking development at the IMO.

4.3.2 Operational Phase

Summary of the design details/Port State Control-file: A file that summarily states any deviations from prescribed practice, high level risks, residual risks and the means to mitigate them and references to risk assessment and maintenance procedures in the Safety Management System. The file also contains statements of approval and/or granted equivalences from the Authority.

Safety Management System, or SMS. Usually these systems are very comprehensive. They describe all safety relevant tasks, anticipated risks, accident records, reporting and corrective action processes, maintenance tasks as well as routing of information in the organisation. The Safety Management System is used on a daily basis on board, as work permits, records and checklists are an integral part of it.

Combining the four maps serves to monitor the level of involvement for the main stakeholders in the process. The markings of each of the previous maps have an own signature in the combined map.



The amount of markers along a stakeholder line indicate an involvement in the process in one or more of the phases, whereas the tint of the perimeter quadrants indicates the stage the stakeholder is involved in.

The two upper quadrants are mainly relevant during design, approval and construction, whereas the two lower quadrants will become increasingly important when a vessel approaches the operational phase.

A high level of involvement does not necessarily generate qualification upgrade requirements, as these will depend on the currently available qualifications (which we will discuss later), but it provides an indication of the stakeholders which will in particular have to scrutinize the potential and challenges in their organisation (Fig. 4.9).

The above illustrates a typified situation, and other constellations are possible.

From the combined map, the following categorization of the stakeholders is drawn:

Designer: Involvement is concentrated in the design and construction phase, and qualification upgrade focus is on application of risk based design tools. This means, that the designer will have to scrutinize his organisation, to verify whether the necessary expertise on such tools is available, or has to be developed.

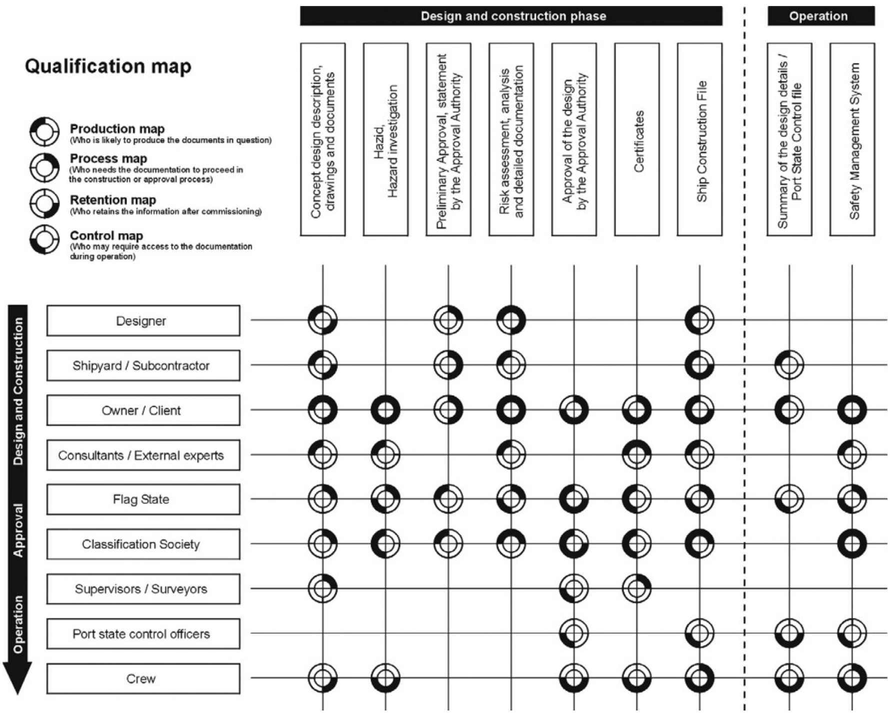


Fig. 4.9 Combined qualification map Winther and Juhl (2008)

Yard/Subcontractor: Even if involved with the risk based feature(s), the yard is likely to focus on the building specification, as well as the details to be submitted for the operational stage (if the design has been bought from designers/consultants), and a substantial amount of effort with regards to risk based features will arise when compiling the SCF, which is assumed to contain all relevant documentation produced in the design and construction phase.

Owner/Client: Attains a major role in the risk based project. The owner is responsible for fulfilling any requirements specific to his project as well as initiating assessment and analysis of any alternative features. The owners' involvement prevails consistently from selection of design/setting requirements to the design through the approval and construction phase up to and through the operation phase.

Consultants/external experts: As consultants and external experts are mainly involved with the production of material related to risk based features, their knowledge with regards to risk analysis and risk based methodologies and approaches is required to be substantial. As this is a prerequisite to perform analysis, consultants can be called upon, if insufficient qualifications are found with other stakeholders.

Approval authority/Administration: The approval authority will encounter risk based approaches through all stages of a lifecycle, and through all steps of the process (as will the RO/classification society) to varying levels, by being involved in the approval in principle, by setting requirements ensuing the risk assessment, granting final approval, by way of inspections on registration and later, at port state inspections. This again requires the authority to possess a variety of types and levels of knowledge with respect to risk based approaches.

Recognized organization: Are involved in both statutory and commercial issues pertinent to risk based approaches, and are also confronted with vessels at all stages of a life cycle. As it is evident from the map, the RO is also involved at most stages in the process. Thus, knowledge on risk based approaches should be widely available, on an expert level as well as more operational knowledge, depending on the roles assumed by the RO. Some Classification Societies acting as Recognised Organisations have extensive experience with risk based approaches applied in the offshore industry for years, thus some expertise is already available.

Supervisors/surveyors: When supervising the construction of a vessel, it is necessary for this stakeholder group to comprehend the conditions for approval, especially if these are of a risk based nature. The features are expected to become part of the specification, and the task of supervisors will thus not change significantly. The level of expertise required may be limited, due to the lack of in depth involvement with individual vessels.

Port state control officers: PSC-officials have to be acquainted with the fact that vessels can be approved with arrangements which are not in conformity with standard vessel designs. They are concerned with the vessel in operation, and will not be required to produce or process the information from the design and approval phases but will mainly require access to documentation. The qualification upgrade needs are hence not expected to be substantial.

Crew: For the time being, the crew is relatively uninvolved in the production of on board documentation, even if changes to the SMS may be instigated by on board operational experience. The new building crew is usually involved with a project from a relatively early stage, and ideally, their knowledge of the vessel increases through the construction phase. The crew retains and handles the on board documentation, and wherever special requirements to maintenance, manoeuvring, reporting or supervising become relevant, the crew should be aware of the features and the decision making basis arising from the risk based approaches applied.

Qualification requirements are of course pertinent to all parties involved in the process, as this is the only way to ensure a sound decision making basis. However the map also shows where it is necessary to ensure or even enhance qualifications, because the specific stakeholder has a crucial role in the design process, e.g. owner, Approval Authority, Recognized Organizations – and the crew. The latter is maybe not that obvious.

When first identified, it is much easier to focus adjustments to qualifications. However all parties need a familiarization process, to a level of knowledge in accordance with their type of involvement in the risk based design.

As seen from the qualification maps some stakeholders will necessarily have a highly intense level of involvement with a risk based design, throughout the life cycle of the project. Given the concerns on recruitment in the maritime industry, financial resources and career options within an organisation are primary motivational factors for attracting qualified candidates for open positions. Some of the stakeholders mentioned necessarily have greater potential for attracting qualified candidates.

Due to organisational size and resources, owners, recognized organisations, consultants and to some extent designers and yards have relatively high recruitment potential, should they require expertise that they do not possess, while other stakeholders may have to upgrade existing personnel due to limited recruitment potential (limited size or limited financial flexibility, for instance with public authorities, crewing agencies, universities/research institutes - the trend can be confirmed by comparing the number of qualified applicants for maritime technical position with the respective stakeholders).

4.4 How Do Risk-Based Design and the Associated Approval Work Together?

Approval of risk-based ships and their systems – often called risk-based approval – is the process to identify and resolve issues relating to the regulatory acceptance of the proposed design. Obviously, the approval process needs to take into account the risk assessment for the ship and its systems and, therefore, a careful review of risk analysis and establishment of risk acceptance criteria are central elements of the approval process.

Currently accepted and used risk-based design approaches are two-step approaches involving qualitative and quantitative steps. The currently proposed risk-based approval process is also a two-step process. The qualitative step ends with a preliminary approval which documents the requirements for the full approval. The obvious question for future risk-based design is how much effort is needed upfront to explore the design solution space before preliminary approval from an approval authority.

New activities within risk-based design and approval processes have to be aligned with existing schedules for owners, yards and suppliers. Ideally, a yard seeks to build-up complete knowledge of the expected risk analysis and its results before the contract with the owner is signed. This means that significant amount of analysis may have to be carried out prior to application for preliminary approval and before the detailed approval requirements are issued. On the other hand, investing too much before an indication of feasibility is not advisable.

Key milestones in the combined schedule are presented in the figure below, showing on the left yards' activities, in the centre the owners' actions and to the right the approval authorities' steps. It is emphasized that the shown alignment may vary according to the actual case.

The depicted alignment of schedules indicates that after signature of the letter of intent, the yard commences the production of a full design concept which is then previewed with the approval authority to decide whether a risk-based approval is needed or not. If needed, the qualitative phase of the design and approval is entered which concludes with the preliminary approval by the approval authority. Once the conditions attached to the preliminary approval are known – and are acceptable – the yard approaches the owner to sign the contract. Following this key milestone, a quantitative analysis is started which – together with the traditional design activities in this stage – eventually result in an approved design (Fig. 4.10).

Partners of SAFEDOR have intensively debated the above schedule. In particular, the discussion centered on how much effort by the yard or designer is spent before the letter of intent. For truly challenging and large projects, the quantitative part of the risk assessment is most likely carried out before the letter of intent and, therefore, well before the preliminary approval.

The main reason is that yards do not want the process to be interrupted by the relatively late preliminary approval. Yards ideally seek to have all issues affecting the design and approval process solved before applying for approval.

It is noted in this context that one objective of risk based design is to increase the knowledge about the ship design in the early design phase and, therefore, facilitate decision making. Thus, with advanced tools available, a risk analysis on key aspects can be performed cost-effectively before a letter of intent is signed. Note that this early design activity was presented in the introduction as a risk-based design optimisation.

Taking into account the above discussion, the alignment of owner and regulatory processes is more or less fixed. The alignment of the design process can vary depending on the level of challenge.

In the shown schedule, the design concept is established before the signing of the letter of intent. More importantly, the design concept is enhanced by a preliminary risk assessment involving preliminary HazId, qualitative risk ranking, risk analysis and evaluations of risk control options.

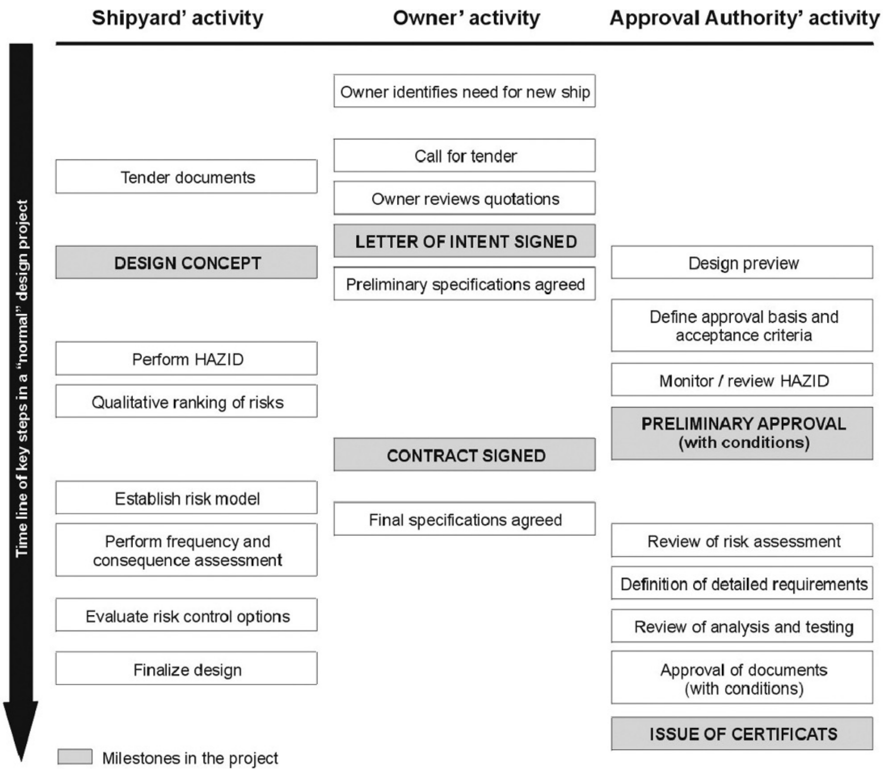


Fig. 4.10 Overview of key steps for "normal" projects

The yard thus establishes a clearer picture on the feasibility of the concept prior to signature of the letter of intent. Obviously, following the design preview with the approval authority, only updates of the supplied documentation (HazId, qualitative risk ranking, risk models, risk analysis and evaluations of risk control options) is expected to be required.

It is unlikely that any ship will be entirely risk-based in the near future.

The reason is that prescriptive rules offer a far more competitive approval basis than a risk-based approach for many standard elements of a ship. Therefore, risk-based approaches will only be applied in selected area of ship design.

Today we already see many ship designs with alternative arrangements related to fire safety following SOLAS-II.2/17. Here, risk-based approval comprises a challenge related to a single design aspect. The overwhelming part of the ship design is prescriptive (not risk-based) and the traditional design and approval process are pursued as before.

For the rule challenge, safety equivalence is demonstrated, and if the safety equivalence fails (for whatever reasons), the vessel is likely to be approved and built with another solution in compliance with existing rules. For ship designs adopting this partial risk-based approval case, a schedule as presented in figure above is applicable.

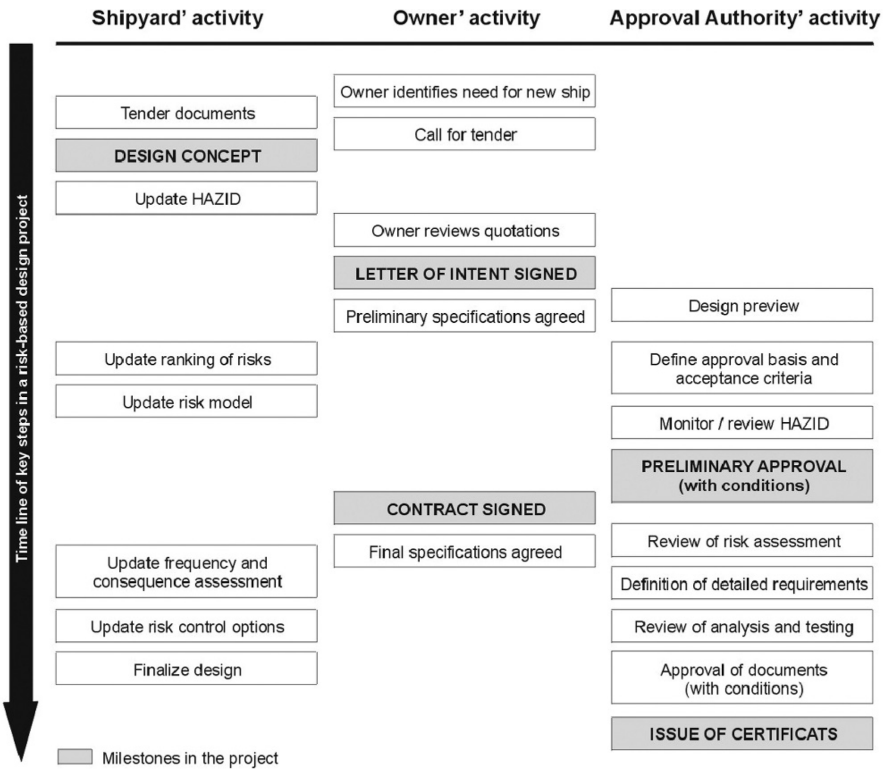


Fig. 4.11 Overview of key steps in risk-based design and risk-based approval

In the future, however, a complex case of risk-based approval comprising several rule challenges could be anticipated. The major portion of the ship design is prescriptive (not risk-based). However, if the safety equivalence fails, the project could probably not be realised. For ship designs in correspondence with this case, a schedule as presented in Fig. 4.11 seems more applicable.

4.5 Requirements to the Documentation Related to the Approval

Due to an expected increase in the number of novel and risk-based ship designs over the past years, an increasing need within the maritime industry for a formal approval process which allows for such innovation has become evident.

Presently, guidance exists for class approval of novel concepts. Also, guidelines for the development of risk based regulation have been issued within the auspices of the international organisation, as set out in the guidelines for formal safety assessment, FSA.

The form of the expected requirements set by a regulatory body for an actual risk based ship or system design is, however, less prominently described.

No fully risk based set of statutory regulation for ships exist for the time being.

When setting requirements to documentation, a main concern is, to anticipate how compliance to the approval process can best be recorded for later reference.

Approval normally requires compliance with two types of rules:

- Statutory requirements
- Class rules/industry standards

Even if these two types of rules at numerous instances overlap in scope and intent, it is important to note, that certain aspects do indeed differ.

The justification for a statutory requirements and regulation is found in a need to manage risks to life and occupational health for crew, passengers and third parties as well as risks to the environment.

Rules of the classification societies may have a different role, as these rules sometimes are best practices based on more commercial considerations.

Statutory requirements do not traditionally set detailed performance requirements, corrosion margins, requirements to weld seams or minimal maintenance on machinery (unless such machinery maintenance may be deemed safety critical) as the industry, classification societies or standardisation organisations already have developed such rules.

Statutory requirements will be concerned with specific features relevant for the preservation or rescue of lives and environment, including life saving, environmental protection equipment and redundancy requirements for safety critical functions.

As we have previously stated, rules and regulations can be challenged in a number of constellations:

- A ship design challenging both class requirements and statutory requirements. (Example: A vessel applies a novel (for maritime use) type of fire protection of the superstructure).
- A design, which challenge the statutory requirements, but does not challenge class requirements. (Example: Occupational health and safety issues (An engine room floor which is not adequately secure against slipping), access to radar mast inadequate).
- A design, which challenges the class rules only. Due to SOLAS II-1 Part A-1, reg. 3-1, this situation will not be considered.

SOLAS II-1 Part A-1, Regulation 3-1:

"*… ships shall be designed, constructed and maintained in compliance with the structural, mechanical and electrical requirements of a classification society which is recognized by the Administration (in accordance with the provisions of regulation XI/1), or with applicable national standards of the Administration which provide an equivalent level of safety*."

Beyond the above mentioned constellations, however, there are other instances whereby the rules and regulation may be challenged. Such situations require increased attention due to rising numbers of novel and risk-based ship designs. Hence these largely unregulated situations are likely to occur:

- A design which is an entirely novel concept (no comparable or equivalent designs exist)

Example: a Panamax cargo vessel built in carbon fibre material, a container vessel exceeding the dimensions covered by the rules.

- A design, which does per se not challenge neither class nor statutory requirements, whereas the intention of the rules does not match the intended scope of operation, and leaves this in essence unregulated.

For obvious reasons it is important to all stakeholders in the approval process to find a commonly accepted level in relation to the amount and type of documentation to be submitted prior to acceptance of the design. The balance to be achieved is that of an adequate level of documentation, conceived as the necessary amount of information without being redundant.

Traditional approaches to achieving safety on board ships have involved the adoption of a number of complex and often disjointed requirements for different components of the system "ship." The value of each to the overall design objective is sometimes unknown and the complementary or compensating nature of these provisions cannot be quantified. Hence it is of most importance to the novel design that competent personnel deals with all links of the design chain.

A design team acceptable to the Administration needs to be identified (probable at day 1 of the project) by the owner and may include, as the alternative design and arrangements demands, a representative of the owner, builder or designer, and expert(s) having the necessary knowledge and experience in safety, design, equipment, and/or operation as necessary for the specific evaluation at hand.

Other members may include marine surveyors, vessel operators, safety engineers, equipment manufacturers, human factors experts, naval architects and marine engineers. The levels and types of expertise (including construction, automation and/or human interaction) that individuals should have to participate in the team may vary depending on the complexity of the alternative design and arrangements for which approval is sought.

The alternative design process may involve substantial deviation from the prescriptive requirement. This means that the documentation process needs to be clear and transparent and well prepared to avoid misinterpretations. The alternative design and arrangements should be clearly documented in a simple and transparent format, such as a comprehensive report.

When checking that a design complies with traditional codes and guidance documents, it is relatively straightforward to establish whether the various provisions of these have been correctly implemented.

The risk-based document, however, provides a report of flexible approaches to design, using performance-related objectives rather than prescriptive solutions. It is therefore not possible for an approval body simply to compare the proposed design against a set of well defined criteria.

Due to this fact, the results of an engineering assessment should be fully documented in a way that can be readily assessed by a third party. The report should set out clearly the basis of the design, the calculation procedures used and any assumptions made during the study, and pertinent aspects of the design which require on-going supervision, inspection or maintenance should be included in the ship construction file and specialized specific survey report kept on board.

The novel approval procedure will be linked to each phase of the vessel life cycle. Table below presents the relation between life cycle phases of the vessel and elements of the approval procedure. The typical planning phase in design will be complemented by an identification of rules that will be challenged. In addition, the design team has to be assembled. The design phase will be risk-based and a risk assessment has to be performed. During the construction phase, new building survey needs to be directed with the help of a specific survey plan. In the operation phase, enhanced annual validation surveys addressing the items in the specific survey report are expected.

The approval flow chart for a risk-based designed ship with safety equivalence can be taken from IMO (MSC/Circ 1002, IMO (2001)). The steps from FSA are compared with the flow chart to indicate that both approaches are compatible.

Lifecycle phases	(Novel) regulatory framework
Planning phase – Market segment (cargo type) – Transport concept (bulk, containers, tank) – Area concern (restricted waters, short voyages, world wide, ...) – Ship specification (size, tonnage, weather requirement, ...) –	*Identification process* – Identify the relevant regulations for the transport concept – Identify the availability of necessary experts in the design group. – Preliminary risk assessment
Design phase – Hull – Propulsion system – Structure – Cargo handling – Survey friendly – ...	*Approval process* – Approval of the design team(s) – Preliminary risk assessment – Plan approval – Final risk assessment with concern to the specific system. – Sensitivity report – Specialized specific survey report. – Ship construction file/report

Construction phase – Ship specifications – Quality of work – . . .	*Approval process* – Survey and inspection related to the specialized specific survey report – Ship certificates
Operational phase – Trade – Maintenance – Compliance to legislation – ISM – . . .	*Approval process* – 12 month enhanced validation survey related to the specialized specific survey report – Periodical surveys reflecting the present SOLAS regime
Operational phase II – Change of flag – Modification	*Approval process* – Review of specialized specific survey report and ship file report – Periodical surveys reflecting the present SOLAS regime
Recycling – Decommissioning – Basel Convention – . . .	*Approval process* – Certificate of "Clean Ship ready for Decommissioning" – Green Passport/Report

4.5.1 The Approval Matrix – An Easy Guideline

4.5.1.1 Project Category

In order to rank the novelty of a design, a simple categorization may be used. Technology in category 1 is proven technology used in known application areas where methods for classification, testing, calculations and analyses exist. Technology in categories 2–4 is defined as new technology, and shall follow the procedures described in this report. The distinction between categories 2–4 serves to facilitate the focusing of efforts on areas of concern. Another objective of the categorisation is the establishment of, whether or not the design qualifies as a novel design, and to align estimates of required workload with the requirements eventually stated by the approval authority. The categorization also serves to assist in defining the level of detail of the analyses required in the following phase (Fig. 4.12).

	Technology status		
Application Area	**1 Proven**	**2 Limited field history**	**3 New or un-proven**
1. Known	**1**	**2**	**3**
2. New	**2**	**3**	**4**

Fig. 4.12 Categorization of new technology Winther and Juhl (2007)

A matrix as shown in Fig. 4.13 may be applied for guidance to the client when performing preliminary estimates on the extent of the work to be performed and submitted for approval.

The matrix has two axes: one referring to the level of novelty in the design (project category); the other referring to requirements in the risk assessment and to the amount of documentation (row A–E). The following paragraphs are explanatory notes to the approval matrix.

Row A: Basic risk assessment: This row contains information on description of hazards to individuals, arising from a specific setup or operation. Reference can be made to existing practice; hazards are ranked in qualitative terms.

Row B: Further analysis requirements: Due to the difference in complexity in the various ship designs it is obvious that a differentiation in the requirements to documentation is required.

- Semi-quantitative risk assessment: A description of frequency and impact of the consequences of a setup or operation, qualitative as well as quantified. Scenarios are described, and categorized according to their probability and impact. Elements are prioritised according to their severity (sometimes described as a consequence analysis).
- Quantified risk assessment: A description of probability and consequence of hazards (usually to a well defined group of people) through a specific operation or activity. The risk levels are represented numerically to be compared with agreed criteria. Varying levels of depth in the quantitative risk assessment may be required. It can demonstrate and quantify the effect of event sequences/scenarios which may affect structural integrity and/or may be a significant impediment to normal operational conditions, it can perform an evaluation of impact on individuals immediately involved or affected and quantifies potential fatalities, as well as amounts of environmentally noxious substances released and analyse the total impact on group health and the impact on the environment.

If a qualitative risk assessment describes (and suggests reduction of risks) to a satisfactory level, then requirements for quantitative assessments are redundant.

Row C: Qualifications of Analyst: This subject will be dealt with in depth in Chapter 4.3, but stems from the general assumption, that the client will to a certain extent be able to perform or contribute to at least basic risk assessment by means of own qualified personnel, as such assessments benefit as much from operational experience as from expert knowledge in specific analysis disciplines. Actual risk analysis, however, require specific expertise in the field. The guiding principle remains to limit the amount of external experts the client will need to employ, if a sufficient level of risk reduction can be achieved by relatively simpler means.

Row D: Applied rules and guidance: This element reflects the various sources of regulation and guidance on specific requirements in the individual case.

Row E: Potential additional tests, surveys and compliance control (after commissioning): Anticipated follow-up after construction.

Due to the variety and difference in complexity of novel ship designs, the application for approval of risk based designs will be assessed on a case by case basis.

Project Category Requirements	Known application of proven technology (conventional process) (1)	Known application of a technology with a limited field history/New application of proven technology (2)	New application of a technology with a limited field history/Known application of a new or unproven technology (3)	New application of novel or unproven technology (4)	Activity performed by:
A) Basic risk assessment	Not required	Required (unless rule challenge deemed insignificant or of negligible impact on safety and environment.)	Required	Required	Client (yard, supplier)
B) Further analysis requirements	Not required	Depending on Basic risk assessment outcome. Hazards medium or high, if any, should be examined further, at least by semi-quantified analysis	Semi quantified assessment. All hazards medium and high should be examined by means of quantified analysis	Quantified risk assessment to all risk contributions (due to the novelty of the design, it may not be possible to rank such hazards credibly. Hence, all should be examined in depth)	Client in cooperation with the AA
C) Qualifications of analyst	N/A	Operational experience. General knowledge of risk assessment techniques.	Operational experience. In-depth experience with risk assessment. Some knowledge of analysis techniques	Operational experience Risk assessment and analysis experts	N/A
D) Applied rules, and guidance	Existing prescriptive rules (SOLAS, MARPOL, relevant codes, national, regional and international legislation, prescriptive class rules)	Existing prescriptive rules where no rule challenge prevails (SOLAS, MARPOL, relevant codes, national, regional and international legislation, prescriptive class rules) applicable standards if available from other industrial sectors, class guidance on risk based approval as applicable	IMO circulars on alternative arrangements, class guidance on risk based approval, other relevant industry standards	IMO circulars on alternative arrangements, class guidance on risk based approval	N/A
E) Potential additional tests, surveys and compliance control (after commissioning)	As per Safety Management System (SMS), and existing regulation	Internal surveying. Additional review at safety related events subject to recording and corrective action	Internal/external surveying, recording and additional intermediate surveys of risk based features, if deemed necessary.	Continuous monitoring and review subject to reporting to the AA until a sufficient level of experience is gained	Client (operator

Fig. 4.13 The approval matrix

Furthermore, requirements for tests and analysis may vary with the confidence in the design within the Approval Authority. When reference designs or similar projects exist, and have been approved, characteristics inferred from one design may be applied to other similar designs.

Alternative evidence of compliance may be deemed acceptable by the approval authority, provided such evidence (in the form of certificates or documents of compliance) is produced as a result of testing or verification by an accredited independent third party.

The responsibility for documentation, testing and analysis, as required to achieve a reasonable level of safety rests with the client. This is no different from the well-known existing approval process.

The risk based approval process will apply a staged approach, initially stating conditions based on analyses of the proposed design as it is known at that stage, and later refining the requirements on which approval will be based, as knowledge of the design increases.

Assumptions made in the risk assessment in the design phase will be subject to verification, and the design as such will be subject to greater scrutiny through the initial phases of operation than what is expected for a conventional design.

The above is prevalent until appropriate references exist for most types of deviations from existing regulation.

Completely novel designs will be evaluated from scratch, case by case, and can thus become subject to more extensive documentation requirements. It is, though, expected, that such requirements will be relaxed as confidence in the methods and techniques applied for evaluation of safety grows, as well as the knowledge base on potential reference systems.

Traditionally, in the marine industry, "safety" has been interpreted as "compliance with rules". The risk based approach, on the other hand, encourages the industry to actively examine their goals with regards to safety, and also requires a re-examination of existing regulation – indeed it requires to redefine safety, and considers just how safe ship operations should be in the future.

A main challenge in this process is the balance between a volume and level of documentation, encouraging the client to examine his design and his systems (without imposing extensive burdens) and at the same time supplying sufficient information for the approval authority to have confidence in the safety of a design.

4.6 Approval of Ship Systems

The risk-based ship system approval process is based on elements as described above and the system approval process is often seen as a part of the overall risk-based approval. However, it may also be an isolated approval in case a system manufacturer wants to use the risk-based approach for a certain system.

The risk-based ship system approval process is based on the experience gained with the traditional type approval process. New steps have been introduced to achieve a transparent approval process minimizing the effort in each step and to limit the economical risk for the supplier in case of non-compliance with the requirements/acceptance criteria.

During the development of the proposed system approval process discussions with ship yards shows that risk-based design is more time consuming compared to the traditional process. More experience with risk-based design will increase efficiency and will lead to a reduction of the time required.

Due to the fact that additional work is required for the risk-based design and the approval process there will always be a difference between risk-based design and traditional prescriptive rule compliant design. To overcome the conflict between required analysis effort and available time in the bid process or realisation process, stand alone projects for the development of new designs are proposed.

In the following the alignment of the risk-based system approval process with the shipyard's main business process is illustrated in Fig. 4.14. The proposed system which includes a pre-approval process should run, if feasible, at the bid development stage or before as mentioned above. The specific design starts after the yard-supplier contract is agreed. This process will probably be iterative until an approval of the documents has been reached and the next step, the system construction, can be taken.

Given that the system is eventually only partially built by the supplier and completed at the yard on board a ship, some of the milestones and step transitions in the approval process do not need to coincide with the overall design and construction process (shown on the upper part of Fig. 4.14).

4.6.1 Acceptance

The development of acceptance criteria for main ship functions including development of risk models related to the specific system are crucial elements in the approval.

Overall risk and ship functions are normally linked via a risk model. The risk model describes the relation between a ship function failure causing harm (accident) and the outcome of the accident (consequence).

Ship functions explored within SAFEDOR are structural integrity, watertight/weathertight integrity, stability and floatability, propulsion, power supply, communication capability, navigation, manoeuvrability, sea keeping performance, emergency control, habitability and cargo handling. The absence (failure) of one or more ship functions is an incident, which in case of further escalation, may cause harm (accident).

The relation between overall risk and ship function can be used to determine the risk for a ship or a ship type or conversely to assign limit values for the different ship functions. As long as the relation between ship function and risk category is

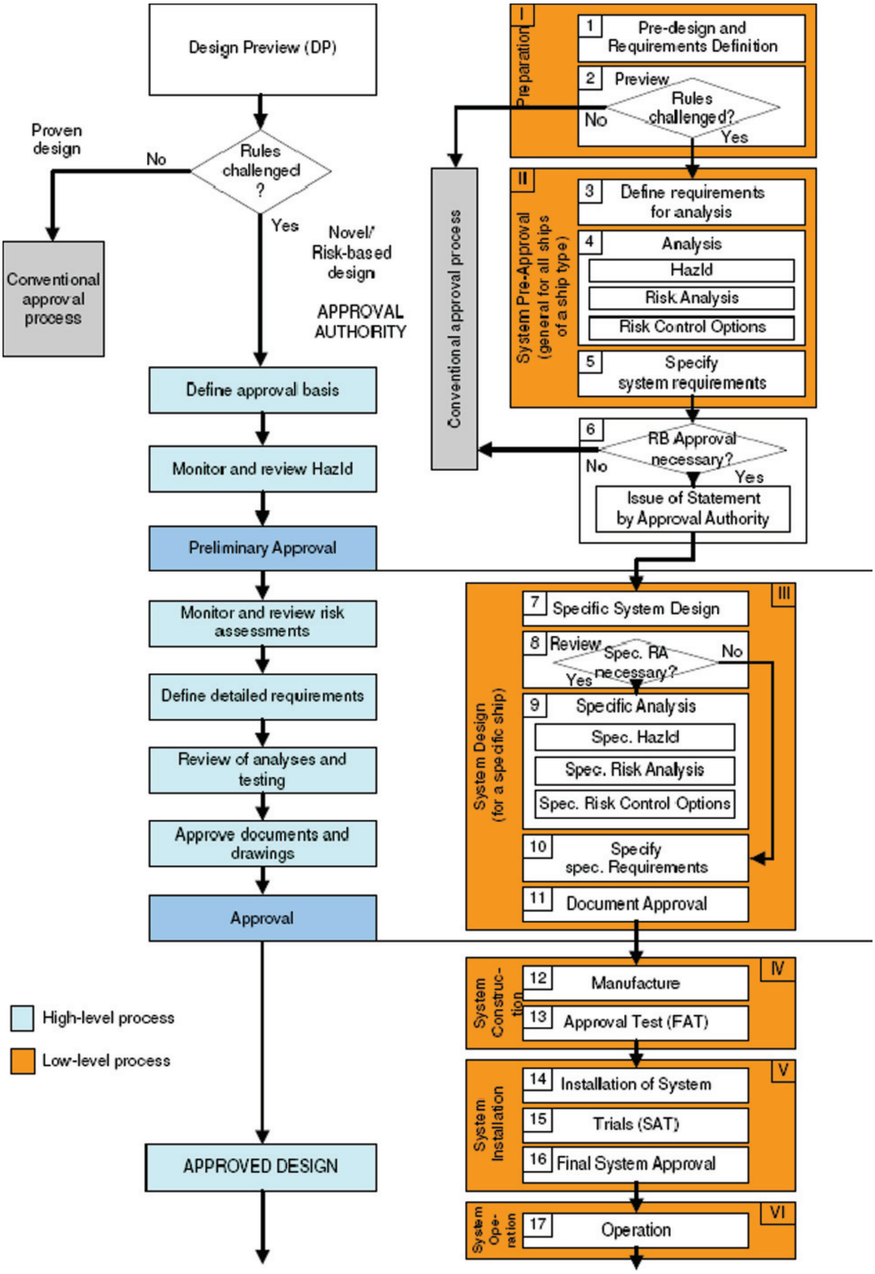


Fig. 4.14 Risk-based ship system approval flow diagram Hamann et al. (2007)

not affected by the design process, the acceptance criteria for ship functions can be reduced to target failure probability.

The relation between overall level of risk and the ship functions is not a one-to-one relation and thus the definition of an overall level of risk is not sufficient to define criteria for ship functions. For each ship function, acceptance criteria for safety, environment, reliability and availability shall be defined.

The acceptance criterion for the design is the minimum risk of the risk categories safety, environment, reliability and availability. For the approval process only safety and environment are relevant. It is expected, that for a significant number of systems the owner's demand for reliability will be the relevant acceptance criterion.

It is possible to develop the functional categorisation in a hierarchical manner proceeding from more general requirements (e.g. propel ship at required speed) to specific ones (e.g. supply fuel to main engine). However, establishment of a functional hierarchy becomes progressively more difficult at lower levels. Thus, it is proposed to define the relationship between "systems" and "ship function" and to use "system requirements" for the design of systems.

Since the acceptance criteria are specified in different levels of abstraction for ship functions, systems, sub-systems and components, the acceptance criteria also have to be broken down or distributed according to the relation between instances of different levels.

This breakdown is an arbitrary process because in most cases no one-to-one relation between criteria of different levels exists. If, for example, a system built of several sub-systems should reach a specified failure rate, which in this case represents the criterion, this can be achieved by various combinations of the failure rates of the sub-systems (taking into account possible interactions with other systems). Risk analysis of present ship systems can be a sound basis for the definition of failure probabilities for systems. Evidently, a detailed model of the system is required and will need to be developed.

With regard to the accuracy of the developed risk acceptance criteria and the process of risk analysis, it is obvious that the accuracy of the failure probability, for instance, determined by means of a reliability model (e.g. fault tree, Bayesian network) depends on the accuracy of the model itself and the data used.

The reliability model must consider all relevant contributors to the failure probability. However, the significance of a specific component varies with its failure probability and the relation to that one of other components of the system. Sensitivity analysis will demonstrate the level confidence of the calculated failure probability.

Guidelines for risk analysis describe the development process for the reliability model of the system examined, especially concerning issues like:

- **Determination of the interfaces to the global risk model (impact on ship functions and event trees)**
  Identification of the possible risk increasing influence of a specific RCO, for instance on RCO like the net around a helicopter landing which should prevent people from falling from the helicopter deck, but is also a hazard source when a helicopter is caught up in this net. The data (failure probability) used for the analysis (determination of the system failure probability) influence the result, and

their determination will follow certain quality standards. For instance, the determination of the failure probability of a component may be done by:

- Expert judgment
- Historical data (stochastic parameters)
- Probabilistic analysis

Expert judgment has been used in a variety of risk analyses and it forms a good basis in all cases where no other data is available. Risk perception, however, may be a problem and, for instance, a sensitivity analysis should demonstrate the stability of the result. This influence is smaller in a comparative analysis (comparison of two designs) than in a risk analysis using an absolute risk acceptance criterion.

Historical data are always useful; however, the data have to be evaluated to check the validity of the data used, e.g. is the sample representative or is the database comprehensive enough to calculate stochastic parameters. Appropriate methods are available, but not discussed in this handbook.

In certain cases probabilistic analysis can be used to calculate the failure probability. The applied limit state used has to be described clearly. In the risk based-design risk-balancing can be used in the sense of risk compensation between a system which violates the acceptance criteria and one or more systems which are sufficiently below the relevant acceptance criteria, e.g. on ship function level. The basic idea of risk balancing is that the required overall risk-level is achieved also in the case that one system violates the lower level requirement. Through the definition of maximum permissible risk values for functions and systems an overstretching of risk balancing shall be avoided.

Risk based design for ships and ship systems offer a higher flexibility to develop optimal solutions tailored for a specific task, and risk-based analysis and design is used in different industries. These applications demonstrate the advantages compared to traditional design and analysis. Further, appropriate methods required for risk-based design have been developed in these industries and can be adopted for the maritime industry.

As we have previously discussed, the engineering costs will in most cases increase with risk-based design compared with the traditional design process. Thus, the discussions show that one major application of risk-based design will be the development of new system types outside a specific ship design. This process is then comparable to the "type approval process". In this context the issue of direct dialogue between supplier and approval authority, especially the flag state, was raised.

Risk-based system design requires the definition and application of acceptance criteria. Acceptance criteria can be related to safety, the environment or to economic (reliability, availability) factors. Usually, only one of these risk categories gives the relevant design criterion and is the dimensioning criterion. However, the approval process is focused on safety and environmental criteria. The approval process and the acceptance criteria used should provide an objectivity and transparency to make the influence of the specific approval authority negligible.

Even if tentative risk acceptance criteria can be developed, presently available data are limited and only in special cases risk acceptance criteria can be deduced for ship systems from historical data.

4.7 Operating a Risk-Based Approved Ship

Two different perspectives can be distinguished when risk-based ship operation is being addressed. One is the operation of a risk-based designed ship and the other is the use of risk-based approaches in ship operation (as required by the ISM code already). The latter is a clear commercial issue; hence this chapter will be focused only on the operation of a risk-based ship Vergine and Borlenghi (2008).

Operation of the risk-based ship is the logical next step after risk-based design and approval. Even though the operation, as such, is not a part of the construction, operational aspects need to be considered carefully e.g. how to deal with the port state control.

As well as the operation of a risk-based designed ship is expected to be influenced by the design assumptions, at the same time the operational aspects have to be duly considered during the risk-based design phase.

It will be essential that the risk designed ship of the future has very clear and concise records and instructions that identify the risks that were assessed (together with their justifications), and of what the actions and options have been exercised at the design stage so that the operators can manage the risks in the most effective fashion throughout the life of the vessel.

Risk-based ships are already sailing and their operational aspects are aligned with the current regulatory framework treating risk-based elements as exemptions or equivalents today following SOLAS (2004), part a, reg. 4 or 5.

In both cases, details and reasons for the acceptability are to be communicated to IMO and circulated to IMO Member States. However, each case is again a new case with the associated administrative requirements. In the case of the established possibility to implement alternative designs and arrangements following SOLAS II-2, reg.17, the relevant flag state administration is required to "communicate to the Organization pertinent information concerning alternative design and arrangements approved by them for circulation to all Contracting Governments." With the advent of more design aspects of a ship becoming risk-based, there is a clear need to ensure proper information and documentation to facilitate smooth operations.

4.7.1 On Board Documentation

When operating a risk-based designed ship, inspections and surveys are some of the most important aspects to address. Every administration checking compliance will in the future, have to take into account possible risk-based elements of the ship.

A dedicated certificate to document risk-based elements on board would certainly help to convince less knowledgeable administrations and port state controls that the vessel in question is properly built and maintained.

A good example is the documentation requirement in SOLAS II-2, reg.17.4.2 stating “A copy of the documentation, as approved by the Administration, indicating that the alternative design and arrangements comply with this regulation shall be carried on board the ship.”

The current discussion at IMO related to on board documentation is referred to the goal-based standards working group, where the so called “Ship Construction File” (SCF) is discussed. Such SCF will initially be carried on board the vessel throughout the lifetime of the vessel.

4.7.2 The International Safety Management Code

The ISM documentation is another instrument. The ISM-code (IMO 2002a/2005) requires to document a safety management system and to carry onboard all documentation relevant to the particular ship.

The ISM code requires the establishment of a safety management system with safety management objectives which lead to “safe practices in ship operation and a safe working environment,” and establishing “safeguards against all identified risks” (IMO 2002a/2005).

Although there is no further explicit reference to this general requirement in the remainder of the ISM Code, risk assessment is essential for demonstrating compliance with most of its clauses. The ISM Code does not specify any particular approach to the management of risk, and it is for the company to choose appropriate methods.

Risk-based ships have been analyzed during the design stage and hazards as well as risk control options have been identified. This constitutes a good part of the risk identification required by the ISM code. It is likely that, for a novel ship, all aspects of the operation will be addressed during the early design stage with risk-based approaches. Thus, including risk-based elements into the ISM-code provisions is simple: the risk assessment of the design stage is the ideal input for establishing the safety management system required by the ISM code.

It also follows that a more formal guidance for identifying risks and establishing safeguards and safe practices would create a harmonized approach to set up the safety management system under the ISM code.

Following from the above, it appears that a complete documentation of all risk-based elements of a ship together with the process and criteria of acceptance should be carried onboard. In addition, a proper summary addressing the concerns of surveyors and port state control officers has been drafted.

4.7.3 Inspection of the Risk-Based Ship

The inspection of a risk-based ship may require special competences for class surveyors and flag state inspectors. Supported by appropriate documentation, see above, the risk-based elements of the ship will have to be understood prior to checking. Likely, special training related to risk assessment is also needed for the inspectors and surveyors.

In the event that the initial assumptions that were made during design and approval are changed (the operational area, the cargo etc), then it will be necessary to revaluate the risk levels and make necessary adjustments, however it is worth being aware of the potential pitfalls in the need for periodic reassessment.

Today, SOLAS II.2, reg. 17.6, requires a reassessment and states that "re-evaluation due to change of conditions if the assumptions, and operational restrictions that were stipulated in the alternative design and arrangements are changed, the engineering analysis shall be carried out under the changed condition and shall be approved by the Administration."

It is expected that a reassessment will also be required if the vessel changes flag and/or class.

Inspection of a risk-based designed ship is required, as well as for traditional ships. Class survey, flag state inspection and port state control have to understand the risk-based nature of the ship. This understanding could be promoted by means of additions to existing certificates affected (quoting on the risk based feature affecting them).

Consideration could alternatively be given to the issuance of a dedicated certificate. Proper authoritative documentation has the advantage of providing an inspector with evidence of the vessel being built and maintained in a satisfactory manner. Except from the certificate, most of the documentation requirements are already in place.

When performing PSC, time is limited. Should the PSC inspector come across a feature (such as an asymmetrical distribution of lifeboats) which he is not familiar with, an easy means to access the information on such a feature should be available.

A "PSC-file", or excerpts from the vessel documentation to ascertain that any such feature is approved by the administration, including further relevant information could be a practical tool.

With regards to PSC-inspections, the risk model and the detailed investigations will not need to be demonstrated to the officials of the port state. Even if "all relevant documentation" related to the operation of the vessel will have to be on board, this is interpreted as all documentation of immediate relevance for the operation of the vessel, and technical source documents are usually not being perused by PSC-inspectors.

4.7.4 Owner's Inspection

Like in many other industries the responsibility lies at the owner to ensure that the information kept on board is correct.

The primary goal of the Owner's inspection is to verify and ensure the safe operations of a risk-based ship relating to current shipboard conditions, and that the ship will pass Flag, Class, Port-state and other inspections.

Owner's inspections may consist of Management/Superintendent visit to the ship, or take place during annual internal company shipboard audits.

Management should verify that the initial assumptions made during design and approval process have not changed (i.e. the route, the ship arrangement, capacity, non-statutory required outfitting, etc) as it will be necessary to re-evaluate the risk levels and make any adjustments required to reflect this change. Levels of spares, consumables and outfitting should also be checked. Any changes compromising risk related design features and operational procedures should be identified, and necessary corrective actions addressed.

The inspection should include a review of onboard documentation, including the Ship Construction File (SCF) to ensure that it is current and being kept up-to-date. Additionally, management should verify that a complete set of risk documentation is carried onboard detailing all risk-based elements of the ship, the process and criteria of acceptance, and that this information is included in a summary to address any concerns of attending surveyors and port state control officers.

Management must also confirm that the Officers and Crew onboard are aware of the risk based design and operational features the ship which should be detailed in the Safety Management System, and verify that they have undergone appropriate training to ensure that these features are not compromised.

4.8 Conclusions

A consistent Approval process is urgently needed to ensure a unified assessment of novel ship designs.

Obviously, further examination into the nature of the presently applied approach may be highly beneficial, and is at present taking place. It may, though, be deducted from the statements in the previous chapters as well as from case stories, that the presently applied traditional approval methods may well, at least to a considerable extent, be interfaced with alternative methods of verification and approval. As it is, queries related to the offshore sector (where the Administration is mainly involved with life saving appliances) take into consideration the safety cases submitted by the applicant, which apply risk based assessments of safety levels.

Summing up, there is potential for elaboration on the concept, to allow a glance at what Administrations may in the future be faced with, as well as possible ways of expanding the existing methods associated to the Approval process.

The development within the SAFEDOR project concerning the approval process will be submitted to the IMO in a comprehensive extract of our work.

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Chapter 5
Methods and Tools

Jørgen Jensen, Carlos Guedes Soares and Apostolos Papanikolaou

Abstract Risk-based ship design demands advanced tools to accomplish the safety assessment of a given design. In this chapter, the background theory for the development and examples of application of related risk-based tools and of assessment procedures will be given. These tools and methods facilitate the analysis of the initiation and of the consequences of a variety of hazards, like system failure, collision, grounding, structural failure, fire, flooding and loss of intact stability. Finally tools for the simulation and analysis of evacuation, mustering & rescue procedures will be presented.

5.1 Introduction

Risk-based ship design demands advanced tools to accomplish the safety assessment of a given design. Such tools have been developed or refined in the course of the SAFEDOR project covering

- Assessment and analysis of system failures
- Fast and accurate prediction of flooding
- Probabilistic assessment of the strength of ship structures
- Probabilistic assessment of intact stability
- Prevention of collision and grounding events
- Prevention of fire and explosion events

Various theoretical methods and procedures have been used to derive these tools: Bayesian network, artificial neural networks, CFD calculations, non-linear time domain calculations and reliability models, virtual reality models and simulation techniques. The results are validated by physical model tests and numerical simulations; where possible, simplified models enabling fast calculations are derived and calibrated. The developed procedures have been applied to a variety of case studies and ship types including container ships, RoRo ships, tankers and cruise vessels. The

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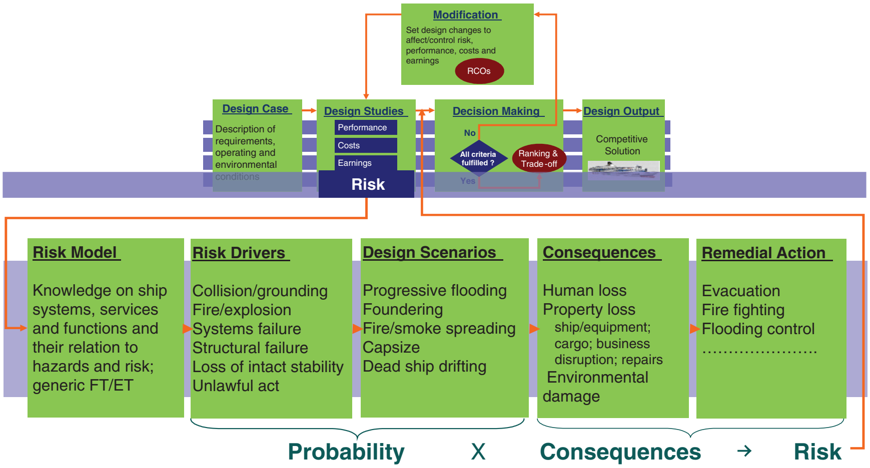
ultimate goal is to provide the ship designer with tools and procedures for fast and reliable evaluation of various risks associated with failure of the ship or its subsystems and able to evaluate the effect of various risk-control options on ship design and operation.

An overview of the risk-based design concept advanced by SAFEDOR and herein adopted is given next.



The following chapter addresses a series of the above risk drivers, their consequences and remedial actions.

The first section deals with system failure as this type of failure is often the initiation event for large-scale damages. The section focuses on a semi-automatic tool for the generation and analysis of fault and event trees; it also addresses the optimization of system for increased reliability and safety.

The topic for the next section is collision and grounding events. These events are treated together as the tools described have strong similarities. The main tools are Bayesian Networks able to estimate the probability of these events. Also Artificial Networks are discussed for fast prediction of collision and grounding damages.

As a natural follow-up, structural failure is considered in the following section. An overview of structural reliability is given, dealing with structural strength as well as hull girder loads, and examples related to structural failure of damaged vessels are given.

Following a structural failure flooding might take place and methods/software tools able to estimate the flooding process and its consequences (*damage ship stability, capsize and foundering*) are reviewed. This topic is a quite complex area in which significant research effort is currently devoted; results appear in some cases not yet mature enough to be routinely used in the actual design of ships.

Another serious type of accident that can occur to a vessel is fire and explosions. Computational Fluid Dynamics (CFD) is able to predict the development of a local fire under rather limiting conditions. However, it represents a promising tool for future developments and some results are presented in the section.

Not all damages to a vessel need an initiating accident as a collision, grounding and fire. Wave loads and specific ship and environmental conditions can under certain circumstances lead to excessive roll angles of the intact vessel. Thereby, loss of or damage to cargo might occur and even capsize (*loss of intact stability, parametric roll*) could happen. This is especially so for large container vessels and hence of significant importance in the design of such vessels. Various methods and tools, which are employed to simulate these phenomena, are described; this includes an effective assessment procedure known from structural reliability, which is used to estimate the roll angle in a stochastic seaway.

The final section deals with tools enabling the simulation of evacuation, mustering and rescue. The pertinent parameters are defined and three different software tools for analyzing mustering and evacuation are presented and discussed.

5.2 System Failure

Increasing complexity in the design of engineering systems onboard ship, especially those incorporating new programmable technologies, challenges the applicability of rule-based design or classical safety and reliability analysis techniques on new designs. As new technologies introduce complex failure modes, classical manual safety and reliability analysis of systems becomes increasingly more difficult and error prone.

To address these difficulties, computerised tools are being developed that simplify aspects of the engineering and analysis process. Two such tools are described in the following. The first tool largely automates the synthesis of two types of predictive model of system failure, Fault Trees and Failure Modes and Effects Analyses (FMEAs), by interpreting reusable specifications of component failure in the context of a system model. The analysis is largely automated and therefore reduces the effort required to examine safety, while the underlying algorithms can scale up to complex systems. The second tool extends the above concept to solve a design optimisation problem that of reliability versus cost optimisation via selection and replication of components and alternative sub-system architectures. The tool employs Genetic Algorithms to progressively evolve initial non-optimal designs to designs where components or alternative sub-systems with appropriate reliability characteristics have been selected and replicas have been allocated in a way that reliability requirements are achieved with minimal cost.

This section outlines these two technologies and their application in an advanced and largely automated engineering process.

5.2.1 Introduction

Fault Tree Analysis (FTA) and FMEA are well-known and widely used system analysis techniques used in reliability engineering. Both are long established – FMEA was formally introduced in the late 1940s, and FTA has been around since the 1960s – and both have been employed in a number of different areas, including the aerospace, nuclear power, and automotive industries. They are methods that we can use to identify potential faults in a system, so that we can then use that information to correct or prevent those faults.

Fault Tree Analysis (FTA) is a flexible tool, equally applicable to quantitative and qualitative analyses, and easy to use and understand. Fault trees themselves are graphical representations of logical combinations of failures, and show the relationship between a failure or fault and the events that cause them. A fault tree normally consists of a *top event*, which is typically a system failure, connected to one or more *basic events* via a system of logical gates, such as AND and OR. Basic events are usually either failures or events expected to happen as part the normal operation of the system. Analysis of the fault tree consists of two parts: *qualitative* (logical) analysis, and *quantitative* (probabilistic) analysis. Qualitative analysis is done by reducing the logical expression represented by the fault tree into a set of *minimal cut sets*, which are the smallest possible combinations of failures required to cause the top event. Quantitative analysis is done by calculating the probability of the top event given the probability of each of the basic events occurring.

In an FMEA, the basic process consists of compiling lists of possible component *failure modes* (which is a complete description of how an entity fails), gathered from descriptions of each part of the system, and then trying to infer the effects of those failures on the rest of the system. Usually, these effects are evaluated according to a number of criteria, such as:

- Severity – how severe/critical is the impact on the rest of the system?
- Probability – how likely is it that this failure mode will occur?
- Detectability – how likely is it that this failure will be detected?

These criteria are then combined into an overall priority figure for the effect of the failure mode, known as the *Risk Priority Number* (RPN), generally by multiplying the criteria together. All of this data is then presented in the form of a table, which allows the analyst to quickly see what the effects are of each failure mode.

There are obvious differences between the two techniques. FTA is a deductive technique, which means it works from the *top down* – assuming the system has failed, and then trying to work out why it failed. This is done by working backwards trying to determine what possible combinations of events might have caused it; the system failure then becomes the top event of the fault tree and the individual component failures form the basic events, and they are all combined using a network of logical gates. FMEA, by contrast, is an inductive technique, and works from the *bottom up* – assuming a component failure has occurred, and then trying to work out what its effects would be. It involves proposing a certain event or condition, and then trying to assess the effects of that initial event on the rest of the system. The end result is a table of failures and their effects on the system, which provide the analyst with an overview of the possible faults.

Both techniques are useful and provide a lot of valuable information about systems, and each can be used to complement the other, but both suffer from the same flaw: they are primarily manual methods. The process of performing these analyses can be laborious, especially for larger and more complex systems. Whilst this has the benefit of providing the analyst with an in-depth knowledge of the system being studied, it can also more likely be that the analyst will make a mistake, or that the results (once obtained) are too numerous to interpret efficiently. As a result, it is not uncommon for FTA and FMEA to take place only once or twice in the life cycle of the system. This is unfortunate, because systems analysis techniques like FTA and FMEA can be of great benefit during an iterative design process. By estimating the reliability and gaining a more thorough understanding of the failure behaviour of the system in each iteration, it is be possible to see how the changes in design impact upon the overall safety of the system. It also enables the analysts to identify and remedy potential flaws much earlier, thereby saving both time and effort and producing a more reliable product.

However, before FTA or FMEA can be incorporated into the design cycle in this way, it is necessary to overcome the problems inherent in such manual techniques. Experience from the aerospace and process industries suggests that the application of classical safety analysis is hindered by the increasing complexity of systems. For relatively simple systems, this is a manageable process, although fault trees and FMEAs can rapidly become very elaborate. In complex systems, however, manual analysis becomes laborious and error prone, and a thorough assessment and interpretation of the results become increasingly more difficult to achieve within the realistic constraints of most projects.

While guidance is given on how technical justification for alternative designs and arrangements can be provided in the form of engineering and safety analyses, such as fault tree analysis (FTA) and FMEA, there is a need for specific supporting measures and tools to assist in the application of such techniques. One obvious approach would be to automate them in some way, or at least enable parts of the process to be carried out in an automated fashion. This would mean that the analysis could be carried out more quickly and efficiently, leaving more time for the results to be studied and allowing more useful conclusions to be drawn.

HiP-HOPS (Hierarchically Performed Hazard Origin and Propagation Studies) is a new technique for the semi-automatic construction of fault trees and FMEAs, developed at the University of Hull, intended to achieve such a goal. In this technique fault trees and FMEA are automatically constructed from topological models of the system that have been augmented with appropriate component failure data. To realise the potential for useful automation offered by HiP-HOPS, an implementation that extends the capabilities of Simulation X, a modelling and simulation tool authored by ITI GmBH, has been developed with new capabilities for automatic safety and reliability analysis. We should note that these capabilities are unique among simulation tools. It is anticipated that with this extension Simulation X could in the near future facilitate the useful integration of a largely automated and simplified form of safety and reliability analysis in the context of an improved design process. This in turn should contribute to addressing the broader issue of how to make safety a more controlled facet of the design so as to enable early detection of potential hazards and direct the design of preventative measures. The utilization of the approach and tools has been shown to be beneficial in cases studies on engineering systems in the shipping (Uhlig et al. 2007) and offshore industries (Hamann et al. 2008). A brief description of the analysis methodology in HiP-HOPS and the developed computerised tools follows.

5.2.2 Overview of Methodology

A HiP-HOPS study of a system under design has three phases:

- System modelling and failure annotation,
- Fault tree synthesis and
- FMEA synthesis.

The first phase is executed manually while the latter two phases are fully automated.

The first phase consists of developing a model of the system (hydraulic, electrical or electronic, mechanical systems, and conceptual block and data flow diagrams) and then annotating components in that model with failure data. In this phase, modelling can be carried out in Simulation X as it would normally have been carried out for the purposes of simulation. Failure annotations are added to components of the model using a developed graphical user interface (GUI).

The second phase is the fault tree synthesis process. In this phase, an automated algorithm is applied to the annotated system model to create a set of fault trees which define system failures and their causes in the architecture. The algorithm works by taking failures of system outputs and progressively working backwards through the model to determine which components caused those failures. System failures and component failures are then joined together using the appropriate logical operators to construct fault trees with the failures at the system outputs as the top events and the root causes as basic events. The concept is illustrated in Fig. 5.1.

In the third phase, fault trees are analysed and an FMEA is constructed which combines all the information stored in individual fault trees. The FMEA is presented in the form of a table listing, for each component, the effects of each component failure on the system. As part of this process, both qualitative (logical) and quantitative (numerical-probabilistic) analyses are carried out on the fault trees. These analyses provide both the minimal cut sets of each fault tree and the unavailability (i.e. failure probability) of top events.

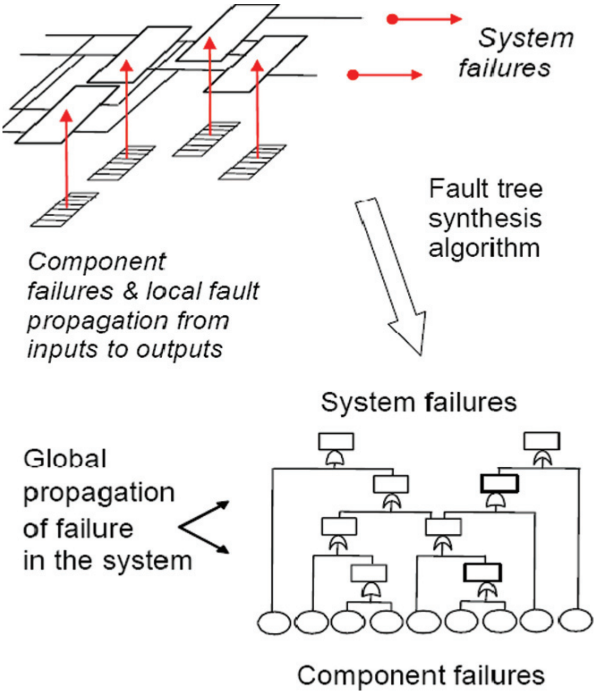


Fig. 5.1 The synthesis of fault trees from the system model

5.2.3 Modeling Phase

HiP-HOP studies can be performed on any model of a system that identifies components and the material, energy or data transactions among components. In practice, such models can be developed in Simulation X and can be hierarchically arranged, to manage complexity, if necessary. The basic idea of HiP-HOP is that an output failure of a component can either be caused by an input failure, an internal failure, or some combination of both. The local component output deviations and topology information are used to determine the relation between local deviations and top events.

For the purpose of the analysis, each component in the model must have its own local failure data, which describes how the component itself fails and how it responds to failures propagated by other components in the vicinity. Essentially, this information specifies the local effects that internally generated or propagated failures have on the component's outputs. This is achieved by annotating the model with a set of failure expressions showing how deviations in the component outputs (output deviations) can be caused either by internal failures of that component or corresponding deviations in the component's inputs. Such deviations include unexpected omission of output or unintended commission of output, or more subtle failures such as incorrect output values or the output being too early or late. This logical information explains all possible deviations of all outputs of a component, and so provides a description of how that component fails and reacts to failures elsewhere. At the same time, numerical data can be entered for the component, detailing the probability of internal failures occurring and the severity of output deviations. This data will then be used during the analysis phase to arrive at a figure for the unavailability of each top event. Once done, the component can then be stored together with the failure data in a library, so that other components of the same type can use the same failure data or this type of component can be re-used in other models with the same failure data. This avoids the designer having to enter the same information many times.

For the specification of the components' failure modes (which are the effects by which the component failures are observed), a generic and abstract language was developed. There are different ways of classifying failure modes, e.g. by relating them to the function of the component, or by classifying according to the degree of failure – complete, partial, intermittent etc. (Rausand and Oien 1996) In general, however, the failure of a component will have adverse local effects on the outputs of the component which, in turn, may cause further effects travelling though the system on material, energy or data exchanged with other components. Therefore in HiP-HOPS, we generally classify the effects into one of three main classes of failure, all equally applicable to material, energy or data outputs. These are, namely, the omission of an output, i.e. the failure to provide the output, a commission of an output, i.e. a condition in which the output is provided inadvertently and in the wrong context of operation, and an output malfunction, a general condition in which the output is provided but at a level which deviates from the design intention. Since this classification adopts a functional viewpoint which is independent of technology, it could provide a common basis for describing component failures and their local effects. However, HiP-HOPS can work with any classification of failure modes as long as it is consistent from one component to the next.

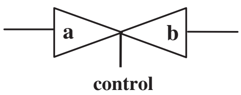
Components do not only cause failures, but they also detect and respond to failures caused by other components or transfer failures of other components. However, components do not only generate, mitigate or propagate failures. They may also transform input failures to different types of output failure. For instance, a controller may be designed to respond to detected sensor failures by omitting any further output to ensure that hazardous control action is avoided. In this case, malfunctions at the input are intentionally being transformed into omission failures. To capture those general patterns of behaviour of a component in the failure domain, we propose a technique that can be used to systematically examine the generation, propagation and transformation or mitigation of failure across the component input and output interface. In the proposed technique, manual analysis is performed at component level and focuses on the output ports through which a component provides services to other components in the system. In the course of the analysis, each output port is systematically examined for potential deviations of parameters of the port from the intended normal behaviour, which generally fall into the following three classes of failure:

a) Omission: failure to provide the intended output at the given port
b) Commission: unintended provision of output
c) Malfunction: output provided, but not according to design intention.

Within the general class of malfunctions, analysts may decide to examine more specific deviations of the given output which, in most applications, will include conditions such as the output being delivered at a higher or lower level, or earlier or later than expected. As an example, Fig. 5.2 shows the analysis of a two-way computer controlled valve. The figure shows the valve as it would typically be illustrated in a plant diagram and records the results of the local safety analysis of the component in two tables that define valve malfunctions and output deviations respectively.

In normal operation, the valve is normally closed and opens only when the computer control signal has a continuously maintained value of a logical one. Valve malfunctions include mechanical failures such as the valve being *stuckOpen* or *stuckClosed*, and blockages caused by debris such as *blocked* and *partiallyblocked*. For each malfunction, the analysis records an estimated failure rate while the effects of those malfunctions on the output of the valve can be seen in a second table that lists output deviations.

This specification of failure modes is generic in the sense that it does not contain references to the context within which the valve operates. Failure expressions make references only to component malfunctions and input/output ports of the component. The failure behaviour described in these expressions has been derived assuming a simple operation that we expect the component to perform in every application (valve is normally closed unless the value of control signal is 1). For these reasons, the specification of Fig. 5.2 provides a template that could be re-used in different models and contexts of operation, perhaps with some modifications, e.g. on failure rates, to reflect a different environment.



Valve Malfunctions

Failure mode	*Description*	*Failure rate*
blocked	e.g. by debris	1e-6
partiallyBlocked	e.g. by debris	5e-5
stuckClosed	Mechanically stuck	1.5e-6
stuckOpen	Mechanically stuck	1.5e-5

Deviations of Flow at Valve Output

Output Deviation	*Description*	*Causes*
Omission-b	Omission of flow	blocked OR stuckClosed OR Omission-a OR Low-control
Commission-b	Commission of flow	stuckOpen OR Commission-a OR Hi-control
Low-b	Low flow	partiallyBlocked OR Low-a

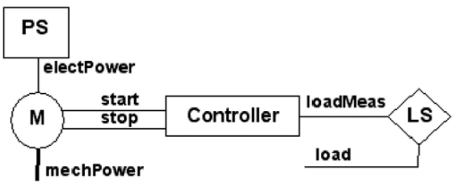
Fig. 5.2 Failure annotations of a computer-operated two-way valve

5.2.4 Synthesis Phase

As it was seen in Fig. 5.2, component failure data relate output deviations to logical expressions that describe the causes of those deviations as component malfunctions and deviations of the component inputs. Each such expression is effectively a mini fault tree which links a top event (the output deviation) to leaf nodes, some of which may represent input deviations. When we examine a component out of system context, input and output deviations represent only potential conditions of failure. However, when we place the component in a model of a system, the input deviations specified in the analysis can actually be triggered by other components further upstream in the model and the specified output deviations can similarly cause more failures further downstream.

This mechanism by which output failures of a particular class at one end of a connection trigger input failures of the same class at the other end results in a global propagation of failures through the system which may ultimately cause significant hazardous failures at the outputs of the system. Given a model of the system and the local safety analyses of its components, it is possible to capture this global propagation of failure in a set of fault trees. These fault trees are mechanically constructed by traversing the model and by following the propagation of failure backwards from the final elements of the design (e.g. electromechanical actuators) towards the system inputs (e.g. material/energy resources, operators and data sensors). The fault tree is generated incrementally, as we parse the local safety analyses of the components encountered during the traversal, by progressively substituting the input deviations for each component with the corresponding output failures propagated by other components. Figure 5.3 illustrates the principle that underpins this process of fault tree synthesis. The figure shows a hypothetical motor and its starter circuit as a unit (M) that transforms electrical power provided by a power supply (PS) to mechanical power on a rotating axis.

The motor starter receives normal start and stop commands from a control computer (Controller). As a safety feature the controller is also connected to a sensor



Component	Output Deviation	Description	Causes
M	OE-mechPower	Omission of mechanical power	motorFailed OR OE-electPower OR OS-start OR CS-stop
PS	OE-electPower	Omission of electrical power	powerSupplyFailed
Controller	OS-start	Omission of start signal	controllerFailed
	CS-stop	Commission of stop signal	elecMagnInterference OR HV-loadMeas
LS	HV-loadMeas	Hi value in load measurement	sensorBiased

Fig. 5.3 Example system and fragments of local safety analyses

(LS) that monitors the load connected to the axis of the motor and when the measurement exceeds a specified load it issues a stop command to protect the motor. To illustrate the fault tree synthesis, the figure also provides a table that contains, for simplicity, only fragments from the local analyses of the Motor, the Power Supply, the Controller and the Load Sensor. For simplicity, deviations in this table refer to names of connections in the model rather than local names of component ports. Collectively, these deviations and their causes define the propagation of failures that result in an omission of mechanical power at the output of the motor.

The local analysis of the motor, for example, defines that this event can be caused by a failure of the motor, an omission of electrical power at the input, an omission of the start signal or, interestingly, a commission of the stop signal. The causes of some of those events can in turn be explored further in the local analyses of the components connected to the motor. For example, the analysis of the power supply defines that a failure of this component will cause an omission of electrical power. In turn, the analysis of the controller defines that an omission of the start signal will be caused by a controller failure while a commission of the stop signal can be caused by electromagnetic interference or in response to an abnormally high measurement of motor load. The analysis of the load sensor defines that the latter is indeed a plausible failure mode that can be caused in normal conditions of loading if the sensor is positively biased.

An overall view of the global propagation of failure in the system can be automatically captured by traversing the model and by following the causal links specified in the local safety analyses of the components that we progressively encounter during this traversal. The result of this process for the above example is the fault tree that is illustrated in Fig. 5.4. Note that this mechanically synthesised fault tree records the propagation of failure in a very strict and methodical way. It starts from an output failure, the omission of mechanical power, and following dependencies between components in the model it systematically records other component failures that progressively contribute to this event. The logical structure of the tree is determined

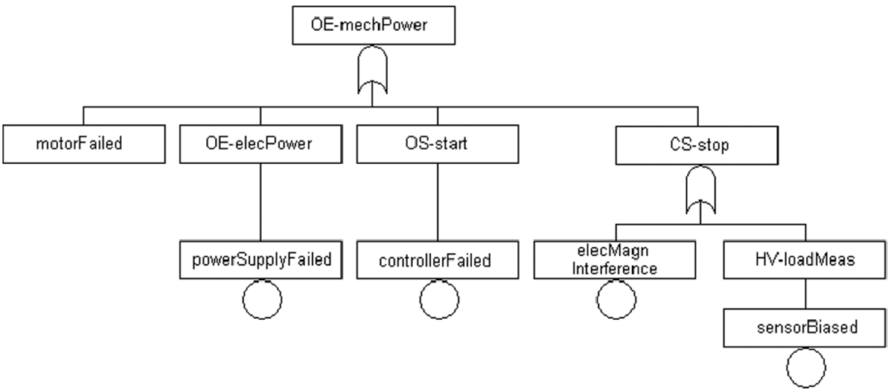


Fig. 5.4 Mechanically constructed fault tree for the example system

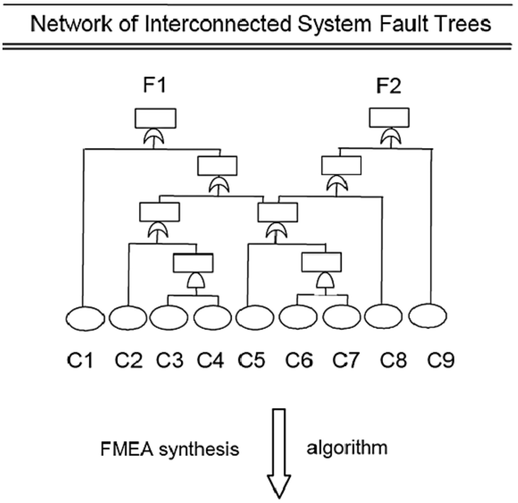
only by interconnections between the components and the local analyses of those components. This logical structure is straightforward and can be easily understood, unlike the structure of many manually constructed fault trees which is often defined by implicit assumptions made by analysts. Note that although in this example the tree only incorporates OR gates, other logical symbols such as AND and priority AND gates would appear in the tree structure if such relationships were originally specified in some of the local analyses.

5.2.5 Analysis Phase

In the final phase, the synthesised system fault trees are analysed, both qualitatively and quantitatively, and from these results the FMEA is created. Firstly, the fault trees undergo qualitative analysis to obtain their minimal cut sets, which reduces them in size and complexity. This is done using a mixture of classical logical reduction techniques, which usually means applying logical rules to reduce complex expressions, and more modern techniques, such as the use of Binary Decision Diagrams (BDDs), (Papadopoulos et al. 2001), to break down the tree into a simpler form. BDDs are graphs that represent the paths of failures through the fault tree, and are much faster and more efficient than classical methods, but unfortunately they cannot be used in all situations. Once the minimal cut sets have been obtained, they are analysed quantitatively, which produces unavailability values for the top events of each fault tree.

The last step is to combine all of the data produced into an FMEA, which is a table that concisely illustrates the results. The FMEA shows the direct relationships between component failures and system failures, and so it is possible to see both how a failure for a given component affects everything else in the system and also how likely that failure is. However, a classical FMEA only shows the *direct effects* of single failure modes on the system, but because of the way this FMEA is generated from a series of fault trees, the FTS tool is not restricted in the same way, and the FMEAs produced also show what the *further effects* of a failure mode are; these are the effects that the failure has on the system when it occurs in conjunction with other failure modes. Figure 5.5 shows this concept.

In Fig. 5.5, F1 and F2 are system failures, and C1–C9 are component failures. For C3, C4, C6 and C7, there are no direct effects on the system – that is, if only one of these components fail, nothing happens. However, they do have further effects; for example, C3 and C4 both occurring in conjunction will cause F1 to occur. The FMEAs produced, then, show all of the effects on the system, either singly or in combination, of a particular component failure mode. This is especially useful because it allows the designer to identify failure modes that contribute to multiple system failures (e.g. C5 in the example of Fig. 5.5). These common cause failures represent especially vulnerable points in the system, and are prime candidates for redundancy or extra reliable components.



Multiple Failure System FMEA		
Component failure	Direct effects on the system	Effects caused in conjunction with (other events)
C1	F1	-
C2	F1	-
C3	-	F1 (C4)
C4	-	F1 (C3)
C5	F1,F2	-
C6	-	F1,F2 (C7)
C7	-	F1,F2 (C6)
C8	F2	-
C9	F2	-

Fig. 5.5 The conversion of fault trees to FMEA

5.2.6 Optimisation Phase

HiP-HOPS analysis may show that safety, reliability and cost requirements have been met in which case the proposed system design can be realised. In practice, though, this analysis will often indicate that certain requirements cannot be met in which case the design will need to be revisited. This indeed is a problem commonly encountered in the design of reliable or critical systems. Designers of such systems usually have to achieve certain levels of safety and reliability while working within certain cost constraints. Design of course is a creative exercise that relies on the technical skills of the design team but also on experience and successful earlier projects. So the bulk of design work is creative. However, we believe that some further automation can assist the decision on the selection among alternative components or sub-system designs as well as on the level of replication of components in the model that is required to ensure that the system ultimately meets its set safety and reliability requirements with minimal cast.

A high degree of reliability and safety can often be achieved by using a more reliable and expensive component, an alternative sub-system design or by using replicated components or subsystems to ensure that functions are still provided when components or subsystems fail. In a typical design though, there are many options for substitution and replication at different places in the system and different levels of the design (component/subsystem). It may be possible for example to achieve the same reliability by substituting two sensors here and three actuators there, or by replicating a single controller, a control subsystem etc. Different solutions however will lead to different additional costs, and the question here is which is the optimal solution; it could be one for example that achieves a certain degree of reliability and safety with the minimum additional cost. Because the design options for replication in a non-trivial design are typically too many to consider it is virtually impossible for designers to address the above questions systematically, so people rely on intuition, or on evaluation of a few different design options. Some automation in that area would therefore be useful to designers in area.

In the present approach, this has been achieved by combining work on HiP-HOPS with recent advances in design optimisation (Papadopoulos and Grante 2005). More specifically, a tool that employs genetic algorithms in order to progressively "evolve" an initial design model has been developed which does not meet requirements to a design where components and sub-system architectures have been selected and where replicas have been allocated in a way that minimizes cost while achieving given safety and reliability requirements. In the course of the evolutionary process, the genetic algorithm typically generates populations of candidate designs which employ user-defined alternative implementations for components and subsystems as well as standard replication strategies. These strategies are based on widely used fault tolerant schemes such as *hot* or *cold standbys* and *n-modular redundancy* with majority voting. For the algorithm to progress towards an optimal solution, a selection process is applied in which the fittest designs survive and their genetic make up is passed to the next generation of candidate designs. The fitness of each design relies on cost and reliability. To calculate fitness, therefore, we need ways in which to automatically calculate those two elements. An indication of the cost of a system can be calculated as the sum of the costs of its components (although for more accurate calculations life-cycle costs should also be taken into account such as production, assembly and maintenance costs) (Grante and Andersson 2003). However, while calculation of cost is relatively easy to automate, the automation of the evaluation of safety or reliability is more difficult as conventional methods rely on manual construction of the reliability model (e.g. the fault tree, reliability block diagram or the FMEA). HiP-HOPS, though, automates the development and calculation of the reliability model, and therefore facilitates the evaluation of fitness as a function of reliability (or safety). This in turn enables a selection process through which the genetic algorithm can progress towards an optimal solution which can guarantee the required safety and reliability at minimal cost.

5.2.7 Tool Support

To enable application of the above concepts in engineering design, a prototype implementation of HiP-HOPS has been developed that extends the capabilities of Simulation X with new capabilities for automatic safety and reliability analysis. The architecture of this extension is illustrated in Fig. 5.6.

Simulation X provides a Graphical User Interface (GUI) that enables annotation of components in the model with the failure modes and failure expressions required for the fault tree and FMEA synthesis. These data become part of the model and are automatically saved and retrieved by SimulationX. Failure annotations are stored together with a component in component libraries and can be re-used either directly or following modifications within the same model or across different models with the obvious benefit of simplifying the manual part of the analysis. The second component of the tool is a parser that interprets an output file produced by SimulationX,

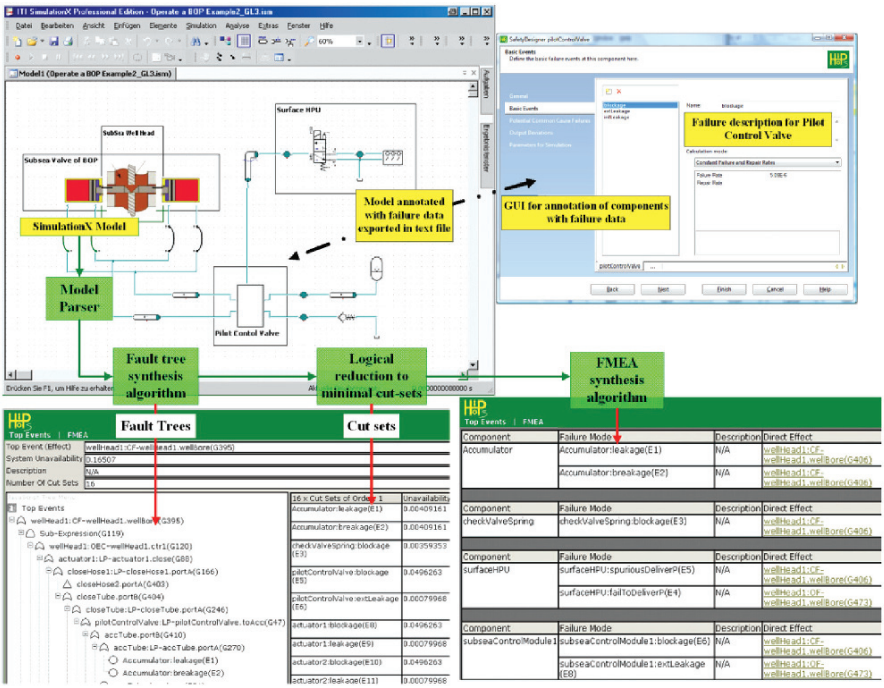


Fig. 5.6 Architecture of the automated safety analysis and optimization tool

and reconstructs the enclosed annotated models for the purposes of fault tree synthesis. The synthesis itself is performed by the third component of the tool, the fault tree synthesis algorithm. The resultant network of fault trees is then logically reduced into minimal cut-sets. Finally, an FMEA synthesis algorithm operates on these cut-sets, and in a single traversal of the cut-sets generates two FMEA tables. The first table is a single failure mode FMEA which shows, for each failure mode of each component in the system, the direct effects on the system. Further effects caused by conjunctions of component failure modes are shown in a second table which presents a lengthier and more detailed multiple failure mode FMEA analysis. In the current implementation of the algorithm, the synthesis of the FMEA is separated from the display of tables. Indeed, an FMEA store is first created in memory and then an HTML generator is used to parse this store and create web pages containing the tables of data. The advantages of this medium include easy distribution and display and the ability, through hyperlinks, to navigate different aspects of the information.

The tool is designed to recognise and handle loops in the model that create circular references to the same failure logic in fault trees (e.g. conditions such as: event A is caused by event B which in turn is caused by event A). When such circles are encountered, the failure logic contained in the circle is only incorporated once in the trees. At the same time, a note is made and the analyst is invited to think what happens in the steady state where it is always possible to decide what is the final effect to an output of an initiating fault further upstream.

To manage complex hierarchical models effectively, the synthesis algorithm was designed to perform traversals both across the vertical and horizontal axis of the design hierarchy. Indeed, the current implementation allows the annotation of hierarchical structures at all levels of the design. If, for example, a subsystem as a whole is susceptible to a failure mode, then the effect of this condition can be directly specified with a failure annotation at subsystem level. This annotation, for example, could define that all outputs of the subsystem are omitted in the event of the global disturbance. Such annotations would typically complement other annotations made at the level of the enclosed components to describe aspects of failure behaviour at this level (e.g. the mechanical and electrical failure modes of each component). In general, when examining the causes of a failure at an output of a sub-system, the fault tree synthesis algorithm creates a disjunction between any failure logic specified at sub-system level and logic arising from the enclosed lower levels.

The HiP-HOPS tool has also been extended with capabilities for reliability versus cost optimisation as these were described in Sect. 5.2.6. Optimization has been applied to a number of known benchmark problems with results that represent improvement to those reported in earlier works (Parker and Papadopoulos 2007). However, despite initial successes, it is still premature to comment on performance or make credible comparisons with earlier work, at least in terms of speed and scalability. However, we can identify at this point a few conceptual differences between our approach and earlier work. Earlier approaches to architectural optimisation, (Coit and Smith 1996, Deb 1999, Grunske 2006) for example, calculate reliability from manually constructed Reliability Block Diagrams in which systems are formed as a series-parallel configuration of components and it is assumed components and the system itself “work” or “fail” in a single failure mode which typically represents a complete loss of function.

The difference between the proposed approach and this earlier work is that, in our approach, the safety and reliability model (i.e. a set of automatically derived system fault trees) is not generated simply from the topology of the system, but from an engineering model which also includes information about the failure behaviour of components. In this model, components do not need to be in series-parallel configurations. The model for example may include bridges between parallel paths, hierarchically nested series and parallel connections as well as complex dependencies caused by control loops. Perhaps a more significant departure from earlier work is that the present basic failure assumption goes beyond the classical “success-failure” model. Indeed, in the present approach, components can exhibit more than one failure modes which include the “loss” but also the “commission” of functions as well as “value” and “timing” failures. These more realistic failure assumptions should help to improve the quality of the solutions reached by this type of analysis.

Acknowledgments Section 5.2 was compiled by Dr. Y. Papadopoulos (University of Hull), based on work jointly conducted within the project SAFEDOR with Dr. R. Hamann (Germanischer Lloyd), Dr. Andreas Ulhlig (ITI) and their colleagues.

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5.3 Collisions and Groundings

5.3.1 Introduction

The focus is herein on two aspects; (1) events that lead to a collision or grounding, (2) damage to the ship after a collision or grounding.

For addressing the first part two Bayesian networks are set up. These describe the interdependencies and joint probabilities in chain of events that lead to a collision or grounding. The input is a given scenario: traffic intensity, area complexity, bridge layout etc. and the output is then the probability that the ship will have a collision. The networks seem to give good qualitative results but the absolute probabilities of collision or grounding seem slightly too high.

The second part calls for an artificial neural network, which is trained with a large number of collision cases and thereby is able to predict new collision cases. The network estimates the training data very well. When estimating the collision penetration for ships not used for training the results are a bit more ambiguous. But for collision speeds in the range 0–12 knots the results are reasonable. Finally, a similar network to predict the damage after grounding was also developed and implemented.

5.3.2 Risk Model for Obtaining the Causation Probability

This section discusses how to model the chain of events that leads to a ship collision or grounding. It suggests using Bayesian network instead of the traditional event-trees. A simple Bayesian network for calculating the collision probability of two ships is presented. The result is compared to observed values of the causation factor. A more detailed approach for collision and grounding is sketched. The results of these more detailed models are not very satisfactory. One reason being, that they need a lot of knowledge about the causal relationships between the different variables. However the models behave qualitatively as expected. Meaning they increase or decrease the probability of an event when variables like weather or navigational aids are changed.

It is virtually impossible to formulate a full risk analysis that properly takes all relevant aspects into account. The modelling should, however, account for a subset as large as possible of the potential error mechanisms. This section describes the traditional risk analytical approach for obtaining the causation probability. We discuss the drawbacks of the traditional formulation and suggest applying Bayesian Networks for the analysis. The subsequent section describes aspects that should be considered in the modelling.

5.3.2.1 Traditional Approach

The traditional approach for calculation of the causation probability P_c (i.e. analysing the cause leading to human inaction or external failures) is to formulate a fault tree or an event tree analysis, see Haugen (1991), as shown in Fig. 5.7.

From this fault tree it is found that the causation probability P_c can be expressed as

$$P_C = X_A + (1 - X_A)X_{C1}X_{C2} \tag{5.1}$$

where

X_A is the probability of human failure
X_{C1} is the probability of radar failure, which will depend on vessel size, age, nationality, etc.
X_{C2} is the fraction of the year with low visibility.

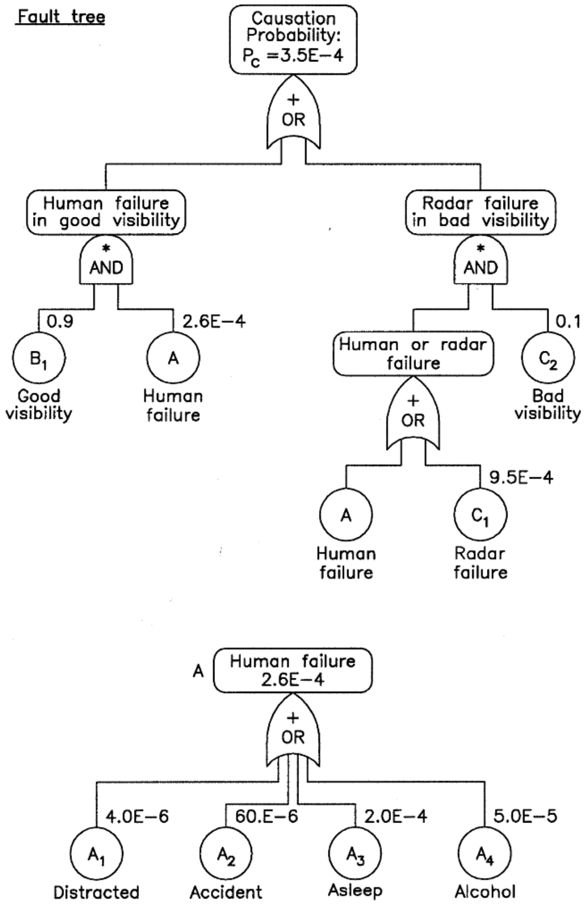


Fig. 5.7 Fault tree for causation probability P_c for collision against fixed object

By application of such fault tree analyses for estimation of the causation probability, it is possible to examine the beneficial effect of new bridge procedures, of having a pilot on board, or of introducing a VTS system in certain geographical areas. Olsen et al. (1992) studied the effect of a VTS system by an event tree analysis.

When inspecting the above fault tree it is questionable whether the modelling actually captures any of the important failure mechanisms relevant for the considered critical situation. Factors that relate to navigational complications are not included in the analysis, although these are of importance for the relevant set of human errors. Moreover, it is seen that human failure contributes with 75% $(2.6 \cdot 10^{-4})$ to the causation probability. The dominance of the human failure is in agreement with observations. However, the "Asleep" node is the dominant contributor $(2.0 \cdot 10^{-4})$ and it accounts for 60% of the causation probability. Although the dominating cause may be attributed to human errors this does not seem to be correct as high vigilance is expected in confined navigational areas. An important concern of the fault tree modelling is that the human factor model does not properly capture the relevant tasks that must be considered in the analysed critical situation.

5.3.2.2 Using Bayesian Networks

Most practical risk analysis problems are characterised by a large set of interrelated uncertain quantities and alternatives. Within the conventional risk analysis different methods such as fault tree analysis and event tree analysis have been developed to address these problems. A fault tree analysis seeks the causes of a given event, and an event tree analysis seeks the consequences of a given event. The two analysis techniques are supplementary methods, and when applied correctly the formulated model may reveal the entire probability structure of the model. Both fault tree analysis and event tree analysis – applied separately and combined – have in the past with success been used in the evaluation of the risk of various hazardous activities. Unfortunately, both fault tree and event tree analyses do have their drawbacks. Firstly, it is difficult to include conditional dependencies and mutually exclusive events in a fault tree analysis (a conditional dependency is, for example, the dependence of the visibility on the weather; mutually exclusive events are, for example, good weather and storm). If conditional dependencies and mutually exclusive events are included in a fault tree analysis the implementation and the pursuing analysis must be performed with utmost care. Secondly, the size of an event tree increases exponentially with the number of variables. Thirdly, if the analysis should capture the primary failure mechanism, the global model, which is combined fault trees and event trees, generally becomes so big that it is virtually impossible for third parties (and sometimes even for first parties) to validate the model.

Here we advocate the use of Bayesian Networks as the proper risk modelling and analysis tool. A Bayesian Network is a graphical representation of uncertain quantities (and decisions) that explicitly reveals the probabilistic dependence between the set of variables and the flow of information in the model. A Bayesian Network is designed as a knowledge representation of the considered problem and may therefore be considered as the proper vehicle to bridge the gap between analysis and formulation.

A Bayesian Network is a network with directed arcs and no cycles. The nodes (to which the arcs point) represent random variables and decisions. Arcs into random variables indicate probabilistic dependence, while arcs into decisions specify the information available at the time of the decision. As an example, one node in the network may represent the weather, whereas another may represent the visibility. An arc from weather to visibility indicates that visibility is conditionally dependent on weather; see Fig. 5.8. The diagram is compact and intuitive, emphasising the

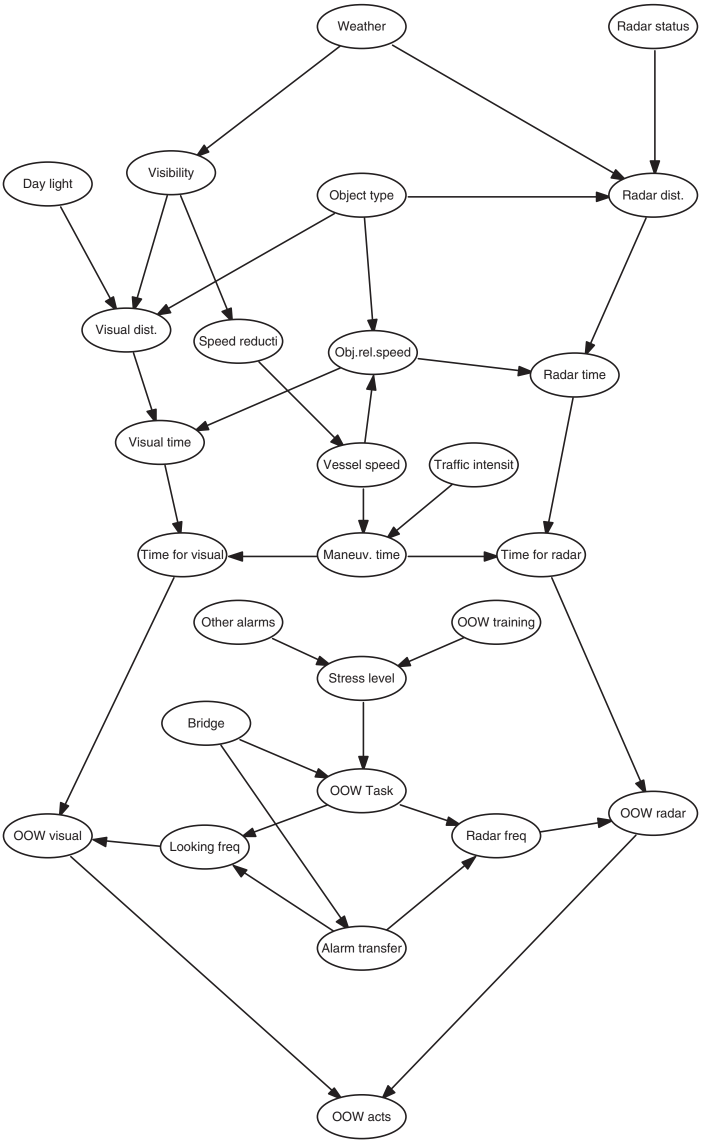


Fig. 5.8 Example for Bayesian Network for a navigating officer reacts in the event of being on collision course with an object, from Friis-Hansen and Pedersen (1998)

relationship among the variables, and yet it represents a complete probabilistic description of the problem. For example, it is easy to convert any event tree or fault tree into a Bayesian Network. Conversely, it may not always be an easy task to convert a Bayesian Network into a combined fault tree and event tree, although theoretically possible.

A drawback of Bayesian Network is that they require the state space of the random variables (the nodes) to be defined as discrete states. In our above-mentioned example of weather and visibility, the state space of weather may easily be discretised into states as good weather, storm, etc., whereas the state for visibility more naturally would have been defined as a continuous state space. The Bayesian Network modelling does, unfortunately, require the state space of visibility to be discretised in ranges as for example, 0–1 nautical miles, 1–2 nautical miles, etc. Although this is mentioned as a drawback, neither fault trees nor event trees offer any better alternatives. A consequence of the discretisation is partly that the result of the Bayesian Network may be sensitive to the selected discretisation, and partly that the calculations involved in the evaluation of the Bayesian Network grow almost exponentially with the number of states of the nodes as it address the entire probabilistic structure of the problem.

A focus on the causal relationship among the variables is most effectively accomplished by the building of a Bayesian Network. This implies that a Bayesian Network becomes a reasonably realistic model of the problem domain, which is useful when we try to get an understanding about a problem domain. In addition, knowledge of causal relationships allows us to make predictions in the presence of interventions. Last, but not least, the model building through causal relationship makes it much easier to validate and convey the model to third parties. We will not give any details here on how Bayesian Networks are analysed. Instead reference is left to Jensen (1996) and Pearl (1988).

The Bayesian Network described above is taken from Friis-Hansen and Pedersen (1998) where a comparative risk evaluation of traditional watch keeping and one-watch keeping has taken pace. The results of the modelling were compared to observations, and good agreement was obtained. Here we extend this modelling to also cover ship-ship collisions.

5.3.2.3 Bayesian Network for Ship-Ship Collisions

The network for predicting the causation factor for ship-ship collisions is rooted in the network shown in Fig. 5.8. The Bayesian Network was extended to model two ships, i.e. ship-ship collision situations. The network used for this analysis is presented as Fig. 5.9. It is seen that this Bayesian Network takes into account the correlation between the two vessels, that is, they have to detect each other under the same conditions. Although the network appears complicated, the elements from the basic network in Fig. 5.8 are recognised. It is noted that the two more isolated groups in the lower part of the network models the behaviour on the two bridges,

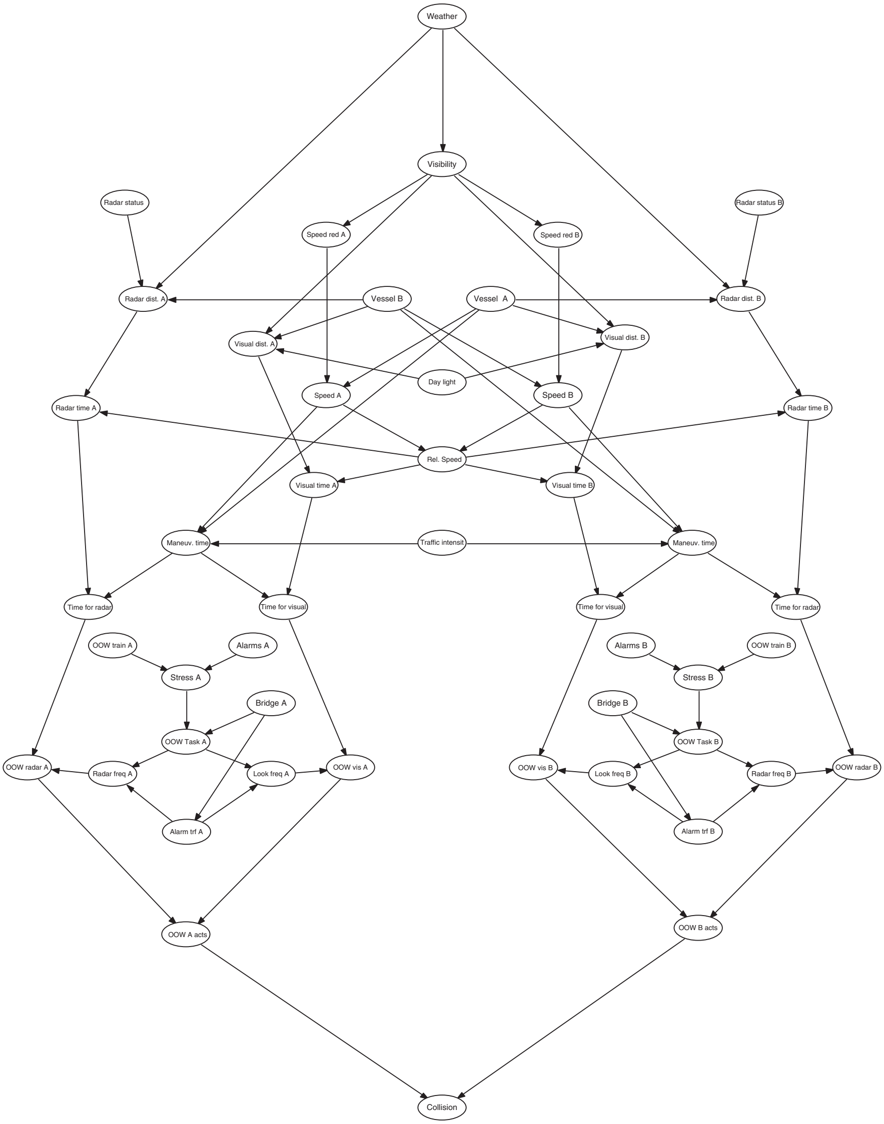


Fig. 5.9 Bayesian Network model for ship-ship collisions accounting for the correlation between the two vessels

whereas the central group in the upper part of the figure models that the two vessels have to be detected by each other.

From the Bayesian Network the calculated causation factor for meetings between conventional vessels is found to be

$$P_c = 9.00 \cdot 10^{-5}.$$

Table 5.1 Causation probabilities. (Fujii and Mizuki 1998)

	Log P	±	P
Head-on	−4.31	0.35	$4.90 \cdot 10^{-5}$
Overtaking	−3.96	0.36	$1.10 \cdot 10^{-4}$
Crossings	−3.89	0.34	$1.29 \cdot 10^{-4}$
Grounding	−3.80	0.26	$1.59 \cdot 10^{-4}$
Object	−3.73	0.36	$1.86 \cdot 10^{-4}$

Table 5.2 Weighing factors for headings

Factor	P · f
0.5	$2.45 \cdot 10^{-5}$
0.25	$2.74 \cdot 10^{-5}$
0.25	$3.22 \cdot 10^{-5}$

This value can be compared with observed causation probabilities determined from large data sets published by Fujii and Mizuki (1998). These observed values are given in Table 5.1. In Table 5.2 the different headings have been weighed to obtain one global causation factor. The result is that the observations indicate that the causation factor is close to

$$P_c = 8.41 \cdot 10^{-5}$$

That is a factor which is very close to the causation factor $P_c = 9.00\ 10^{-5}$ calculated by the Bayesian Network procedure for conventional vessels operating in geographical areas where the frequency of visibility less than 1 km is 3%.

The modelling illustrates that it indeed is possible to establish a realistic modelling of the causation probability.

5.3.3 Factors that Influence the Causation Probability

As seen from the Bayesian Network analysis of the ship-ship collision above, it is indeed possible to accurately model the causation probability. It is, however, very important that the level of detail in the model is at a satisfactory level such that the results of the model become plausible. In this section we list some of the factors that influence the causation probability.

5.3.3.1 Reported Causes for Grounding and Collision

Several researchers have published reports on causes for marine accidents. All studies define that the cause of a grounding or collision may be summarised crudely into the following four main groups:

1. Due to failure in manoeuvring, including inaccurate positioning and poor lookout.
2. Due to incapacitation of personnel such as doze, drunkenness engaged in other tasks and sudden illness. Doze has been identified as one of the main causes for grounding.
3. Due to technical problems with engine, steering gear, or navigational instruments.
4. Due to environmental causes, such as visibility, wind, or waves.

Group 1 and 2 in the list above represent the contribution from human errors. Unquestionable, human error is an important cause to navigational accidents – perhaps dominant, as it is quoted that human errors account for at least[1] 80% of all accidents. More precisely it could be stated that approximately 80% of navigational accidents involves at least some human errors or questionable judgements related to organisational factors. What complicates the assessment is that the blame (or cause) for an accident can be allocated in different ways according to the perspective of the investigator. Typically serious accidents start from basic human errors but the seriousness of the accident is rather a compound of a set of technical failure, operators' error, fundamental design errors, and management errors.

Therefore, any realistic modelling must provide a detailed representation of human error in order to be successful. Unfortunately, the human error mechanisms differ from technical or environmental cause (viz. the remaining 20%), and are – in fact – not yet well understood. A major problem in this respect is that there exists no such thing as a recipe for doing a specific task in the right way (e.g. performing a turn). In an examination of a series of manoeuvring simulations that have led to a grounding accident, (Thau 1999, Personal Communication, Danish Maritime Institute, Denmark) found that the primary human error leading to the accident often occurred more than 10 min prior to the accident. Contrary, technical or environmental causes are generally simpler to model and understand.

5.3.3.2 Human and Organizational Errors

Human errors can be described as actions taken by individuals that can lead an activity (design, construction, and operation) to realise a quality lower than intended. Human errors also include actions *not* taken, as these also may lead to an activity causing a quality lower than intended. Many people typically think of human error as "operator error" or "cockpit error", in which the operator makes a slip or mistake due to misperceptions, faulty reasoning, inattention, or debilitating attributes such as sickness, drugs, or fatigue. However, there are many other important sources of human error. These includes factors such as management policies which pressure shipmasters to stay on schedule at all costs, poor equipment design which impedes

[1] Some researchers even argue that 100% of all accidents are due to human error, since poor man-machine interface, failure of instrumentation (should have been checked more properly), under design, etc. all may be attributed to some sort of human error. Note that any design, construction and fitting are the result of human decisions.

the operator's ability to perform a task, improper or lack of maintenance, improper or lack of training, and inadequate number of crew to perform a task.

The human error factors range from those of judgement to ignorance, folly, and mischief. Inadequate training is the primary contributor to many of the past failures in marine structures. Also boredom has played a major role in many accidents. Based on a study by Bea (1994) of human error factors in marine engineering the following primary factors were identified:

Inadequate training	Carelessness	Ego
Physical limitations	Wishful thinking	Laziness
Inadequate communication	Ignorance	Greed
Bad judgment	Negligence	Alcohol
Fatigue	Folly	Mischief
Boredom	Panic	Violations

Organisational errors are a departure from acceptable or desirable practice on the part of a group of individuals that cause unacceptable or undesirable results. Primary organisational error factors include, (Bea 1994):

Ineffective regulatory requirements	Complex structure	Violations
Poor planning/training	Cost-profit incentives	Ineffective monitoring
Poor communications	Time pressures	Ego
Low quality culture	Rejection of information	Low worker morale

For example, the goals set by the organisation may lead rational individuals to conduct certain operations in a manner that the corporate management would not approve if they were aware of their reliability implications. Similarly, corporate management, under pressures to reduce costs and maintain schedules, may not provide the necessary resources required allowing adequately safe operations.

Other types of organisation and management procedure that affect the system reliability include, for example, parallel processing such as developing design criteria at the same time as the structure is being designed – a procedure that may not be appropriate in economic terms according to the costs and uncertainties.

5.3.3.3 Human Error Evaluation

To date, four methodologies have been developed or adapted for maritime use. These are:

1. The operator function model (OFM) task analysis
2. Cognitive task analysis
3. Skill assessment
4. Error analysis

The OFM task analysis, developed in 1986 by Mitchell and Miller, see e.g. Rasmussen and Whetton (1993), provides a breakdown of a function (such as avoiding collisions with neighbouring vessels) into the tasks that must be performed. This also includes the information needed to perform each task, and the decisions that direct the sequence of tasks. This type of task description is independent of the automation; that is, the same tasks, information, and decisions are required, regardless of whether they are performed by a human or by a machine. For example, in collision avoidance, other vessels must be detected, their relative motions analysed to determine whether there is a threat of collision, and a decision made regarding how to change own ship's course or speed in order to avoid a potential collision. These tasks must be performed regardless of who (human or machine) executes them.

The cognitive task analysis method extends the OFM by considering the mental demands that would be placed on a human operator while performing tasks. For example, in order for a human to detect a new ship as soon as it appears, vigilance (sustained attention) and discrimination (the ability to spot a target against the background) are required. The mental demands of analysing the relative motion of the target vessel include plotting a series of target ranges (distance) and bearings (its angular position relative to own ship) and evaluating the ratio of change over time. Hollnagel (1996) introduced a task transaction vocabulary that categorises mental demands, such as "search", "detect", "code", "interpret", and "decide/select". Assigning the appropriate OFM tasks to humans or machines can thereby represent different levels of automation. Then the cognitive impact of automation can be identified by comparing the number and types of cognitive demands placed on the human operator under the different levels of automation. For example, Froese et al. (1996) found that when collision avoidance by manual methods was compared to the use of ARPA radar, then virtually all of the computational demands of the manual method were eliminated through automation.

In order to evaluate the impact of automation on training requirements, a skill assessment technique was developed at US Coast Guard by combining the OFM and cognitive task analyses with the Knowledge, Skills, and Abilities (KSA) analysis. The skill assessment is performed by taking each cognitive task (from the OFM/cognitive task analysis) and determining what types of knowledge or skill is required for the proper performance of a task. The hybrid analysis thereby focuses on the knowledge and skill assessment at the task level. For example, when comparing the manual task in collision avoidance of plotting target range and bearing to the automated scenario that displays target information on the ARPA, then the basic knowledge requirements of collision avoidance do not change with automation. However, the procedural requirements change radically. That is, the mariner has to understand the theory behind collision avoidance regardless of the level of automation, but the specific set of procedural knowledge and skills the mariner needs is dependent on the level and type of automation. Application of the described skill assessment technique has allowed both US Coast Guard and Schraagen et al. (1997) to distinguish changes in skill level as a result of automation.

The studies by Froese et al. (1996) and Schraagen et al. (1997) conclude that the way an automated system is designed can also affect the mariner's performance.

Some automation "hides" information from the mariner, presenting only what the designer thought was needed. Unfortunately, many system designers do not fully understand the user's task, and consequently we end up with less-than-perfect, error inducing designs. By studying the types of errors commonly made by operators, and by understanding the ramifications of these errors (i.e., are they just nuisance errors or can they cause an accident?), important information is gained that further can be used in training and system redesign. Both error analyses adopted in these references consisted of interviewing mariners and instructors, and observing the use of automation during routine shipboard operations.

5.3.3.4 A More Detailed Collision Approach

In Fig. 5.10 a sketch of the starting point of a more detailed collision approach model is seen. The idea is that our own vessel is on collision course with an object. Given the weather condition we can calculate when it is possible to see the object either visually, by radar or by AIS. Knowing the speed of the two vessels and the angle between them we can calculate the relative speed and the therefore the time available, T_a, before a collision. Now the officer on the watch has to detect the collision danger this takes T_d. Then a plan has to be made which takes T_p. At last, a manoeuvre must be made which takes T_m to perform. If $T_a - T_d - T_p - T_m$ is less than zero then a collision occurs.

Given a number of specified input variables and a weather condition, a collision scenario is setup, Fig. 5.11. In this, the time available before a collision occurs is calculated. In the *Time for Detection network* the time it takes the navigator to detect a collision danger is estimated. This depends on the vigilance of the navigator and on the bridge layout. From the collision scenario a *Collision Diameter* is also established and based on this the time the ship has in order to do a manoeuvre to avoid the collision is calculated. When the collision danger is detected the navigator has to make a plan to avoid the collision. The time for this is calculated in the network *Time for Planning*. At last it can be determined if a collision happens or if there is time to avoid it. In short the network calculates the surplus time before a collision occurs.

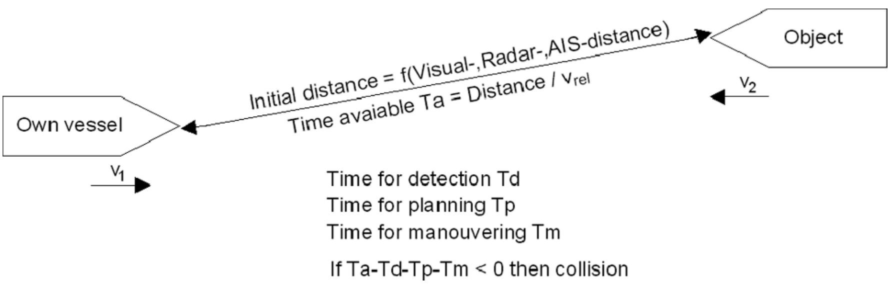


Fig. 5.10 Sketch of the collision scenario

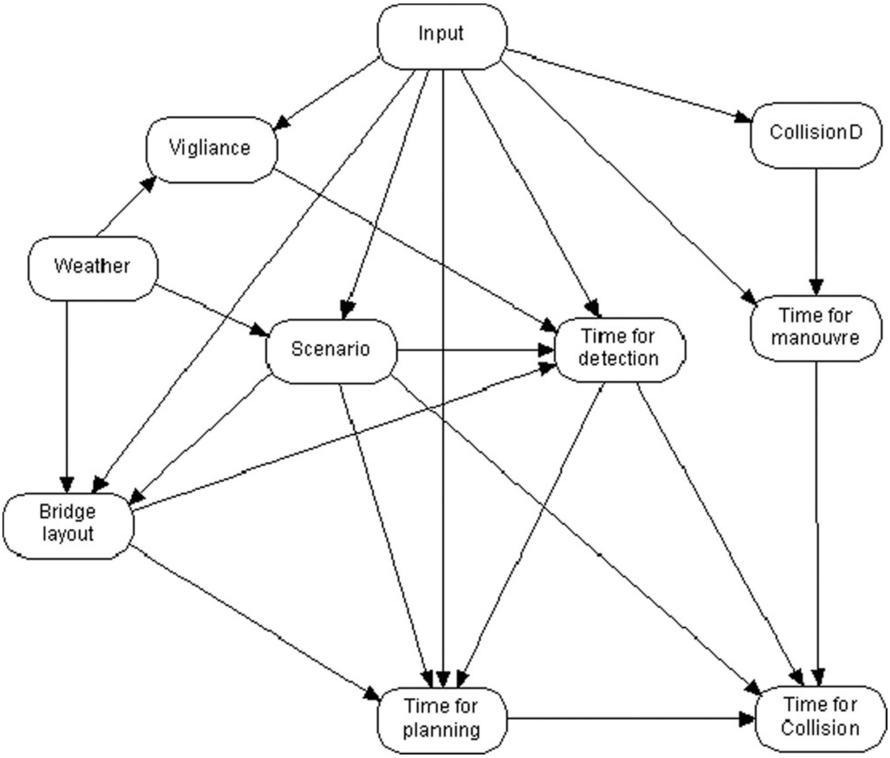


Fig. 5.11 Bayesian Network of the collision model. Each rectangle represents sub networks

In the following examples, there are two ships sailing head-on between 0–30°. The network needs information as regard to the area, traffic, bridge layout, competence of the crew and so fourth. These are not specified here. In Fig. 5.12 the result from the network analysis is shown given different initial distances and speed of the ships.

The figure shows for instance that if the two ships sail between 5–10 knots and the initial distance between them is 0.6–1.25 nautical miles then the probability of a collision is 46.8%. The figure shows that the network behaves correctly, but the probabilities of collision are higher than should be expected.

5.3.3.5 A Similar Approach for a Grounding Model

In the following, a sketch of a more detailed grounding model is presented. The idea is that our own vessel is on grounding course with an obstacle. Given the weather condition we can calculate when it is possible to see the object either visually, by radar, by AIS, by ECDIS or by an echo sounder alarm. Knowing the speed of our ship we can calculate the time available, T_a, before grounding. Now the

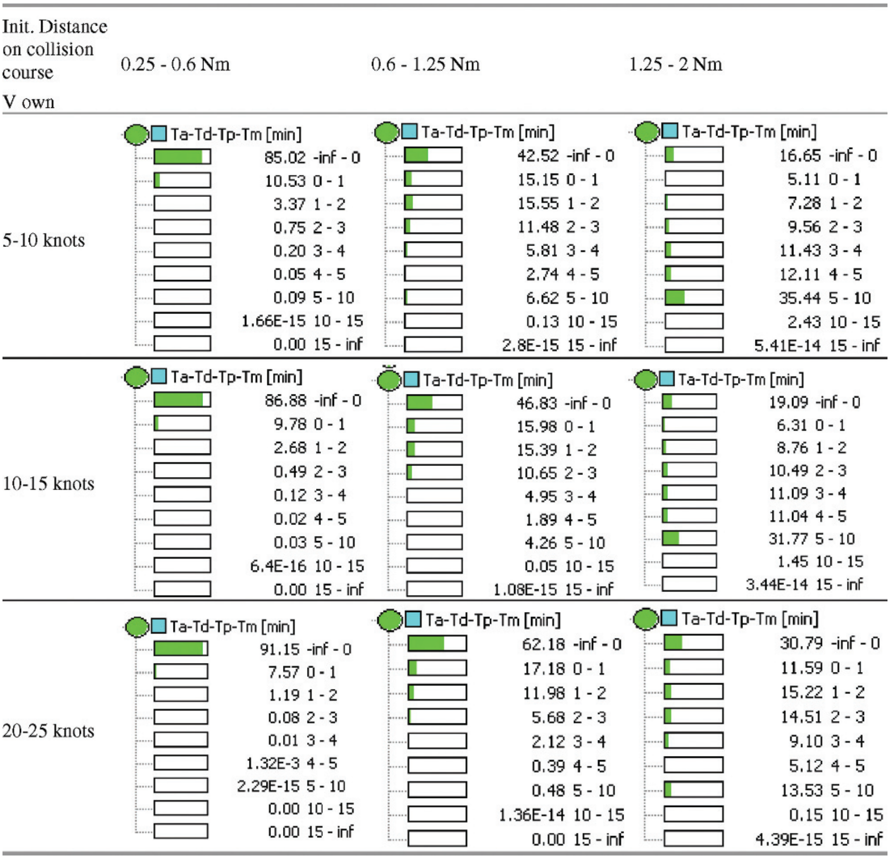


Fig. 5.12 Examples of result from the collision network

officer on the watch has to detect the grounding danger, this takes T_d. Then a plan has to be made which takes T_p. At last a manoeuvre must be made which takes T_m to perform. If $T_a - T_d - T_p - T_m$ is less than zero then grounding happens. This is sketched in Fig. 5.13.

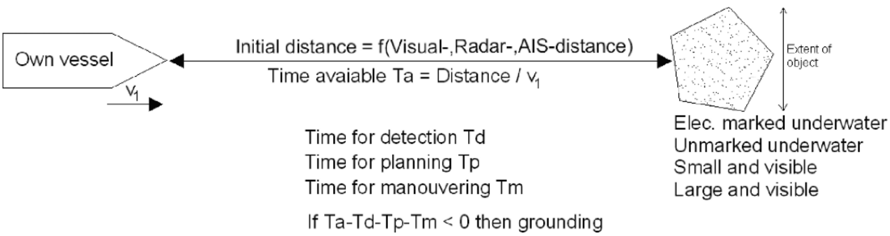


Fig. 5.13 Sketch of the model for calculating if grounding occurs

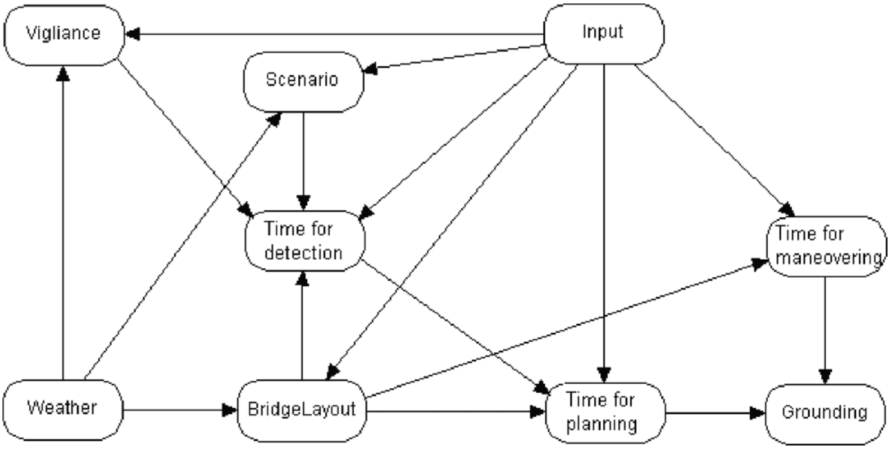


Fig. 5.14 Bayesian Network of the grounding model. Each rectangle represents sub networks

An overview of the entire model is shown in Fig. 5.14. Each rectangle represents a sub network with several input and output nodes. Given a number of *input* variables and a *weather* condition, a collision scenario is setup. In the scenario network the time available before grounding occurs is calculated. In the *Detection the time* network the time the navigator takes to detect a grounding danger is estimated. This depends on the vigilance of the navigator and of the bridge layout. When the grounding danger is detected the navigator has to make a plan to avoid the grounding. The time for this is calculated in the network *Time for planning*. The manoeuvring time to avoid the grounding is calculated in the *Time for manoeuvring* network. At last it can be determined if grounding happens or if there is time to avoid it.

The result of the grounding network could be something like that depicted in Fig. 5.15. Here we see the times available in the different phases. The overall result is that for this particular scenario the grounding probability is 40.46%. The probability of having between 0 and 1 min is 4.94%. The specific scenario is not shown here, as the objective has been herein only to sketch the grounding model.

Overall the grounding network presented here behaves correctly, meaning that increases or decreases in parameters, result in the correct increase or decrease in the grounding probability. The actual values of the grounding probability seem however to be too high.

5.3.4 Damage After a Collision

Finally an approach for estimating the collision damage to a struck ship is presented. The method involves calculating a large amount of collision damages and then training an artificial neural network to predict these damages. The input to the neural network is a few parameters on the striking and struck ship such as the size and speed.

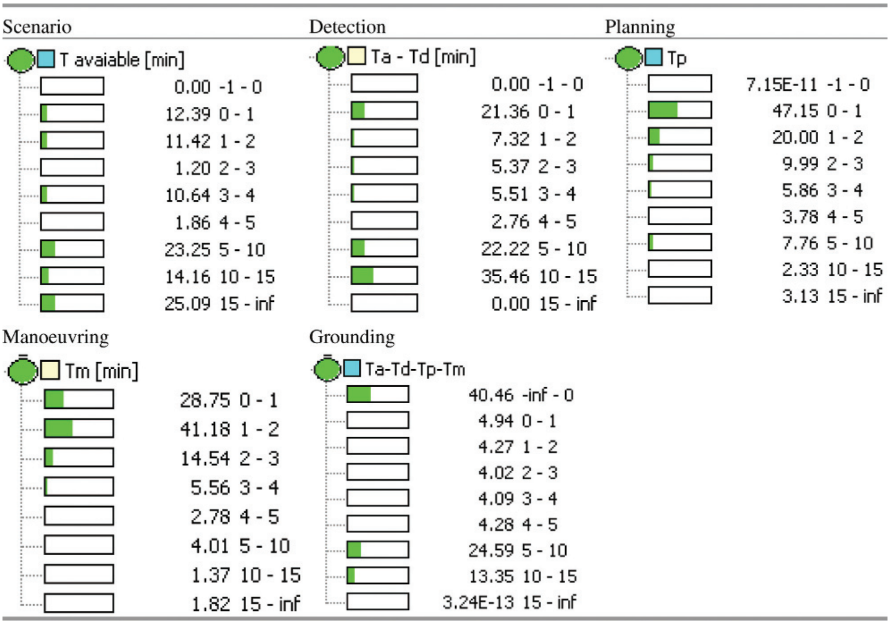


Fig. 5.15 Example of result from the grounding network

Risk consists of likelihood and consequence. When performing a risk analysis these two issues must be addressed. In case of ship collision and grounding the consequence could be the size of the damage to the struck ship (the striking ship is assumed not to be seriously damaged). The most accurate way for calculating the damage is using structural finite element (FEM) procedures. The drawback of this is that setting up a FEM model and doing the non-linear calculations is very time consuming. Another method is semi-analytical. This is relatively fast, a ship scenario can be set up within half an hour and the actual calculation takes seconds. The results are good compared to real cases.

For risk analysis where hundreds or thousands of damage scenarios are needed the semi analytical method is still slow and time consuming to set up. The idea has been to train an artificial neural network (ANN) with already calculated damage scenarios and then use it to predict damages for other ships. The advantage of a neural network is that it is fast and simple to implement. The disadvantage is that it might not come up with a correct answer if no similar data exists.

5.3.4.1 Data Used for Training the ANN

An illustration of the collision scenario has been sketched in Fig. 5.16. Depending on the existence of a bulbous or no bulbous bow on the striking ship the result is one or two damage holes.

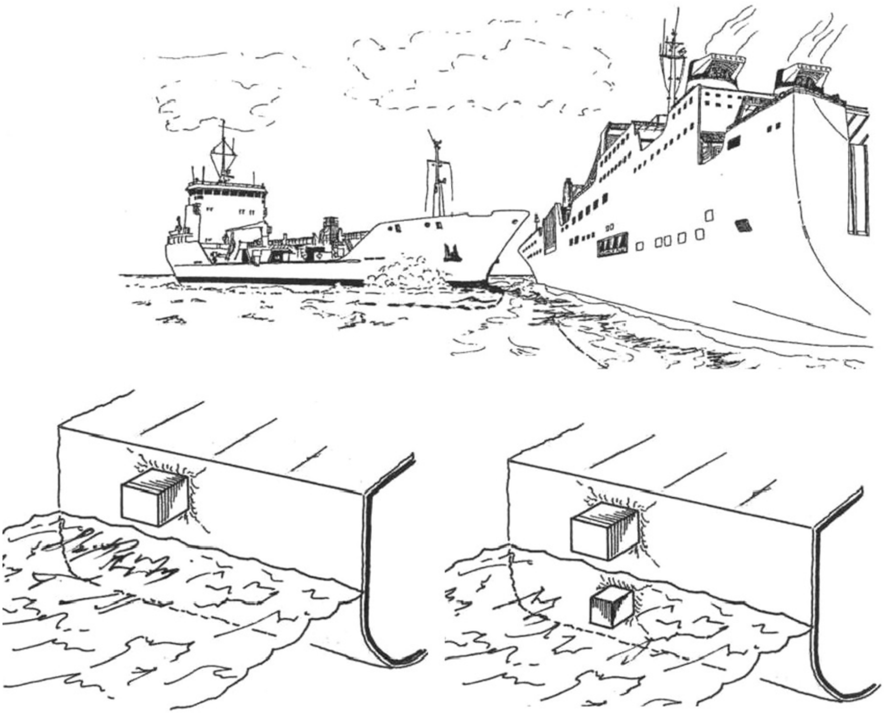


Fig. 5.16 Illustration of damage when the striking vessel is equipped with or without bulbous bow

Two collision networks were trained with results published in the open literature. In the first the striking ship has a bulbous bow and in the second not. The input to the neural network is then the values given in Table 5.3.

From the input listed in Table 5.3, the bulbous bow network calculates the damage outcome given in Table 5.4. In this table, the first column is the penetration divided with the breadth of the struck ship. The second column is length of the

Table 5.3 Inputs to the artificial neural network

Energy [kJ]	Angle	Lpp struck	Lpp striking	Draught striking
38948	150	180	160	9.2

Table 5.4 Inputs to the artificial neural network

Pen/B	dxU/L upper	dzU	zU	dxL/L lower	dzL	zL
0.098	0.112	3.57	14.8	0.003	1.93	2.6

upper hole divided by the length of the struck ship. The third column is the height of the upper hole and the fourth column is the vertical location of the upper hole. The three last columns refer to the lower damage hole created by the bulb.

5.3.4.2 Validation of the Neural Network

The network predicts its training data extremely well. In Fig. 5.17 the penetration prediction of the training data are shown for the case of ships without a bulbous bow. It is seen that network predicts the smooth blue line very well.

The network has also been tested on ships that were not used in the training. Here the results are more ambiguous. Figure 5.18 shows an example of this. Here the penetration for a new RoRo ship is shown as a function of the speed of the struck ship. The penetration calculated by a semi analytical method is also shown. It is seen that up to 10–12 knots the calculated penetration corresponds well to the penetration from the semi analytical approach. But above this speed it starts to deviate seriously. This trend is also found for other ships. Hence, for speeds below 12 knots the network can be used for rough estimates of the damage after collision.

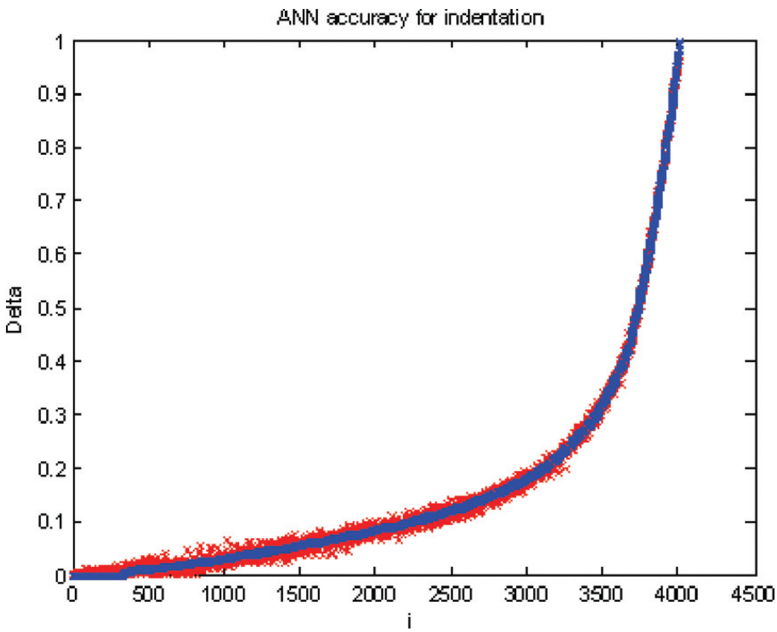


Fig. 5.17 Accuracy of the penetration prediction. The smooth thick blue curve corresponds to the training data. Red x are the predictions. Non-bulbous network. The *x*-axis is the scenario number

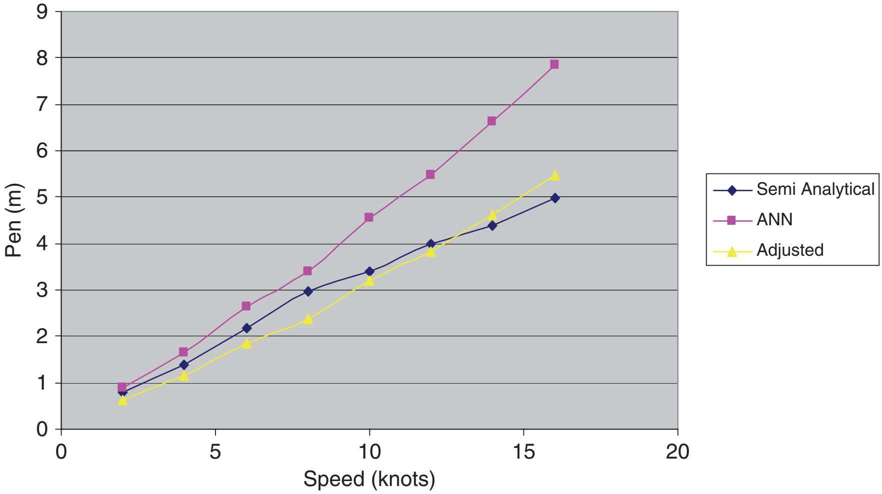
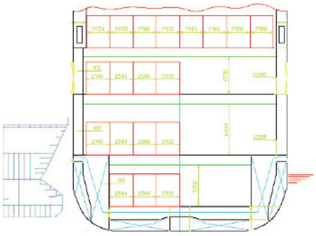


Fig. 5.18 Predicted penetration for a ship not used in the training of the ANN

Table 5.5 Data for the two ships in Fig. 5.17

	Striking	Struck
Length pp	85.0 m	190.3
Breadth	13.6 m	26.50
Draught	5.7 m	6.95
Displacement	5700 t	22600



A line with the ANN adjusted is also shown, but lacks generality and will not be discussed herein further (Table 5.5).

5.3.4.3 Conclusion for the Collision Network

An artificial neural network has been established for predicting the size of damage after collision of two ships, where the struck ship is a RoRo vessel. The striking ship, with or without a bulbous bow, hits the struck ship in the side and creates one or two holes modelled as rectangular boxes. Here the focus is on getting the penetration correctly, as the other dimensions of the box can be estimated from the size of the striking ships bow.

The network estimates the training data very well. When estimating the penetration of ships not used for training the results are a bit more ambiguous. But for collision speeds in the range 0–12 knots the results of the uncorrected network are reasonable. The speed of the striking ship should in general be equal to the speed of the struck ship. However, if the struck ship's speed is zero the network still gives good results.

The parameter studies performed show that the network behaves well in most cases. The network did not show a very strong correlation between the size of the striking ship and the penetration into the struck ship.

Acknowledgments Section 5.3 is written by Dr. E. S. Ravn, based on information from work of Peter Friis-Hansen, Preben Terndrup Pedersen and Erik Sonne Ravn.

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5.4 Structural Failure

During the last decades there have been considerable developments of methods and tools for structural reliability assessment, as reviewed by Rackwitz (2001) and to be found in textbooks as e.g. Madsen et al. (1986).

The applications of these methods have varied in different areas of engineering. They were first applied in civil engineering where the most notable advances were registered both in the area of research as well as in their use in construction codes and regulations. Reliability methods and risk analysis have long been used in the offshore industry, being introduced into the regulations governing design and construction of offshore platforms. The maritime industry has been slower in adopting these methods but recently studies can already be found on specific aspects and a general implementation of these methods to various aspects of ship design is underway.

The application of structural reliability to the analysis and design of structures developed in complexity and detail at the same as the reliability methods were evolving. The first formulations proposed by Mansour (1972) and Mansour and Faulkner (1973) basically contemplated one variable which represented the loads derived from all cargo on the structure and another variable that represented the strength of the structure. Only with the development of the First Order Reliability Methods (FORM) (Rackwitz and Fiessler 1978) it was possible to progress and start to deal with problems relevant to engineering. These methods evolved to efficiently solve the problems of many variables by computational means, to take into consideration information about the type of probabilistic distribution of each variable and even to solve series, and parallel, systems of various components. There were also appreciable advances in efficient methods to reduce the variability of the results obtained from Monte Carlo simulations, which came to be utilized as an alternative, or as a complement to first order methods.

This set of methods operates with random variables, which keep therefore their properties constant during the lifetime of the structures. Therefore, the set of problems which are solved by this type of methods have become known as time-invariant methods.

This designation appeared in contrast to time-variant methods, which recognize that random variables vary in time and in reality they are random processes. This type of model describes, for example, components subject to degradation or corroding or loads which vary significantly in time. Typically these models allow the representation of the effect of structural degradation and of repairs which serve as the basis to establish policies of maintenance or of structural design bearing in mind their future maintenance.

Currently, structural reliability methods are used mainly to evaluate the implicit reliability level of ship structures for different failure modes with the state-of-the-art models and representative uncertainty measures, and to calibrate design formats where a consistent reliability level is required.

The reliability index obtained by a structural reliability analysis is a nominal value, dependent on the analysis models and uncertainties included, rather than an absolute reliability value, which maybe given a frequency interpretation. Therefore the calculated reliabilities can only be compared when they are based on similar assumptions with respect to analysis models and uncertainties taken into account. In this context an important application the structural reliability methods is on the assessment of the notional probability of structural failure that result from different ship types as well as from different actual concepts of the same ship (Guedes Soares and Teixeira 2000). More recently structural reliability analysis has been used to assess the safety level of damaged ships structures due to accidental events, as to be discussed at the end of this section.

One of the main applications of the structural reliability methods has been as a tool for codified design and in particular to derive probabilistically based partial safety factors. Although, several application examples have already been published along the years, showing how reliability analysis could be applied to the analysis of ship structures, only relatively recently have the Classification Societies been motivated to incorporate the results of such studies in their codes by calibrating design formats for a consistent reliability level (Guedes Soares and Moan 1985, Spencer et al. 2003, Teixeira and Guedes Soares 2005, Hørte et al. 2007).

The present contribution aims at reviewing some recent work that has been performed on topic of the probabilistic assessment of ship structural safety. It will concentrate on the type of reliability formulations that are presently in use for ship structures. It discusses the formulations for hull strength and then the probability models of the still-water loads, of the wave induced loads and of load combination. Finally it deals with the formulations for reliability of damaged structures.

This work concentrates on the ultimate collapse situation and does not discuss the fatigue reliability case which is generally considered a serviceability limit state and is studied in connection with maintenance and inspection planning, as reviewed by Guedes Soares and Garbatov (1996).

5.4.1 Probabilistic Modelling of the Strength of Ship Structures

In order to be able to determine structural reliability of the ship it is necessary to evaluate the longitudinal strength of the hull girder and to define probabilistic models which can characterise the variability expected from the structural strength estimates.

In general, the manner in which structural collapse can occur include reaching the yield stress, with the beginning of plastic flow, the elasto-plastic buckling subjected to the compressive load effects, and the increase of fatigue cracks or facture. These various collapse modes have different consequences that also result from the importance of structural component.

Typically, global structural behaviour, also called primary, is considered to be everything involved in the behaviour of the structure as a whole, that is, its bending as a beam. Secondary structures are normally important components such as the deck or the bottom of the ship and tertiary components are typically panels or stiffened panels.

On a global behaviour level, Classification Societies Rules used to relate the longitudinal strength of the ship with the bending moment that causes the beginning of yield on the deck or on the bottom, which once more is a conservative situation since the structure normally has higher strength. This strength comes not only from material properties but also from the geometrical characteristics of the structure. Considering the global flexibility of the hull as a beam, the moment M_e corresponding to the elastic stresses that develop is given as

$$M_e = Z_e \sigma_y = \frac{I_v}{d} \sigma_y \tag{5.2}$$

where σ_y is the yield stress of the material and Z_e is the elastic modulus of the section given by the ratio of the moment of inertia of the section I_v by the distance d of the neutral axis to the end of the section. This formulation allows the calculation of the moment, which corresponds to the reaching of the yield stress on the deck or bottom and is therefore a lower limit of the moment that makes the section collapse. The higher limit is given by the plastic moment that represents the moment that is necessary to apply to the section in order for it to collapse with all the material of the transversal section totally plasticized.

Although the elastic bending moment has been widely treated as a measure of longitudinal bending strength of the ships, it does not provide with information concerning their resistance in extreme conditions. This can be achieved by the evaluation of ultimate capacity – maximum bending moment a hull can carry – which becomes an important parameter in ship structural rational design and in the reliability analysis of ships.

One of the first methods for calculating the ultimate strength of a midship section was suggested by Caldwell (1965). In the method the structural members were lumped into panels and as the collapse load was known, either from experiments or analytical methods for each panel, the collapse moment of the midship section was estimated by simple summation. In this way the method indirectly accounted for buckling of compressed members as well as yielding of tensile members. However, Caldwell's method did not account for the post-collapse strength of the structural members which significantly influence the collapse strength. This problem was addressed by Smith (1977), who assumed that each element of the cross section, made up of a longitudinal stiffener and the respective associated plate, behaves in its pre- and post-collapse phase, independently from the neighbouring components and that the contribution of the various components is summed up to produce the bending moment which makes the transverse section collapse. In this way, the ultimate moment of the transverse section, M_u, is given as:

$$M_u = \sum_{i}^{n} \frac{\sigma_{ui}}{\sigma_y} d_i \sigma_y \tag{5.3}$$

where d_i is the central distance of the structural element to the neutral axis, σ_{ui} is the ultimate strength of each element which can be the yield stresses σ_y if it is in tension or the elasto-plastic buckling stress, σ_c, if it is in compression. A number of calculation methods that adopt this type of approach have been proposed and they were compared in a recent ISSC study (Yao et al. 2000). The FEM can also be a powerful method to perform progressive collapse analysis of ships. However, the hull girder is too complex to perform progressive collapse analysis by the ordinary FEM and therefore most of the studies on the probabilistic modelling of the ultimate strength of hull girders have been based on predictions of Smith-type simplified progressive collapse methods.

In several reliability analyses the calculated bending moment by the deterministic methods has been considered to be the expected value of the ultimate strength of the mid-ship section, and all uncertainty in the prediction is concentrated in a model uncertainty random variable. A log-normal distribution with a mean value of unity is usually selected to describe this model uncertainty. It takes into account both the uncertainty in the yield strength and the model uncertainty of the method to assess the ultimate capacity of the mid ship section. Since the coefficient of variation of the yield strength of the steel normally range from 8 to 10% it has been assumed that the additional uncertainty will bring the overall coefficient of variation to 0.15 (Guedes Soares and Teixeira 2000). This result has been demonstrated by Hansen (1996) who quantified the uncertainty of the predictions of hull collapse, showing that it is very small and dominated by the uncertainty of the yield stress of the material, slightly increased by the uncertainty of the collapse strength.

Alternatively, First Order Second Moment approaches, Monte Carlo simulation or response surface methods can be used to construct the probabilistic models of the ultimate strength of the ships based on the probabilistic models of the geometrical and material properties of the mid-ship cross section.

As indicated previously, the hull collapse moment is a result of the contribution of the different plate elements that make up the cross-section. Therefore the basic structural element is the plate and the next step in the level of complexity is the stiffened panel. It has been shown by different authors that the strength of the plate elements depend on the shape and amplitude of initial imperfections, on the level of residual stresses and on the boundary conditions. Although there are several simplified formulations to predict the strength of plate elements under uniaxial compression, as reviewed by Guedes Soares (1988), probably of the most used is due to Faulkner (1975).

5.4.2 Probabilistic Modelling of Still Water Induced Loads

The still-water load effects result from the longitudinal distribution of the cargo onboard and thus they are likely to change at each departure and even smaller changes may occur during a voyage. Once the distribution of cargo is known, the still-water load effects can be calculated. They include bending moment, shear force and lateral pressure, but typically, the most important still water load is the vertical still water bending moment. The still-water load effects will vary with time and so they can only be described by a probability distribution (Guedes Soares and Moan 1988, Guedes Soares and Dogliani 2000).

Recently, characteristic values of the loading manual (such as its maximum value) have been adopted to define the probabilistic models of the still water bending moment used in the reliability analysis of individual ships. (Hørte et al. 2007) found that the mean value of the still water bending moment in sagging was between 49 and 85% of the maximum value in the loading manual. They also found that when the mean value of still water bending moment is large the standard deviation is relatively small. Based on the analysis of 8 test tankers, Hørte et al. (2007) proposed a stochastic model that describes the still water vertical bending moment by a normal distribution with mean value and standard deviation of 70 and 20% of the maximum value in the loading manual, respectively.

5.4.3 Probabilistic Modelling Wave Induced Load Effects

The models of wave induced load effects adopted in the first reliability formulations described the probability distribution of exceeding a given value of bending moment at a random point in time during the ships lifetime. They were a natural generalisation of the models that described the long-term probabilistic nature of the waves.

Wave induced wave loads are normally represented by a succession of stationary sea states during which the amplitude of load effects follows a Rayleigh distribution. The transfer functions are calculated by strip theory and the most frequently used spectra to represent the sea states are the JONSWAP spectrum and the ISSC version of the Pierson-Moskowitz spectrum.

The adoption of transfer functions is based on the hypothesis that the responses are linear and in that case they can also be represented by a stationary process which can be described by probabilistic models.

In the case of ships the transfer function depends on the relative direction between the ship and the waves, α, the speed V of the ship and the cargo conditions C. Therefore, the response spectrum S_R is conditional or depends on all of these variables:

$$S_R(\omega, H_S, T_Z, V, C) = S_H(\omega, H_S, T_Z) . H^2(\omega, \alpha, V, C) \tag{5.4}$$

and for each combination of variables, its variance is given by:

$$R(H_S, T_Z, \alpha, V, C) = m_0 = \int_0^\infty S_R(\omega, H_S, T_Z, \alpha, V, C)\, d\omega \tag{5.5}$$

where ω is the encounter frequency of the ship with the waves.

This value of the variance is related to the specific situation of the sea state and operational condition of the ship. However, when considering any instant of time during the lifetime of the ship the value of the variance of the response at that instant can be represented by a random variable. In this manner, the distribution of sea surface elevation or of any other variable obtained from it through transformation is obtained by weighing the conditional distributions by using the density function of the probability of the variance of response:

$$Q_L(x) = \int_0^\infty QS(x|r)\, f_R(r)\, w(r)\, dr \tag{5.6}$$

where $w(r)$ is a normalization factor which depends on the number of peaks in the considered time period, or what is equivalent, depends on the average response period in consideration.

For reliability analysis, the resulting long-term distribution $Q_L(x)$, which represents the exceedance probability of the vertical wave bending moment x, can be approximated to the Weibull distribution $F_{VBM}(x)$ given by:

$$F_{VBM}(x) = 1 - \exp\left[-\left(\frac{x}{w}\right)^k\right] \tag{5.7}$$

where w and k are the scale and the shape parameters to be estimated from a Weibull fit of $F_{VBM}(x)$ to $1 - Q_L(x) = P(VBM \leq x)$.The Weibull model fitted to the long-term distribution describes the distribution of the peaks at a random point in time. However one is normally interested in having the probability distribution of the maximum amplitude of wave induced effects in n cycles, where n corresponds to the mean number of load cycles expected during the ship's lifetime. Gumbel (1958) has shown that whenever the initial distribution of a variable has an exponential tail, the distribution of the largest value in n observations follows an extreme distribution. Thus, the distribution of the extreme values of the wave induced bending moment over the time period T is obtained as a Gumbel law:

$$F_e(x_e) = \exp\left[-\exp\left(-\frac{x_e - x_n}{\sigma}\right)\right] \tag{5.8}$$

where x_n and σ are parameters of the Gumbel distribution that can be estimated from the initial Weibull distribution using the following equation:

$$x_n = w \cdot [\ln(n)]\,\frac{1}{k} \tag{5.9}$$

$$\sigma = \frac{w}{k}\,[\ln(n)]\,\frac{1-k}{k} \tag{5.10}$$

where w and k are the Weibull parameters and n is the return period associated with one year of operation.

In the case of ships, the probability density function of the response variance is in reality a multivariate distribution dependent on different random variables:

$$
\begin{aligned}
& f\left(H_S, T_Z, \theta, V, C\right) = f_0\left(\theta \left| H_S\right.\right) f_D\left(\theta \left| H_S\right.\right) \\
& f_M\left(\theta \left| H_S\right.\right) . f_M\left(V \left| H_S\right.\right) f_{H_S, T_Z}(h, t)\, f_c(c)
\end{aligned}
\tag{5.11}
$$

where f_0 is the density function of the probability of the directions in relation to the predominant direction of the waves, f_D represents the directionality of the wave climate, f_M is the effect that the manoeuvre provokes during storms, conditional on the direction Θ, on the speed V of the ships and on f_C which is the probability density function of cargo conditions of the ships. It is worth noting that this equation implies that there is statistical independence between the cargo condition of ships and the wave climate, but that there is correlation between the climate and the manoeuvring effects as is understood by conditional distributions.

The choice of probabilistic models which describe the wave climate to which structures are subject is an important element in the equation referred to above. Until very recently, the atlases with wave climate information which were available were based on visual observations and then on data calculated by reconstituted numerical models. The variability provoked by the chosen data can be overcome by adopting a reference wave climate with the agreement of the Classification Societies and which can serve as a comparison value for different designs of ships.

The accuracy of the forecast of wave induced loads can also be improved, especially for extreme cases by using non-linear theories, see e.g. recent ISSC studies Watanabe and Guedes Soares (1999) and Jensen et al. (2000).

In order to reduce the computational effort the contour line method can be applied. This method, proposed by Winterstein et al. (1993) is based on the idea of determining the contours of equal probability on the diagram of joint probability of significant height and peak period of sea states from the ones which have equal probability of originating responses of a certain level of probability. However, the responses are basically calculated with linear methods as the ones described in the initial part of this section.

The advantage is that after having identified this, it is possible to calculate the non-linear response just for this small set of sea states and in so doing in a more consistent manner obtain the most probable maximum values of the type of loads to be considered, as suggested by Adeegest et al. (1998).

These methods have been compared with the long term approach and with others, including the effect of abnormal or freak waves in Guedes Soares et al. (2008) and Fonseca et al. (2007).

5.4.4 Load Combination

In the reliability assessment of the primary ship structure it is required to know the maximum value of the two most important load effects. Considering that both have a statistical variability due to different factors, it is easy to deduce that the maximum value of both does not occur simultaneously and therefore the maximum value of the sum of two loads is usually less than the sum of the two maxima that can occur in any time.

The reducing effect of the maximum value of the combined loads is taken into account in the regulations and in the reliability assessment of the primary ship structure by means of load combination factors, which can affect both the sum of two components as well as only the component that has the highest variability.

The combination between the still water and wave induced bending moment (M_{te}) can be done using stochastic methods, which combine the stochastic processes directly, or by deterministic methods that combine the characteristic values of the stochastic processes. The different load combination solutions have been compared by e.g. Guedes Soares (1992) and Wang and Moan (1996). Turkstra's rule is probably the most often method applied. It assumes that, for the sum of two independent random processes, the total maximum moment occurs when either moment of the individual processes has its maximum value,

$$M_{te} = \max\left\{(M_{se} + M_w), (M_s + M_{we})\right\} \tag{5.12}$$

where M_{se} and M_{we} are the extreme value distributions of still water and wave induced bending moment, respectively, and M_s and M_w are the arbitrary-point-in-time values of the random variables. Ferry Borges and Castanheta (1971) proposed a representation of a stochastic process as a sequence of pulses of a fixed duration as being equal to the average duration of the variable being considered. The probabilistic distribution F_{te} of the maximum value during n repetitions of the load i or equivalently during the time $T = n\tau$, where τ is the pulse duration, is given by:

$$F_{te}(x) = [F_x(x)]^n \tag{5.13}$$

where $F_x(x)$ is the probability distribution function of the load intensity. This model has been adopted Ferry Borges and Castanheta (1971) to represent a combination of vertical bending moments induced on the ship hulls in still water and in waves. For this purpose, it is necessary to define the average duration of the voyages (τ_s) and the average period of the waves meeting the ship (τ_w). In this case, defining the reference time period as T, the average number of voyages is $n_s = T/\tau_s$ and on each voyage the average number of wave motion cycles which occur is $n_w = \tau_s/\tau_w$ (Fig. 5.19). Thus the distribution function of the maximum value of combined loads during a time period T is:

$$F_{te}(x) = \left\{\int_{-\infty}^{x} f_{Ms}(z)\,.\,[F_{Mw}(x-z)]^{n_w}\,dz\right\}^{n_s} \tag{5.14}$$

where z is an auxiliary variable, f_{Ms} is the density distribution function of the still water bending moment in one voyage and $[F_{Mw}]^{n_w}$ is the distribution of the extreme wave induced bending moment in one voyage, assuming n_w wave loads in one voyage. The distribution of extreme combined vertical bending moment can be calculated for the different load conditions according to the operational profile that indicates the number of voyages n_s in each load condition.

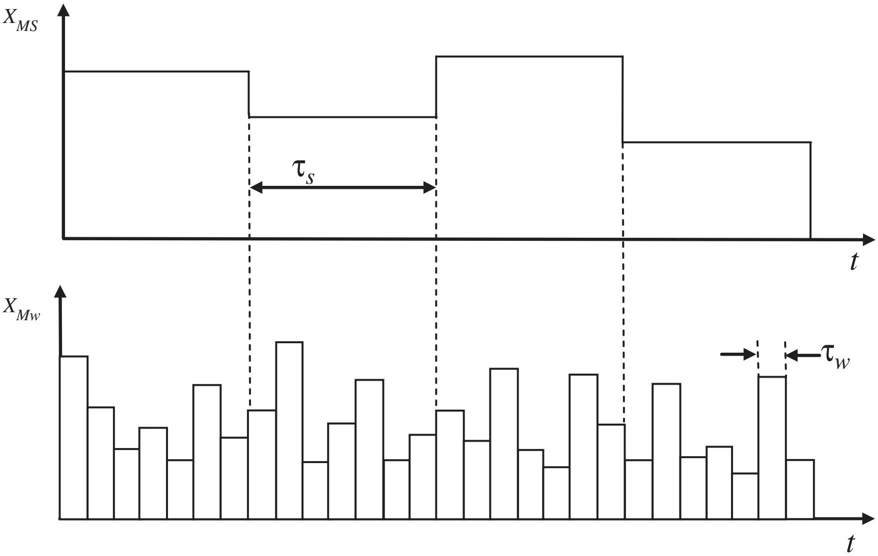

Fig. 5.19 Illustration of the Ferry-Borges model

The most exact formulation is to consider both processes as being stochastic and then determine the average upcrossing rate of a given level ν_{Mte} by the M_{te} process which represents a combined load as proposed in Guedes Soares (1992):

$$\nu_{M_{te}}(x) = \int_{-\infty}^{\infty} f_{M_W}(x)\,\nu_{M_S}(x-y)\,dy + \int_{-\infty}^{\infty} f_{M_S}(z)\,\nu_{M_W}(x-z)\,dz \tag{5.15}$$

where ν_{Ms} represents the upcrossing rate by still water loads, which are modeled by a standard variable and ν_{Mw} the rate of level crossing for a variable with Weibull type distribution, which was given by Naess (1984). These formulations have been used to determine the load combination factor Ψ by solving the following relationship,

$$F_{te}(x) = F_{se}(x) + \Psi F_{we}(x) \tag{5.16}$$

where extreme distributions are considered at 0.5 exceedance level. Thus, the combination factor is evaluated by:

$$\Psi = \frac{F_{te}^{-1}(x=0.5) - F_{se}^{-1}(x=0.5)}{F_{we}^{-1}(x=0.5)} \tag{5.17}$$

Table 5.6 shows the resulting values of the load combination factor for a 236 m long tanker in full, ballast and partial load condition, which lie within the range calculated by Guedes Soares (1992) and Casella et al. (1996).

Table 5.6 Values of the load combination factors

Load cond.	$F_{se}^{-1}(x=0.5)$ (MN.m)	$F_{we}^{-1}(x=0.5)$ (MN.m)	$F_{te}^{-1}(x=0.5)$ (MN.m)	Ψ
Full load	1186	4210	5074	0.923
Ballast load	1661	3751	5085	0.913
Partial load	1545	3475	4337	0.803

5.4.5 Reliability of Accidentally Damaged Structures

Having the problem of reliability assessment of intact ships relatively well understood and incorporated in the rules of Classification Societies, the attention has been moving gradually towards considering at design stage how to better design ships so that they can still sustain some of the damage situations that are more likely to occur.

The main consideration is the longitudinal strength of a damaged hull girder and a sub problem is the strength of damaged components such as panels. The studies concerning the survivability of ship following accidental damage lead to an important collection of hull damage data that can also be used to determine likely damage patterns for hull strength assessment.

Finite elements are obviously adequate tools to predict the damage of ships in collision and grounding situations. However they are not practical tools to be used together with reliability assessments. Therefore it was only after approximate methods have been applied to damaged sections that reliability approaches could be developed.

Paik et al. (1998) developed a fast method to assessing the collapse of the hull girder in the damaged condition using the formulation of the American Bureau of Shipping. Gordo and Guedes Soares (2000) as well as Ziha and Pedisic (2002) adopted Smith type approaches to calculate the ultimate strength of damaged hulls. Fang and Das (2004, 2005) have adopted simplified methods initially developed to calculate the vertical ultimate bending moment to predict now the ultimate longitudinal strength of damaged ships. This type of methods have been compared with each other and with results of finite element calculation and shown to be consistent Guedes Soares et al. (2008).

The approach generally adopted in these studies was to remove the elements within the damaged area from the section to be analysed and the ultimate strength was recalculated using the simplified method. It was found that the width of the damaged area influenced considerably the ultimate strength of the ship. However, accidental damages of ships can occur in any number of ways being the two most concerning ones the collision with other ships and grounding on rocky seabed.

Luís et al. (2007) have used that type of approach to study the effect of the position and extent of damage on the ultimate strength of the damaged ship providing thus useful insight about its effect on hull girder reliability. Luís et al. (2006) and Hørte et al. (2007) have determined the reliability of damaged ship hulls by using a FORM assessment. In addition to determining the ultimate strength of the damaged section according to the methods just described the load conditions were based on the distribution for the intact ship, and the change in still water loads as a consequence of the damage was added by a deterministic value. Typically flooding of ballast compartments in the midship region was found most critical, and this causes the sagging moment to increase.

Santos and Guedes Soares (2007) have developed an accurate method to determine the still water bending moments during the flooding process and have shown that during transient situations the hull girder loads can be larger than in the steady state situation, a finding that needs to be taken into account in future reliability evaluations.

5.4.6 Conclusion

This section provides an overview of the reliability approaches that are presently available for the assessment of the reliability of ship hulls under intact and damaged conditions. Attention is given to the approaches to determine hull girder strength and to assess the still water and the wave induced load effect as well as their combination, which are the required information to perform reliability analysis. Finally reliability of damaged vessels was discussed.

In general it can be said that there are a number of tools available to determine structural reliability which is mature to be applied in intact structures and has already been applied to damaged structures.

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5.5 Flooding

The analysis of the dynamic behaviour of damaged ships in waves may be carried out today using theoretical-numerical models which allow the calculation of the nonlinear motions of the ship and the details of the flooding in the time domain. Numerical simulations of the damaged ship behaviour are an efficient way of evaluating ship's survivability compared to physical model experiments. In both cases the probability of capsize and/or sinking is calculated by inspecting the time series of roll and of other ship motions and related quantities.

The accuracy of numerical calculations depends on the accuracy of the modelling of the physical phenomena and remains in some respects in doubt; a fact which is easily comprehensible given the complexity of the phenomena at stake. Numerical simulations are however very advantageous compared to physical model experiments due to their flexibility when attempting to vary systematically the variety of parameters related to the ship or to the sea environment.

Numerical methods for damaged ship survivability in waves comprise the solution of the ship equations of motion in the time domain. The results consist of the time series of ship motions and of the water mass in the flooded spaces and are free from typical limitations imposed by physical model experiments, like limits of tank dimensions, ship's shell thickness modelling problems and rigidity in changing internal ship's layout.

Seakeeping models typically use formulations in the frequency domain, which are sufficient for most design purposes. However, when considering nonlinear phenomena such as large amplitude motions, effects of wave profiles on hydrodynamic forces, loads due to current, wind and mooring, forces due to flooding, a time domain approach is required. Numerical models for calculating damaged ship dynamics in waves are formulated in the time domain and generally comprise three basic components: a model of the ship geometry including subdivision, a model for the sea environment and a model of the flooding process. These models and their interactions are integrated into the overall model of the damaged ship behaviour, which basically consists of the set of equations for ship motions under the effects of flooding and waves (Fig. 5.20).

It is worth pointing out that the dynamic behaviour of the ship acts back upon the flooding because it interacts with the motion of water inside the flooded compartments. The main parameters of these models are listed in Table 5.7.

5.5.1 Modelling the Sea Environment

Most numerical models in the time domain use linear deep water theory. This theory proved to be adequate for modelling large amplitude waves in deep water, with good results regarding wave profiles, particle kinematics and pressure distribution in the proximity of the free surface. Its application to situations involving progressive flooding is therefore assumed adequate. However, modelling extreme phenomena

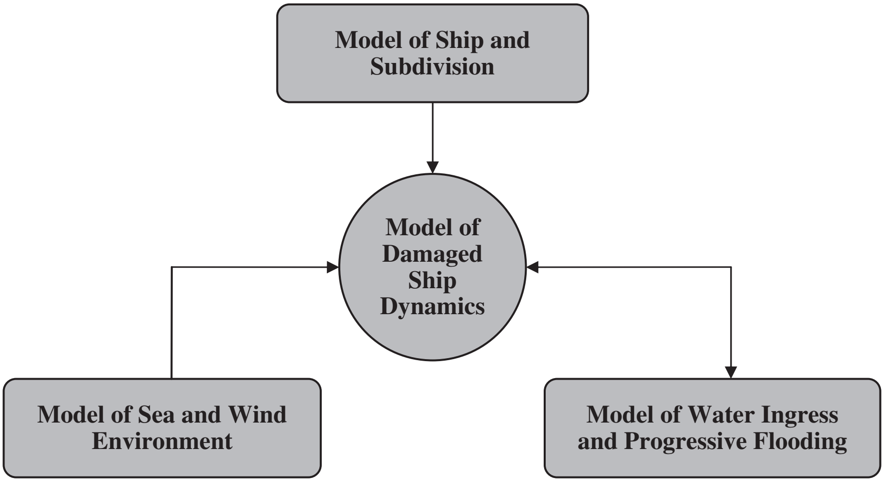

Fig. 5.20 Structure of damaged ship dynamics numerical models

Table 5.7 Main parameters and characteristics of employed numerical models

Model		Main parameters
Sea environment		Wave theory, direction and spectrum, water depth, restricted waters, current, wind
Ship and damaged compartments		Hull shape, ship subdivision, geometry of damage, loading condition, ship speed
Damaged ship behaviour	Equations of motion	Number of degrees of freedom numerical method
	Potential forces	Hydrostatic forces, Froude-Krylov forces, radiation forces, diffraction forces
	Viscous forces	Roll viscous damping, viscous coupling drift-roll, viscous forces due to manoeuvring, drift due to waves
	External forces	Wind, cargo shifting, propulsion, resistance to advance, rudder, automatic pilot, mooring, collision
Flooding	Water in-/ouflow	Hydraulic models, CFD
	Accumulation and motion of floodwater	Static effects, dynamic and sloshing effects
	Progression of flooding	Hydraulic models, CFD

such as breaking waves is not possible by linear theory and these phenomena may be of interest when considering the behaviour of small ships in shallow waters in the presence of strong waves and currents. In these conditions, water rotational speeds may have a substantial importance in ship capsize, especially in beam seas.

However, for medium and large ships, these phenomena are less important since the probability of capsize is very small for such large vessels.

Dynamic behaviour of ships is very much influenced by the direction of waves. Numerical models should be able to consider waves coming from different directions, although today the situation predominantly studied for damaged ships is the beam sea condition, as it is the most serious. Furthermore, damaged passenger ships in case of severe flooding tend to stop and align themselves parallel to the predominant wave crests. Most numerical results available today relate to beam seas, as this is also the classical case of damage ship stability assessment according to SOLAS regulations; Chang and Blume (1998) and Chang (1999) presented numerical results also for other wave directions.

Numerical models describe the natural seaway by means of wave spectra, a technique which allows the simulation of time series of the wave elevation resulting from the superposition of a large number of wave components with different frequencies, amplitudes and phases. This type of modelling of the sea surface is generally adequate to model wave conditions in a certain fixed point in space, assuming the wave elevation to be a Gaussian process and for large water depths. Most numerical models consider unidirectional sea states defined by use of the JONSWAP spectrum (for coastal waters), as reported in Guedes Soares (2003). For deep sea waters, the Pierson-Moskowitz or Bretschneider spectrum is more frequently used.

In fact, as most passenger ships typically follow routes along the coasts, the JONSWAP spectrum is generally found to be appropriate. Experimental results regarding the behaviour of damaged passenger Ro-Ro ships in irregular waves have been made available for sea states defined by JONSWAP and Pierson-Moskowitz spectra, as reported in (ITTC 2000). Waves are generally accompanied by wind, whose effects are generally important for passenger ships, for which the exposed areas are typically very significant. Wind effects are generally modelled using constant wind speed profiles and empirical formulae.

Shallow water effects can also be of importance since there are effects on the wave shape but also because squat effects can arise when the ship speed is significant. These types of effects are generally not considered in the damaged ship behaviour numerical models, except for Dand (1988) in a case of flooding through the bow door of a ferry under way; thus, shallow water effects should be considered, when flooding occurs for a ship with speed, as most passenger ships travel along coastal waters with limited water depth and most accidents occur near ports where the water depth is even smaller. Currents are not considered in these models of damaged ship behaviour, although coastal areas are usually subject to strong currents which also have effects on the waves and damaged ship behaviour. The effects of currents have not been considered in numerical models of this type so far, but can be included as external forces applied to the ship.

5.5.2 Modelling the Damaged Ship

Several numerical models use strip theory for calculating the hydrodynamic forces, making it a requirement for the ship's hull to be slender and be defined using transverse sections. Some recent numerical models use panel methods to obtain the hydrodynamic forces and in these cases, the ship's hull is described using panels, as reported in Zaraphonitis, Papanikolaou et al. (1997), offering the advantage of increased precision in these forces.

Simulating the flooding of a ship in the presence of a certain sea state requires modelling both the geometry of the ship's hull (wetted and dry surfaces) and of the damaged compartments. Most numerical models adopt this approach as reported in Van't Veer et al. (2004). Modelling of the number, shape and location of the damage holes in the hull and between the different compartments is also required if progressive flooding is to be taken into account and simulated, as reported in Santos et al. (2002). Very often, the ship's hull damage opening is specified as according to relevant SOLAS regulations (SOLAS 90 or Res. 14/SOLAS 95 provisions, IMO 1995).

The loading condition of the ship at the time of the accident is generally specified in terms of her displacement and centre of gravity. Additionally, the moments of inertia of the ship are also required, which can be calculated from the ship's mass distribution, if available or estimated using empirical formulae. The location of centre of gravity is important mainly for the hydrostatics and the inertias for the dynamic behaviour of the ship. The ship's speed is also of importance since it influences the hydrodynamic forces and causes additional wave systems which, for example, change the shape of the wetted surface. However, for reasons stated above and in compliance with relevant SOLAS regulations, the damaged ship is generally assumed at zero speed (*dead ship* condition) and excited by transversely travelling (*beam*) waves.

5.5.3 Modelling Damaged Ship Dynamics

5.5.3.1 Equations of Motion

Most numerical models consider all six degrees of freedom of the ship and solve the equations of motion in the time domain. The first introduced models, like those of Sen and Koustantinidis (1987) and Spouge (1985) simply simulated the behaviour of the ship using a quasi-static approach. No wave effects were considered. De Kat and Paulling (1989), based on the works of Oakley et al. (1974) developed the first numerical model in the time domain capable of dealing with all degrees of freedom. Rakhmanin and Zhivitsa (1996) presented a set of simpler equations of motion which only dealt with drift, heave and roll. These equations included the dynamic effects of water inside the compartments by adding a set of terms to the intact ship equations of motion. A similar approach was used to include the effects of inflow/outflow.

Turan (1993) and Vassalos and Turan (1994) adopted a similar approach and presented a coupled model in three degrees of freedom. Lee and Adee (1994) presented a numerical model of similar characteristics. Vassalos and Letizia (1995) and Letizia et al. (2003) further developed the work of Turan (1993) and derived a set of equations which included the effects of floodwater in a more realistic different way. A non-linear coupled six-degree of freedom numerical model, coupled with a water ingress/egress model was presented, characterised by the following set of coupled differential equations:

$$
\begin{aligned}
&[M+M_w(t)+A]\ddot{X}(t)+\left[\dot{M}_w(t)+B_{viscous}\right]\dot{X}(t)+\int_0^t K(t-\tau)\dot{X}(\tau)d\tau = \\
&= F_{wave}+F_{drift}+F_{wind}+F_{current}+F_{restoring}+F_{gravitational}-F_{wod}
\end{aligned}
\tag{5.18}
$$

where:

M is the ship's mass inertia matrix
$M_w(t)$ is the flood water matrix moving independently of the vessel but with an instantaneous free surface always parallel to the mean waterline
$M_w(t)$ is the rate of flood water matrix (acting as damping)
A is the added (hydrodynamic) mass matrix
$B_{viscous}$ is the viscous damping matrix
$\int_0^t K(t-\tau)X(\tau)d\tau$ is the convolution integral, representing radiation damping
$K(t-\tau)$ is the kernel function and τ is the time lag
F_i are the various generalised force vectors comprising wave (1st and 2nd order), wind and current excitation as well as restoring, gravitational and water on deck effects.

Numerical models of damaged ship dynamics were also further developed by others; Vermeer et al. (1994) introduced a model that considers the drift, roll and yaw motions and Journée et al. (1997) presented a six degrees of freedom model and its partial validation by model experiments. Spanos et al. (1997) introduced their work at the National Technical University of Athens (NTUA) on damaged ship dynamics and presented a six degrees of freedom numerical model, which is based on a 3D panel method for the calculation of the hydrodynamic forces; this work was later further developed by Spanos and Papanikolaou (2001). The theoretical approach of the NTUA model is similar to that of De Kat and Paulling (1989), except for the refined calculation of the hydrodynamic forces by a 3D panel method; additional equations are introduced describing the floodwater motions on deck or inside compartments by the lump mass concept and their coupling with the ship motions.

Chang and Blume (1998) further developed the original work of Söding (1987) and Kröger (1987) and presented a hybrid model which considers the six degree of freedom; however, some of the motions are determined by linear modelling in the frequency domain while the roll motion is solved in the time domain. The roll motion is determined using the following nonlinear motion equation:

$$\ddot{\varphi} = \Big\{ -M_D - M\left(g - \ddot{\zeta}\right)h_s - I_{xz}\left[\left(\ddot{\theta} + \theta\,\dot{\varphi}^{\,2}\right)\sin\varphi - \left(\ddot{\psi} + \psi\,\dot{\varphi}^{\,2}\right)\cos\varphi\right] + M_{WIND} + M_{WOD} + M_{SY} + M_{WAVE}\Big\} \Big/ \Big\{ I_{xx} - I_{xz}\left(\psi\sin\varphi + \theta\cos\varphi\right)\Big\} \tag{5.19}$$

where:

M represents the mass of the ship
ζ represents the heave motion
φ represents the roll motion
θ represents the pitch motion
ψ represents the yaw motion
I_{xx} represents the inertia around the longitudinal coordinate axis
I_{xz} represents the cross product of inertia
h_s is the righting arm in an "effective" longitudinal wave acc. to Grim and Söding
M_D is the nonlinear damping moment taking into account the bilge keels
M_{WIND} is the moment of wind
M_{WOD} is the moment due to water motion on the vehicle deck and in compartments
M_{SY} is the roll moment due to sway and yaw motions
M_{WAVE} is the moment due to waves.

The main conclusion is that most recent models consider all degrees of freedom, but surge and yaw are frequently neglected. This is partially a consequence also of the fact that in resolution 14/SOLAS 95 (IMO, 1995) testing procedure, used as a standard case for comparison of obtained theoretical results, it is implied that ship's surge and yaw motion are restrained, in order to keep the model in beam seas.

Damaged ship behaviour numerical models should allow the prediction of capsize, which occurs when the ship attains heel angles larger than about 25° to 30°, with currently no clear definition of the precise boundary. For this final stage of flooding, large angle rigid body mechanics is required and this leads to numerous nonlinearities in the equations of motion. Numerical models like those of Turan (1993) and Journée et al. (1997) did not consider large rotation angles. More recent numerical models, such as those presented by Vassalos and Letizia (1995) and Spanos et al. (1997), include proper modelling of these nonlinearities. The roll equation of motion considered by Chang and Blume (1998) is also highly nonlinear with respect to the roll motion. The equations of motion in the numerical models are generally solved using the Runge-Kutta method, with the exception of the model presented in Spanos et al. (1997), which uses an extrapolation scheme.

5.5.3.2 Potential Forces

Hydrodynamic forces acting on the damaged ship are generally divided into potential forces and viscous forces. Potential forces are those that act on the wetted surface due to water, taken as an inviscid and irrotational fluid and viscous forces are those arising due to viscosity. Potential forces can be further decomposed into Froude-Krylov, radiation and diffraction forces.

Froude-Krylov forces result from the integration of the undisturbed incident wave pressure distribution along the wetted surface of the hull. Water pressure is often decomposed in hydrostatic pressure and hydrodynamic pressure, which causes the Froude-Krylov forces. Various authors, such as Vassalos et al. (1997a,b) and Hutchinson (1995) indicate that these two forces, hydrostatic and Froude-Krylov, are dominant with respect to the dynamic behaviour of the ship, especially in beam seas. There are various options regarding the calculation of the Froude-Krylov forces with the most common being to integrate pressures over the mean wetted surface, an approach adopted by Turan (1993). Numerical models such as those of De Kat and Paulling (1989), Spanos et al. (1997) and Vassalos and Letizia (1995) calculate the Froude-Krylov forces taking into account the exact wetted surface under the incident wave.

Radiation forces are the hydrodynamic forces associated with ship motion on the free surface. The most common method for calculating these forces is to use linear strip theory or a 3D panel method. This approach produces hydrodynamic forces in the frequency domain which can then be transferred to the time domain using the impulse response function method introduced by Cummins (1962). Numerical models such as those of De Kat and Paulling (1989), Spanos et al. (1997), Vassalos and Letizia (1995) and Journée et al. (1997) follow this approach ensuring proper consideration of memory effects. Models such as those of Turan (1993) and Chang and Blume (1998) used the frequency domain coefficients directly, at least for some motion responses.

Diffraction forces are the hydrodynamic forces related to the perturbation of the incident wave (pressure distribution and wave profile) due to the presence of the ship's hull. De Kat and Paulling (1989) indicated that these effects are of importance when the damaged ship is exposed to beam seas. Diffraction forces actually also involve memory effects and, therefore, the methods used for radiation forces could be also herein applied. However, numerical models similar to that of De Kat and Paulling (1989) use an equivalent method, which is based on the hypothesis that the motion has been going on for a long time and the use of the transfer functions of the diffraction forces from the frequency domain is sufficiently accurate. Most numerical models such as those of Vassalos and Turan (1994), Vermeer et al. (1994), Spanos et al. (1997) and Chang and Blume (1998) adopt a similar approach.

5.5.3.3 Viscous Forces

Viscous forces act in a similar way like the damping component of the radiation potential forces. In fact, the damping component of the radiation forces is frequently referred to as potential damping in contrast to viscous damping. Roll motion is that DOF in which viscous effects are very important. De Kat (1990) uses an empirical method by Himeno (1981) to calculate the viscous roll damping which is based on a decomposition of the viscous effects in components which are summed up to obtain linear and quadratic coefficients. De Kat (1990) uses, however, a different approach by linearization of all the components of roll damping. The work of Ikeda et al. (1980) and more recently Ikeda (2002) is widely used for estimating the semi-empirical coefficients for the viscous roll damping.

Viscous forces due to ship manoeuvring act on the horizontal plane and are of importance for the drift and yaw motions, when the ship at speed. The method of Inoue et al. (1981) or others of similar nature has been used to calculate these forces by De Kat (1990) and others. Other numerical models do not consider these effects as their main concern is the case in which the ship has no forward speed and is in beam seas.

5.5.3.4 External Forces

External forces comprise a variety of specific forces due to wind, cargo shift, propulsion, resistance to advance, rudder, automatic pilot, mooring and collisions. These may be of relevance or not to the flooding, depending on the specific application of the numerical model.

Wind can induce a significant inclining moment on the ship and has a negative effect on the roll motion of the damaged ship in severe sea states. Its main effect is a quasi-static heel angle to leeward, about which the ship rolls under the action of waves, as explained by De Kat (1990). Wind effects are especially important for passenger ships, typically characterized by large exposed areas, which tend to align themselves broadside to heavy seas when in damage condition. Isherwood (1973) published one of the first works on the effects of wind on ships. Most numerical models applied in damage stability assume a steady wind; recent works such as those presented by Vassalos et al. (2004) and Francescutto et al. (2001), regarding the weather criterion, contain interesting data for improvements in this area. It should be noted, however, that as the wind may be assumed acting in the same direction as the incoming waves that the flooding through a damage opening on the weather side is not increased due to the action of wind, therefore it is generally neglected in the assessment of the damaged ship's stability in waves.

Cargo shifting due to severe weather conditions is possible in many situations and is especially dangerous for Ro-Ro and containerships. Its main effect is to cause a steady list which generally causes an increase of the capsize probability. Most known numerical models do not consider this problem explicitly; but recent works, e.g. by Ericson et al. (2000), describe methods to predict the breaking of the lashing of Ro-Ro cargo due to extreme accelerations.

Some numerical models, e.g. De Kat (1990), which also aim at studying the manoeuvrability of damaged ships, consider the forces associated with resistance, propulsion, rudder and automatic pilot. These forces are all included as external forces and calculated using different methods, some of them of empirical nature. Forces due to mooring are not commonly considered and the same applies to collision forces, which nevertheless may be of interest in the initial transient phases of flooding, as mentioned by Spouge (1985).

5.5.4 Modeling Ship Flooding

The modelling of ship flooding, under the action of waves, involves the following phenomena:

- Inflow/outflow of water to the damaged compartments,
- Accumulation and motion of water inside the damaged compartments,
- Progressive flooding of ship's compartments.

The first two phenomena have been studied also for vessels with water on deck, namely fishing vessels and offshore vessels. Dillingham (1981) and Falzarano (2002) provide results on the effects of shallow water accumulated on large open decks. Inflow and outflow of water have been predominantly studied in connection with damaged Ro-Ro ship behaviour by Vassalos et al. (1997) and others. Progressive flooding has also been studied for similar ships by Spanos et al. (1997) and Santos and Guedes Soares (2001), for warships by Palazzi and De Kat (2003), for cruise ships by Van't Veer et al. (2004) and fishing vessels by Spanos and Papanikolaou (2001).

5.5.4.1 Modeling Inflow/Outflow

The correct modelling of the inflow/outflow process has a significant importance in the determination of time required to sink or capsize the ship and in the actual survivability of the damaged ship. The amount of floodwater which flows at any time instance through the damage opening depends on the pressure difference between the inside of the damaged compartment and the exterior sea environment. The pressure distributions in the flooded compartment depend on the amount of water in the compartment, the phase lag of the flooded water surface relative to the ship motions, sloshing effects and shape of the free surface inside the compartment. Concerning the pressure distribution on the outside, the draft, trim and heel of the ship, the characteristics of the sea and radiation and diffraction effects all affect the pressure distribution.

The first employed inflow/outflow model was a hydraulic model presented by Turan (1993); he assumed a stationary flow dependent on the heads of water on both sides of the damage opening. Also included in the formulation was a hydraulic coefficient, whose value was determined empirically from model experiments. Vassalos and Turan (1994) introduced an expression derived from the Bernoulli theorem which allows the calculation of flow rates through infinitesimal elements of the damage. In general, the flow of water between two interconnected compartments depends on the difference of water levels between both compartments. Bernoulli's theorem is first used:

$$h_{out} + \frac{P_{atm}}{\rho g} + 0 = h_{in} + \frac{P_{atm}}{\rho g} + \frac{v^2}{2g} \qquad (5.20)$$

where h_{in} and h_{out} are the water levels in both compartments, P_{atm} is the atmospheric pressure, ρ is the specific mass of the water, g is the acceleration of gravity and v is the water velocity, which can then be obtained through:

$$v = \sqrt{2g(h_{out} - h_{in})} \tag{5.21}$$

The flow rate is then obtained through:

$$Q = \iint_A K\sqrt{2g(h_{out} - h_{in})dA} \tag{5.22}$$

where K is the hydraulic coefficient, obtained experimentally. The flow rate can then be multiplied by the time step and the amount of water which enters or leaves the compartment is obtained.

Formulations of this type are also used in the works of Hutchinson (1995), Zaraphonitis et al. (1997), Vassalos et al. (1997) and Van't Veer and De Kat (2000). Depending on the relative heads of water on both sides the damage opening at each moment, the flow rate can be estimated and the amount of water inside the compartment updated for the next time step. Vassalos et al. (1997) report good agreement between experimental results for damaged Ro-Ro ships and time domain simulations.

The very nature of the related flow phenomena suggests that the intermittent flooding of the car deck of a Ro-Ro ship involves quite different phenomena. Outflow of water may in many cases be similar to discharging from a dam, while inflow is typically a more complex problem. Hydraulic coefficients remain an important approach in the prediction of inflow/outflow for damaged ships as they well capture the flow rate and the amounts of water in the different flooded compartments in the time domain. Typical values for hydraulic coefficients applicable to the problem of progressive flooding of ships are scarce in the open literature. In that sense, studies such as that of Ruponen et al. (2006) are very valuable and point towards hydraulic coefficients between 0.6 and 0.8, with 0.7 being a common value. However, the open literature reports hydraulic coefficients ranging from 0.5 to 1.2, with some dependence on the shape of the damage hole boundary.

Some numerical models like that of Xia et al. (1999) and Ruponen (2007) also take into account the effect of air flows and entrapped air on the flooding process, which are phenomena of interest in specific situations, e.g. flooding of confined spaces, like the machinery room (Van't Veer et a.l 2000 and Palazzi and De Kat 2002).

5.5.4.2 Modeling Floodwater Dynamics

The static effects of water accumulation inside the compartments of ships are well known. The dynamic effects are not so well understood, however, and different approaches may be followed regarding the treatment of the added mass of water contained in the different flooded compartments. In some numerical models, such as that presented by Vassalos and Letizia (1995), the ship is taken as a variable mass system and added mass and inertia constitute an additional component of damping. In a previous work, Vassalos and Turan (1994) adopted a different approach by considering the floodwater effects as external forces.

Water accumulated inside the ship has also the effect of increasing the draft of the ship, with consequences on the hydrodynamic forces acting on the ship. Studies of this problem indicate that by most forces vary linearly with draft. Hydrodynamic forces associated with roll motion present, however, some nonlinearities as the ship becomes heeled. Trim effects may also be important in case of severe trims due to extensive flooding. The open literature is very poor with respect to studies concerning the effect of heel and trim on the hydrodynamic forces.

The dynamics of floodwater inside compartments has been studied by various authors, with special focus on damaged Ro-Ro ships. The 1st related ITTC benchmark study, ITTC (2000), concluded that the final stages of flooding for Ro-Ro ships are quasi-static in nature, with significant decreases in roll motion in the final stages. However, during the slow flooding process of a Ro-Ro ship, the dynamic effects may be significant. Zaraphonitis et al. (1997) and Spanos and Papanikolaou (2001) indicate that the dynamic effects of sloshing are only significant when the excitation frequency is close to the natural frequency of the trapped water on the main deck. This matching should be very rare for Ro-Ro ships, due to common ship characteristics, but quite relevant to fishing vessel motions, when water is trapped on deck. Other authors, like Molyneux et al. (1997) indicate that in some circumstances these effects may be also significant for Ro-Ro ships. Another type of dynamic effects arises, as reported by Van't Veer and De Kat (2000), when there are obstructions to the freely flow of water inside the compartments, which may cause the shifting of the natural frequency of the water inside the compartments towards common values of the natural roll frequency.

Zaraphonitis et al. (1997) and Spanos et al. (1997) have adopted an approach in which the floodwater is taken as an independent oscillatory system with all its mass concentrated at its centre (*lump mass* concept). The equations describing the motion of floodwater are then solved in the time domain coupled with the ship equations of motion. The motion of the floodwater causes the occurrence of a second roll resonance independently of prime roll resonance of the ship, a fact also noticed in experimental results given by ITTC-Specialist Committee (ITTC 2003). The frequency and amplitude of the first roll peak and the presence of a second smaller peak at higher frequencies has been explained by Santos and Guedes Soares (2008) using a shallow water theory to describe the behaviour of water inside flooded compartments located below the main deck.

Dynamic effects may also be included using an approach by Vassalos et al. (1997) which uses empirical data from model experiments to build a database on phase and amplitude differences between ship motions and floodwater motions.

Finally, the behaviour of floodwater can also be described using computational fluid dynamics methods. Van't Veer and De Kat (2000) applied the Volume of Fluid (VOF) CFD method introduced originally by Hirt and Nichols (1981). This approach encompasses the discretization of the space of the flooded compartment, which is not occupied with machinery or cargo, by small volumetric elements. The equations of motion of the fluid are than solved and the velocity field obtained. Spaces occupied by equipment or cargo are modelled as impermeable cells. The numerical results obtained in the mentioned study compare quite well with experimental results obtained by forcing the oscillation of a model of the damaged compartment. However, the authors indicate that 3 h computing time are required to simulate 10 s of fluid motion.

Armenio and La Rocca (1996) presented a method for simulating fluid dynamics inside flooded compartments using the Navier-Stokes equations. Woodburn et al. (2002) use a similar approach in connection with turbulence models, using also the volume of fluid method to take into account the free surface. The forces obtained using these methods are then applied in the ship equations of motion as external forces. Again, this approach showed considerable computational time and some discrepancies compared to experimental results.

Another approach to the problem of calculating the motion of floodwater, applicable when its depth inside the compartment is small, is to use shallow water flow theory. The flow is then described using nonlinear hyperbolic equations which can be solved numerically using the random choice method described in Glimm (1965). This method permits obtaining the velocity and water depth in cells across the flooded compartment and may also be used for studying the water on deck problem. Dillingham (1981) used the method for one-dimensional cases and Pantazopoulos (1988) and Huang and Hsiung (1996) extended the method for three-dimensional flows. Santos and Guedes Soares (2003, 2008) applied the same method to describe the floodwater motion inside a flooded compartment under the main deck.

The numerical model by Chang and Blume (1998) uses this method to describe the behaviour of water on deck when depth is small. For larger depths of water on deck or higher roll angles, employs another method has to be employed, consisting of assuming that the free surface is plane but not horizontal. The Lagrange equation is used to obtain an equation of the motion of the free surface, which is solved in the time domain using the Runge-Kutta method.

5.5.4.3 Modeling Progressive Flooding

Progressive flooding refers to the flow of water between different compartments through non-watertight openings. This flow continues until a state of equilibrium is reached or sinking/capsize occurs. During this flow, the ship is subject to the so-called transient flooding and is said to be at *intermediate stages* of flooding (using the IMO terminology). This phase of flooding is generally not considered when the survivability of the ship in damaged condition is addressed, since this is generally assessed only for the final damaged condition. However, as a ship might capsize during transient flooding conditions, some provisions for checking her stability at intermediate stages of flooding are taken in SOLAS.

Numerical models of the dynamic behaviour of damaged ships are generally not adapted to deal with complex progressive flooding situations of multiple compartments, especially under the action of waves. An exception is the modelling of the flooding of asymmetric spaces, such as cross-connected side compartments. This type of arrangements is common in passenger Ro-Ro ships and its effects have been studied by De Kat (2000) using hydraulic models for reproducing the flow characteristics. The studies of Vermeer et al. (1994), Van't Veer and De Kat (2000) and Xia et al. (1999) also present numerical and experimental results regarding the same type of problems. In later works, apart from the simulation of the flow through ducts, effects of air compression and trapping in the flooded compartments are also modelled using the thermodynamic laws for gases. Recently, Ruponen (2007) developed a similar numerical model for calculating progressive flooding in complex subdivision arrangements in calm waters, taking into account air trapping and compression.

Van't Veer et al. (2002) have studied the progressive flooding of passenger spaces onboard a cruise ship with the objective of calculating the ship's time to sink or capsize in a certain seaway. Santos et al. (2002) applied a similar numerical model to the study of the flooding of the machinery spaces of a passenger Ro-Ro ship which suffered an accident and capsized.

These studies have been conducted mainly for passenger ships, but warship progressive flooding has also been considered by Palazzi and De Kat (2003), who studied the effects of cross-flooding arrangements in the dynamic behaviour of a damaged frigate in regular and irregular seas.

5.5.5 Benchmark Studies

The numerical methods described above have been evaluated within the scope of benchmark studies organised by the Specialist Committee on Extreme Motions and Capsize (now Committee on Stability in Waves) of ITTC. These studies have focused on the assessment of the survivability of damaged passenger ships, especially Ro-Ro ships, in waves. The main objective is to assess existing methods and tools regarding its capability to predict accurately damaged ship survivability.

The first conducted ITTC benchmark study, reported by Papanikolaou (2001), allowed first some conclusions regarding intact ship dynamics, namely that roll decay tests and intact ship responses in waves, even if extreme waves are considered, can be accurately predicted, although some deviations in the resonance region were noticed due to insufficiencies in the used semi-empirical roll damping models. In what concerns damaged ship motions, inconsistencies were found when simulating roll decay, roll natural period and roll damping in damage condition. This indicates a lack of proper modelling of damage ship hydrodynamics and of the flooding effects (inflow/outflow and floodwater dynamics). The simulated time series of motions in irregular waves indicate. substantial differences between numerical and experimental results, which result from inaccuracies in the calculation of hydrostatic properties of the ship and in the calculation of the exciting irregular seaway. However, as shown in Fig. 5.21, most participants of the benchmark study could predict with

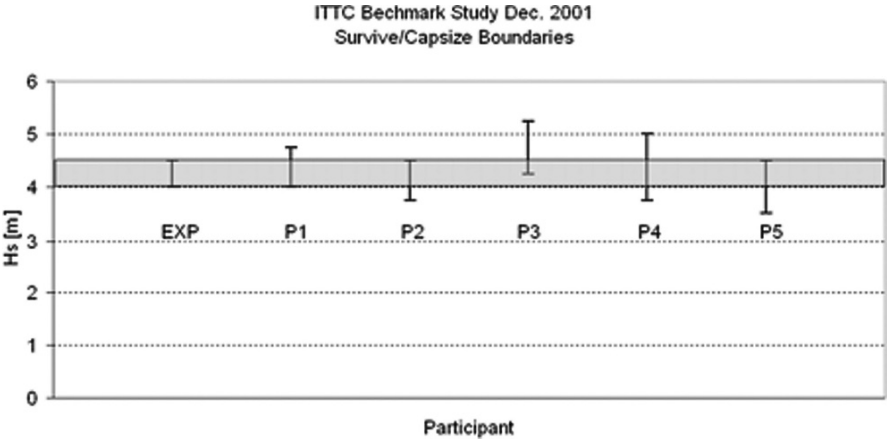

Fig. 5.21 Survival boundaries (Papanikolaou 2001)

good precision the survival/capsize boundaries and critical seastates of the benchmark Ro-Ro ship by using various numerical simulation models.

Building upon knowledge gained in the first benchmark study, a second study was conducted by Papanikolaou and Spanos (2004) on behalf of ITTC aiming at providing more in depth comparative information about the basic features of the numerical methods when applied to the simulation of the behaviour of the damaged ship in calm waters. The numerical methods results regarding the roll natural period show some scattering although the overall modelling of inertia and restoring forces was found to be satisfactory. The methods are highly sensitive to inaccuracies in roll damping prediction even in calm waters. At present, experimental data for determining semi-empirical roll damping coefficients seems necessary for all numerical codes. Regarding the dynamics of a tanker with a partially flooded compartment, it was concluded that numerical methods that consider the floodwater having its free surface continuously horizontal cannot capture the floodwater dynamics properly. Finally, the simulation of roll decay of a passenger Ro-Ro ship during transient flooding showed the importance of employed hydraulic coefficients for the simulated results.

Within the framework of SAFEDOR, as reported by Papanikolaou and Spanos (2008), a further benchmark study on the accuracy of the numerical codes in the prediction of damaged ship survivability in waves was carried out, complementing past and related benchmark studies of ITTC.

The numerical estimates on survivability of the damaged ship were found to be sensitive with respect to the periods of the incident waves, while less sensitive with respect to the assumptions for the discharge coefficients and ship loading condition. No conclusions could be derived for the effect of the viscous roll damping, while the present results seem to contradict conclusions from earlier benchmark studies, suggesting an increased importance for the values of the semi-empirical roll damping coefficients.

Table 5.8 Survival boundaries

Participant	$H_{s,\ surv}$	Mean	Diff. from mean	Exp
P1	3.23	3.00	+0.23	< 3.00 m
P2	1.75		−1.25	
P3	4.00		+1.00	
P4	3.00		+0.00	

The aggregate performance of the benchmarked codes appears divergent. Estimates for the survive boundary could deviate up to 1.0 m, compared to model experiments, which is quite high, while the codes have partly predicted opposite trends with respect to variations of basic parameters. Even for the codes that appear to be very accurately predicting the survival boundary (2 codes out of 4), it was found that they are characterized by a substantially different performance in the background (Table 5.8).

Studies on numerical methods have recently focused on the time-to-flood. Accordingly, a 3rd ITTC benchmark study was conducted in 2006, as reported by van Walree (2007). The objective of this benchmark study was to establish current capability and weaknesses in predicting, qualitatively and quantitatively, the time-to-flood for a quite complex configuration of compartments in a barge-like hull form. Experimental results from Ruponen et al. (2006) were used to validate the numerical codes regarding time-to-flood, motions and flooded volumes in compartments.

A typical result regarding the flooding of an upper deck compartment ("up-flooded" from a lower compartment) is shown in Fig. 5.22. Overall it can be stated

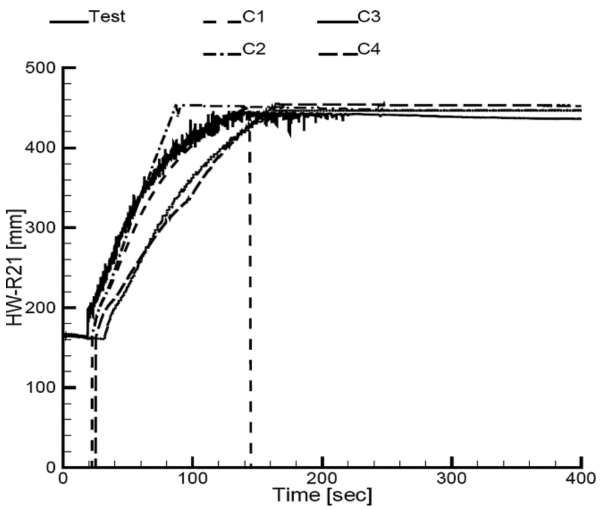

Fig. 5.22 Numerical and experimental levels of water in flooded compartment

that the steady state condition of all conducted tests was reasonably well predicted by the codes. The prediction of the flooding rates and transient phenomena was, however, less satisfactory. Reasonable time to sink predictions appear feasible, although with some uncertainty, by present numerical codes, for calm water conditions. However, their performance in waves still has to be evaluated.

5.5.6 Summary

A review of the open literature indicates that there are very few mature numerical models and tools for assessing damaged ship behaviour in waves available today.

The University of Glasgow and Strathclyde has developed and validated the code PROTEUS, mainly for passenger Ro-Ro ships and cruise vessels, which is available in different versions according to the type of application envisaged. There are versions of this code which consider three degrees or all six degrees of freedom and different modelling of floodwater behaviour.

The National Technical University of Athens has developed the code CAPSIM which includes all six degree of freedom; this code has been validated for passenger Ro-Ro ships, naval ships and fishing vessels. The same code may be applied to the assessment of ship's intact stability in waves.

MARIN disposes also its own numerical model, namely FREDYN, which is capable of describing the dynamics of damaged ships. This tool is also capable of evaluating the coupled manouvering and seakeeping performance of intact or damaged ships in various headings and has been validated mainly for naval and Ro-Ro ships.

HSVA has also developed in collaboration with the University of Hamburg a numerical model, namely the code ROLLS, which is also able to evaluate damaged ship dynamics. This tool calculates roll and surge motions in the time domain and the other motions in the frequency domain. It has been applied extensively in the evaluation of damaged passenger Ro-Ro ships.

Finally, Instituto Superior Técnico has also developed its own numerical model capable of simulating damaged ship motions in waves, progressive flooding and water on deck effects.

Closing, it should be noted that in the framework of project SAFEDOR some simplified but fast methods and tools have been developed for the probabilistic assessment of flooding and its effects on ship's damage stability and floatability. These methods and tools are elaborated and demonstrated in Chap. 6, Sect. 6.3 and Chap. 2, Sects. 2.1 and 2.2.

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5.6 Fire

5.6.1 Introduction

Fire is a very serious hazard both to people and cargo onboard a vessel. Therefore, a fire safety assessment is essential in risk-based ship design. A variety of methods are available for such an assessment along with the support by empirical data related to the vulnerability of humans exposed to fire and the associated smoke.

In principle, a numerical simulation of the generation and evolution of a fire and smoke movement can be performed using Computational Fluid Mechanics (CFD), e.g. *ANSYS-CFX*. However, all the input data needed are seldom at hand and, furthermore, the computational effort is enormous if more than just one single compartment or unit is to be considered. Therefore other more approximate methods, like the so-called zone methods, have been developed able to capture the qualitative behaviour of the evolution of a fire.

In the following a short outline of some of the methods dealing with the prediction of fire evolution will be given, illustrated by a few specific fire scenarios applications. Some of the main results and conclusions will be presented.

5.6.2 Fire in Containers and Cargo Space

In terms of cargo fire safety, a quantitative risk model for cargo fires has been developed, Povel et al. (2008). The model used fire engineering calculation results and Bayesian probabilistic modelling. Following from a Qualitative Design Review, which includes hazard identification (HAZID) according to the guidelines given by IMO, a fire scenario inside a closed cargo hold of a container vessel has been evaluated.

A representative vessel design (2500 TEU) was used as case study where prescriptive (according to currently available rules) fire protection measures were adopted. These measures, referred to as risk control options (RCOs), include measures such as improved container designs with better sealing and better thermal resistance/properties, fire detection systems for containers, advanced fire detection for cargo holds, as well as different automatic and manual fire extinguishing measures.

The development of a risk prediction model for cargo fires integrates two major parts. The first part comprises detailed CFD calculations and provides essential data of the fire development inside a 40 ft container as well as the fire spread in a cargo hold. These calculations were carried out using the *ANSYS CFX* software.

For the second part a model has been developed that addresses the quantification of risk by determining the probability of consequences resulting from defined fire scenarios. This was achieved by using the Bayesian Network modelling technique by use of the *HUGIN* software.

5.6.2.1 Fire Simulations

To represent a 40 ft container, the corresponding geometric model is 12 m long, 2.35 m wide and 2.4 m high. The container boundary has openings to represent the side vents as well as possible gaps around the doors and between the floor panels. The cargo is modelled as a set of boxes, each 1.2 m long, 0.8 m wide, 1.6 m high and raised 20 cm above the floor to simulate the air gap associated with the pallet that the cargo sits on. The gap between the cargo boxes was set to be 10 cm.

In the real container, the side vents are composed of a 2×5 grid of 9 mm diameter holes. These are represented in the CFD model by a single rectangular hole having the same total area of the holes and the aspect ratio of the grid. In the real container the gaps around the doors are composed of a narrow continuous horizontal slot at the top and bottom of the container frame and a vertical slot down the middle where the two doors meet. To reduce the number of nodes in the mesh the door gaps were modelled as a line of square holes such that the total area is the same as a continuous 2 mm wide gap. Similarly, the container floor is composed of panels with gaps of approximately 2 mm between them and these were represented in the CFD model as 3 square holes for each gap having the same total area. The modelling of the gaps around the door and between the floor panels is based on a conservative assumption for the air leakage of the container sealing. The leak areas are small but it has been shown previously that leakages can have a major effect on under-ventilated fires, and this is why they have been represented explicitly. The mesh consisted of 105,979 nodes and 336,229 volume elements. The mesh was inflated off all the walls using 3 inflation layers with the first layer height being set to 5 mm.

The fluid in the container was considered to be a combusting mixture of methane and oxygen as the fuel and oxidant and water and carbon dioxide as the combustion products (plus nitrogen as an inert component). All the openings (door gaps, floor gaps, side vents) were modeled as a pressure boundary having a default atmospheric pressure. The heat loss from the metal walls of the container was modeled with an external heat transfer coefficient of $5\,\mathrm{kW}/(\mathrm{m}^2\mathrm{K})$. The wooden floor was set to have a fixed temperature of $20\,^\circ\mathrm{C}$.

The effect of pyrolysis was modeled by keeping track of the temperature of all surface elements on the cargo. When the temperature exceeded a user specified critical value, in this case 500 K, a source of methane was applied to the surface element at a constant mass rate, which represented an equivalent fixed heat release rate for a fixed length of time such that the total amount of methane released reflected the estimated heat content of the cargo. An ignition source was simulated by turning on pyrolysis at the bottom corner of the cargo near the door.

An exploratory transient analysis has been performed with a total simulation time of 10 min. In this simulation the time step quickly attained the maximum allowed value of 0.5 s during the initial heating phase, was reduced to 0.05 s during the rapid fire spread phase and rose back to 0.5 s after the fire stopped spreading. Some results for the temperature distributions are shown in Fig. 5.23.

The above figures also show an iso-surface of temperature at 500 K, coloured grey. The cargo with the ignition source slowly heats up to the pyrolysis temperature

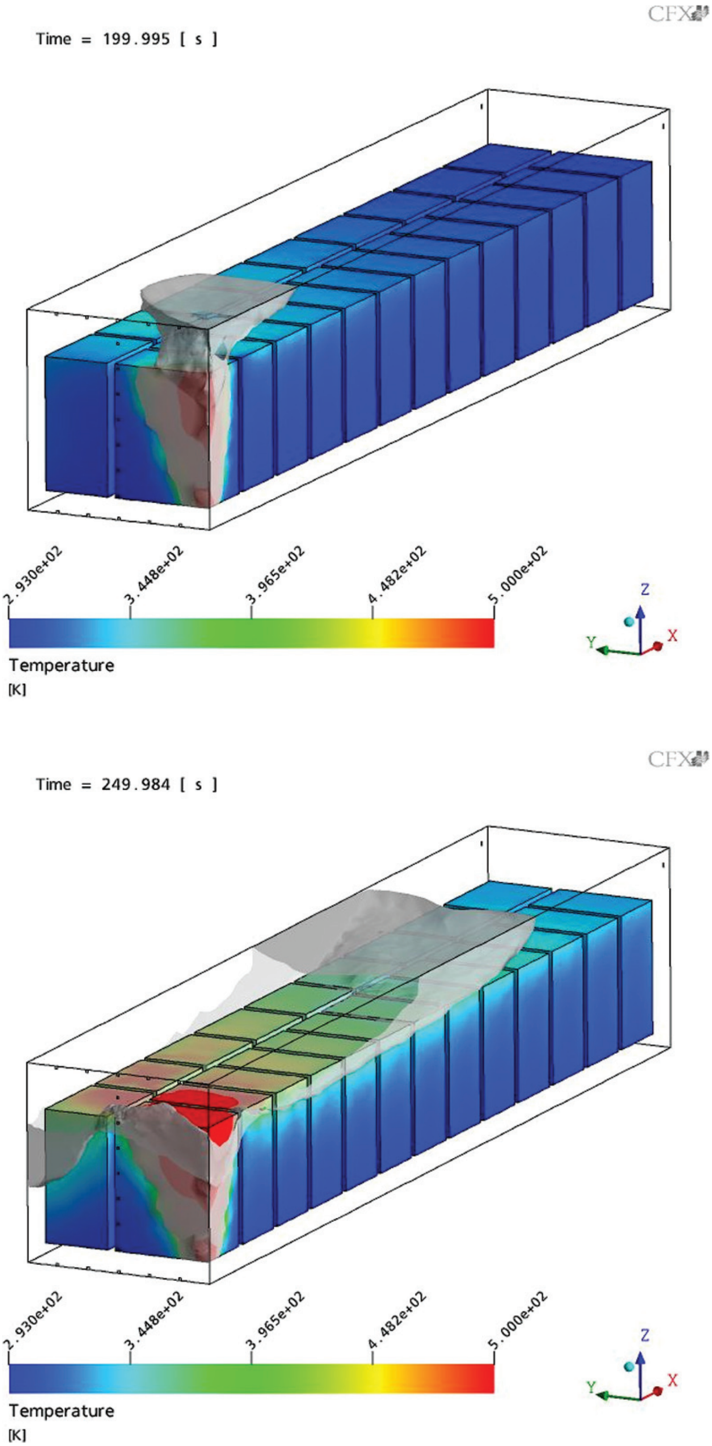


Fig. 5.23 The temperature on the cargo at 200 s (*top*) and 250 s (*bottom*)

along its exposed vertical corner resulting in more methane being released. At the same time a plume of hot gas spreads along the roof heating the top of the cargo blocks. At 250 s the top of the cargo blocks is close to the pyrolysis temperature and as a result, flame spread occurs rapidly across the top of the cargo blocks over the next 20 s. After this time the level of combustion diminishes, despite the continuing supply of fuel, due to the diminishing amount of available oxygen. At 300 s all of the oxygen has been consumed and the cargo blocks begin to cool.

In reality, it is expected that pyrolysis will be reduced as the concentration of methane in the container increases, thus allowing fresh air to enter the container. Under such a pyrolysis model, one of two possible burning modes is likely: A steady state mode representing a smouldering fire with a low pyrolysis rate and a continuous supply of air, or a mode in which the pyrolysis rate oscillates about a mean value. In either event, the maximum external surface temperature is unlikely to be greater than in the current simulation. More details can be found in Povel et al. (2008).

5.6.2.2 Bayesian Risk Model for Cargo Fire

In order to quantify the risk associated to cargo fires a model has been developed, Povel et al. (2008), determining the probability of a particular outcome that has been identified by the HAZID and being influenced by several prescriptive and additional risk control measures. Prescriptive measures are based on SOLAS regulations and classification guidelines, whereas additional measures arise from innovative and novel designs. Using this model it is possible to quantify the impact of these measures on risk. Various modelling techniques can be applied to assess the risk and Event Trees and Fault Trees, or the combination of both complementary methods, are the most common approaches. Unfortunately, both techniques have their disadvantages, since incidents are modeled as a sequence of specific events, in which it is difficult to represent the state of the system and the environment being analyzed. Furthermore, much effort has to be spent in order to include conditional dependencies into tree structures. Therefore, in the last years, Bayesian Networks, which are a familiar approach for modeling expert systems, is becoming popular also in safety applications. Since their formulation is more generic it is possible to convert any Event Tree or Fault Tree to a Bayesian Network.

The nodes in a Bayesian Network, representing either a certain event or a condition of the system, can have an arbitrary number of states, which can be distributed based on probability. A directed arc connecting two nodes symbolizes an influence of the states of one node on the distribution of the states of the other node. That means, for every node the number of probability distributions corresponds to the number of states of its parent nodes (or the combination of the states if there is more than one parent node).

To describe a cargo fire by means of a Bayesian Network first the fire incident itself has to be analyzed in order to identify possible scenarios with essential probabilistic parameters, which can be represented by nodes.

In the model discussed here it has been assumed that the fire will grow from the ignition inside a single container to a fire that affects more than one cargo hold. Therefore, the fire is separated into four particular fire stages based on the number of containers being affected and whether damages to the vessel structure will occur. Every fire stage relates to a consequence, namely, "minor damage", "major damage", "hazardous consequences" and "catastrophic consequences". The probability of suppression or containment of a fire in certain stage is influenced by various other parameters, such as fire fighting measures that can be undertaken. In order to exemplify the dependencies in the network a part of the model that represents the first stage (fire inside a single container) is shown in Fig. 5.24.

In order to demonstrate the conditional probabilities or dependencies in the network one can look at the node "Fire Spread of Goods". This node can have states such as "Very Fast", "Fast", "Moderate", etc. These states are distributed on probabilities based on experience. In case of an ignition inside a container the fire development is strongly dependent on the goods that are transported and their class of

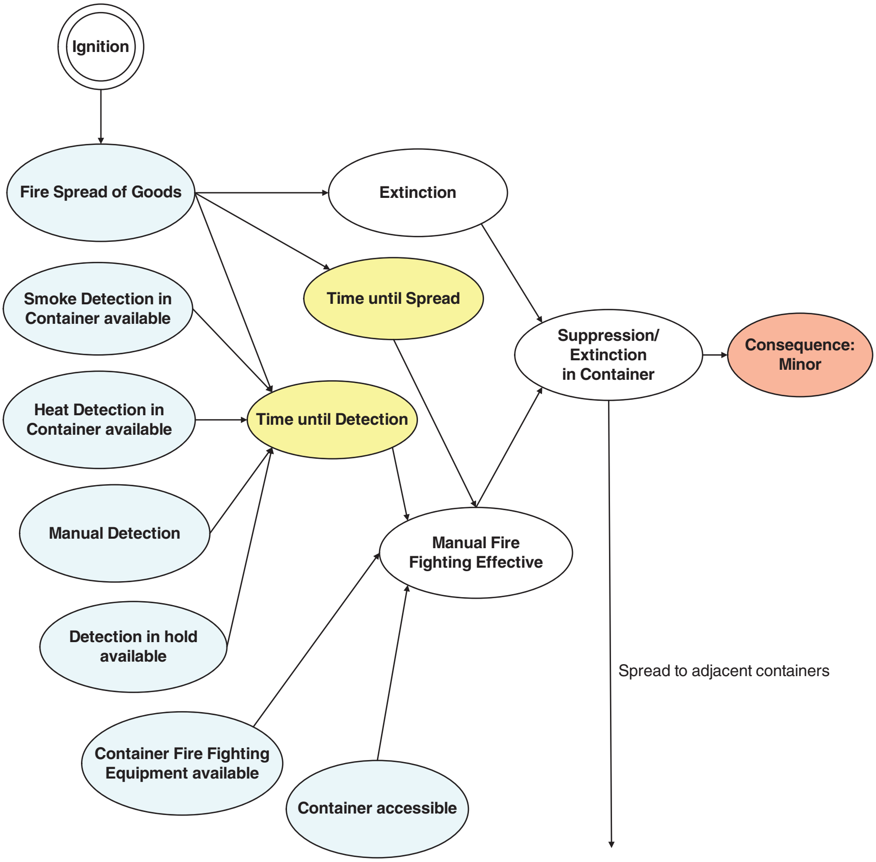


Fig. 5.24 Bayesian Network representing a fire in one container

fire spread. Apparently both, the probability of self extinction and the time available for fire fighting until fire spread to adjacent containers occurs, will be influenced as well.

The Bayesian Network presented is only a simplified representation of the real scenarios, but it can help understanding and quantifying the influence of different risk control options (RCOs). The impact of a particular option can be determined by using a procedure that is called “Observed Evidence”. In the context of risk control options it means that certain options, such as detection or fighting measures, can be either accounted or dismissed for the analysis by assigning the nodes representing a particular RCO a predefined state, rather than complying with a probability distribution. Thus, the direct influence of a particular Risk Control Option can be evaluated.

The main work when using a Bayesian Network is filling the probability tables of the nodes being influenced by each other. This information can be obtained from expert judgments, statistic evaluations, as well as from Fault Tree analyses.

Results from CFD simulations inside a container as well as inside a cargo area were used as an essential input to the Bayesian Network model since they deliver important characteristics having an effect on risk. From temporal and local parameters such as the development of fire spread and time lines for heat and thermal radiation not only the consequences for the transported cargo and vessel structure can be derived but also the response time of fire detection systems as well as the fire fighting measures can be obtained. Furthermore, the influence of risk control options on the above-mentioned parameters can be quantified and their costs effectiveness estimated.

By looking at the incident frequency of occurrence needed for “Break Even”, which is the frequency when expenses for the additional RCO pay off, only three of the options are interesting. These are “Improved Detection in Hold”, “Improved CO_2 System” and “HiExFoam System”, as shown in Fig. 5.25. It must be said that these results should be interpreted with care due to the large number of made assumptions.

The work carried out in Povel et al. (2008) led to the following main conclusions:

- Although CFD modelling proved very useful in gaining insight, the overall level of understanding about the fire progression inside containers and into the hold as well as the effectiveness of fire suppression options is still insufficient for proper quantification of the consequences, and hence of the risk.
- Very little information is available about fire ignition inside containers. This makes it difficult to address the probability modelling of ignition.

Given the various uncertainties and the lack of understanding associated with fire progression and suppression in cargo areas a general quantification covering a top-level scenario at the current stage is impossible. Thus, although the benefit from the developed model can be considered to be the introduced methodical approach to the problem, a more qualitative approach might have been more useful.

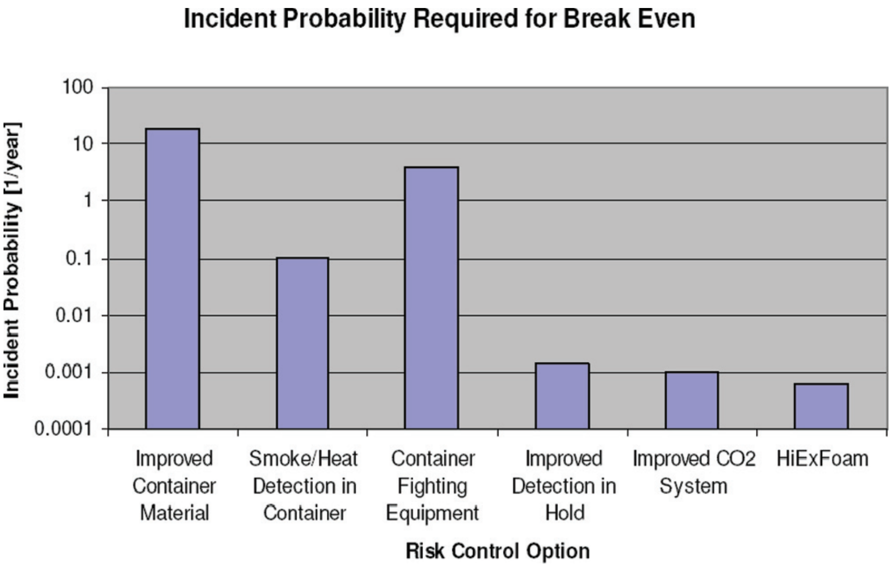


Fig. 5.25 Incident frequencies of occurrence required for pay-off of different RCOs

5.6.3 Fire Risk Analysis – Human Life

Following a Qualitative Design Review (QRD), the work on a Quantitative Risk Analysis (QRA) framework that could be used during concept design stages can be initiated. The following elements have been addressed: The probability of ignition in a particular space of the ship (p_{ign}), the probability of escalation (p_{esc}) and, the severity of the consequences of a serious fire event and the expected number of injuries or fatalities (p_i) was estimated. This approach can be adopted for the quantification of risk to human life in terms of the risk acceptance criteria proposed in the form of individual risk and FN curves. The main principles are illustrated in Figs. 5.26 and 5.27.

Work on the ignition and escalation models is still needed. In relation to the consequence analyses, the developments relate to an engineering tool to address the escalation and fire/smoke impact on occupants for specific scenarios, reported as follows:

- Modelling the environment insofar as it is relevant to the scenario.
- Spread simulators, e.g. fire/smoke propagation models, progressive flooding models, toxic gas diffusion models and water supply line contamination models.
- Occupant mobilization simulator, i.e. a model of crowd flow that can be controlled and programmed to follow any desired operation involving the shipboard occupants.

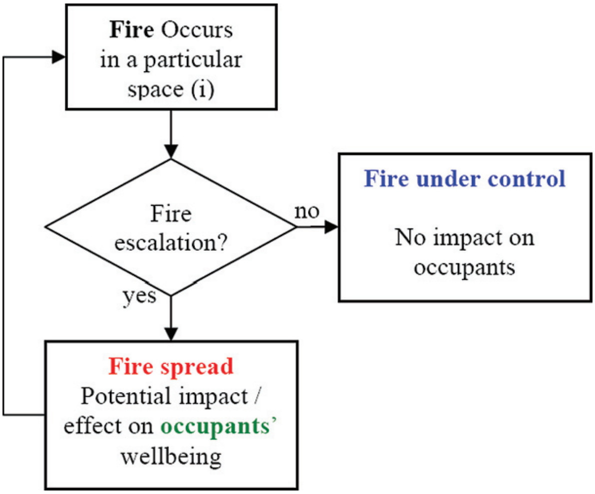


Fig. 5.26 Principle for fire risk analysis

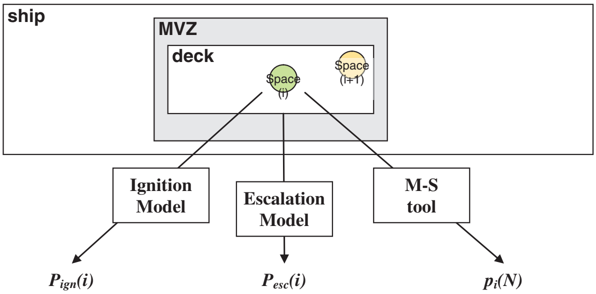


Fig. 5.27 The three main probabilities needed for a fire QRA

- Numerical model of the effect of the detriments, e.g. floodwater, smoke, heat, toxicity on the occupants.

A software platform where the above models are integrated has been used in the SAFEDOR project to evaluate the severity of consequences in specific fire scenarios. The principle of QRA has been illustrated with a case study of a main vertical zone (MVZ) of a typical large cruise vessel. Two scenarios including passenger accommodation and public spaces were evaluated for a SOLAS design (regarding the maximum size of a MVZ) and for an alternative design featuring a MVZ larger than the current SOLAS limit. The necessary fire engineering calculations were carried out using both a field (CFD) and a zone model, see Fig. 5.28. These analyses have been used to evaluate the risk to human life in terms of the number of occupants affected by the fire hazards (mainly smoke). Selected results from the CFD model are shown in Figs. 5.29, 5.30 and 5.31.

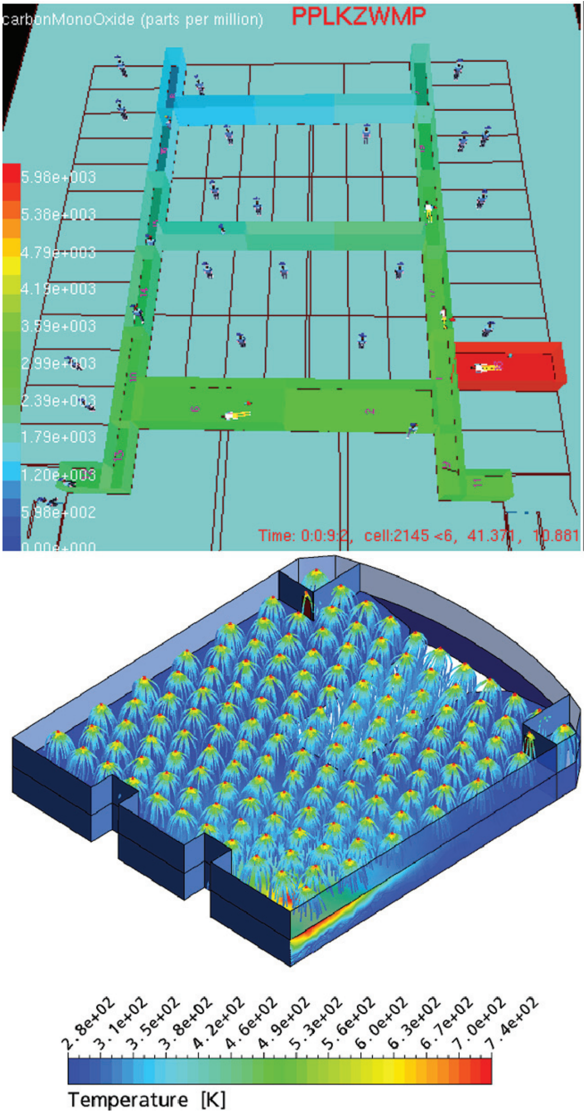


Fig. 5.28 Sample of results for passenger cabin fire scenario (*top*: SSRC zone and escape model) and public space fire scenario (*bottom*: ANSYS/CFX field model)

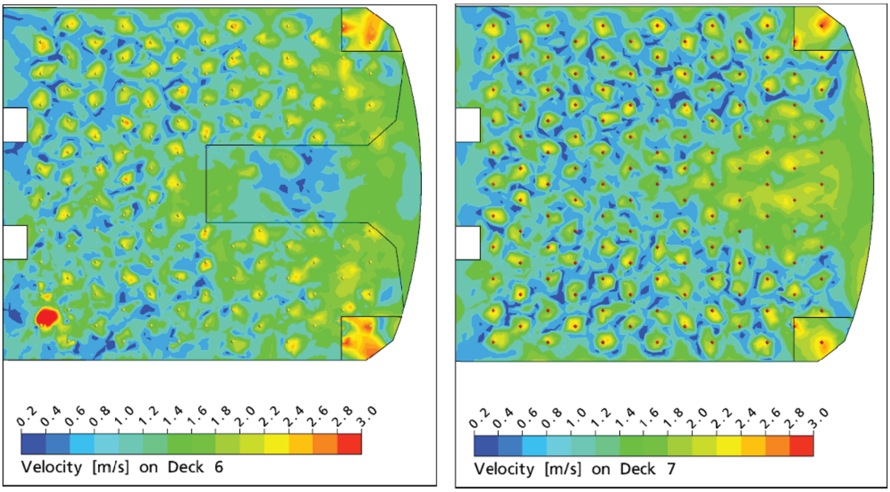


Fig. 5.29 Velocities at 260 s and 1.5 m from the floor: *left* Deck 6, and *right* Deck 7

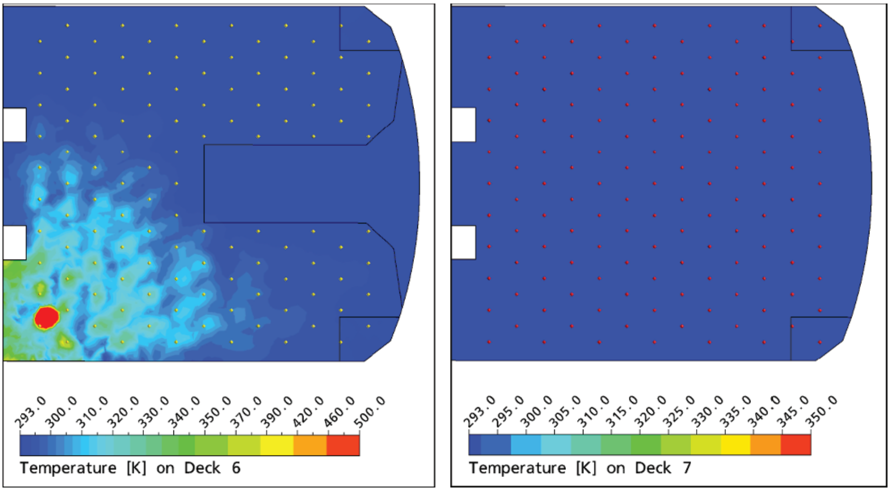


Fig. 5.30 Temperatures at 260 s and 1.5 m from the floor: *left* Deck 6, and *right* Deck 7

A non-structured numerical grid was built for the simulation. The grid contains 26,469 nodes that form 119,935 tetrahedral elements. Around the source, the mesh was locally refined and the mesh spacing reduced to approximately 25 cm. High resolution numerical scheme was used for mass, momentum and energy transport equations, whereas for the k and ε transport equations, an upwind scheme was selected to improve convergence.

Radiation intensities were calculated on a coarser mesh, which was obtained by joining 64 adjacent control volumes. For each of these volumes, the radiation

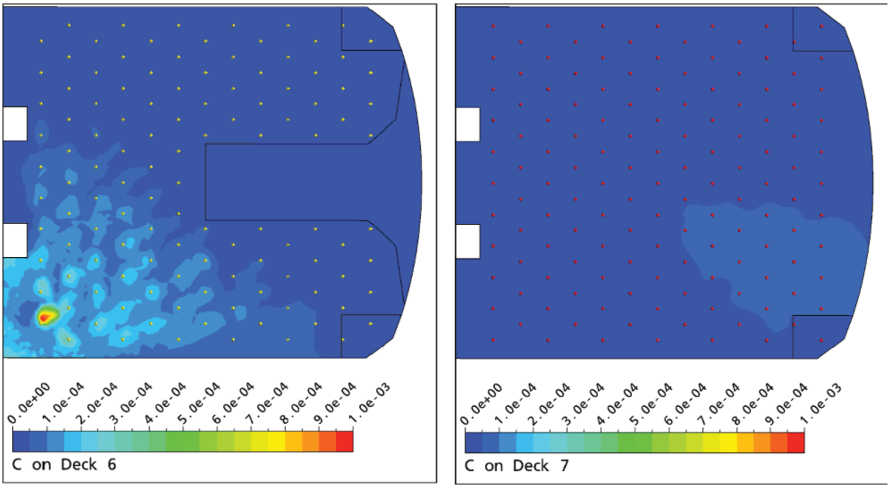


Fig. 5.31 Soot at 260 s and 1.5 m from the floor: *left* Deck 6, and *right* Deck 7

contribution was calculated from 24 rays in each angular direction. Particle injection frequency of a sprinkler was $10\,s^{-1}$.

The numerical simulation covered 1700 s of a real time fire scenario and it was performed in two parts. After the initial 360 s, when the doors are open, the simulation was stopped. The setup was changed to model the closed-door scenario. Then the simulation continued using previous results for the initial conditions.

Figure 5.29 presents the air velocity field. Velocities are high around the heat source and in stairways, where sprays and opening boundary conditions generate significant draft. Locally, each sprinkler separately induces a significant downward air movement due to entrainment, which is manifested as a local velocity peak.

Figure 5.30 shows temperature distribution 1.5 m above the floor on Deck 6 and on Deck 7. The simulation results show that at this level almost half of the Deck 6 is affected by a temperature rise, although only 10% of the area reaches temperature above 350 K. The Deck 7 temperature is unaffected. This indicates that the layer of hot gases is thinner on both decks and do not reach 1.5 m level except close to the source, where it is affected by a rising plume from the fire.

Figure 5.31 shows mass fractions of soot (C) determined from composition ratios.

The conclusions reached from the above results and the related analysis can be summarised as follows:

- Quantitative risk analysis using results from numerical models is a sound approach to evaluate the fire safety of novel designs.
- On the other hand the number of occupants affected by fire/smoke in particular scenarios is a strong function of the peak values of toxicity and temperature encountered by the occupants. This indicates that the fatality count so computed

should not be taken at face value, at least at the current stage of the predictive technology.

- The fatality count does, however, give a good insight and a reasonable figure for comparison between scenarios and between design alternatives.
- There is a need for standardization of fire-loss and fire risk calculation procedures. A standard procedure will ensure that the results computed independently by different analysts and simulation tools would numerically agree.

Another challenge faced in quantitative fire risk analysis is that of inadequacy of the available product model. In the present context, the spatial distribution of the combustibles along with their combustion related properties (e.g. ignition temperature, calorific content, chemical species content etc.) should be a part of the product model for fire-safety analysis. The thermal properties of walls, bulkheads, linings etc. should also be a part of the product model. Currently the information about these aspects is not formally available in the ship product models. A standardization effort should be directed to enforce creation and maintenance of the product model that satisfies the information requirements of fire safety analysis.

Acknowledgments Section 6 is based on work performed and documented within the SAFEDOR project by Daniel Povel, Uwe Langbecker, Kay Dausendschoen, Yehuda Sinai, Susann Gehl, Björn Forsman, Joanne Ellis, Kurt Riedel, A. Hovat, C. Staples, Jayanta Majumder, Romanas Puisa, Camille Azzi, Luis Guarin, George Psarros.

Reference of Section 6

Povel D, Langbecker U, Dausendschoen K, Sinai Y, Gehl S, Forsman B, Ellis J, Riedel Kurt (2008) Risk Assessment for Container Ships Focusing on Cargo Fire. Proceedings of the Interantional Conference Design & Operation of Container Vessels, The Royal Institute of Naval Architects, London, UK, November 2006.

5.7 Intact Stability

5.7.1 Introduction

Large roll motion of ships can lead to various types of failures ranging from seasickness over cargo shift and loss of containers to capsize of the vessel. Hence, it is important to minimise the roll motion during a voyage. Currently, on-board decision support systems, e.g. Rathje (2005), Nielsen et al. (2006) and Spanos et al. (2008), are being installed in vessels with the aim to provide the officer on watch with guidance on the best possible route, taking into account the weather forecast, the time constraints for the voyage and the limiting criteria for motions, accelerations and loads.

A main problem is real-time estimation of the sea state. Here two approaches are being tested in full scale. The first is based on the use of a wave radar, e.g. the *WAVEX* system, see Borge et al. (2000), and the second uses ship responses (e.g. motions, accelerations and strains) measured in real-time by sensors installed on board together with linear transfer functions to estimate the sea state, see Nielsen (2006), where a comparison between the two approaches is also found.

After estimation of the sea state, a real-time estimation of the maximum ship responses within the next few hours as function of ship speed and course is needed to guide the officer on the action to take if excessive responses are foreseen with the present course and speed. To linear responses the standard frequency domain approach using transfer functions can easily be applied. For non-linear responses, to which extreme roll motions belong, mostly nonlinear or quasi-nonlinear time domain simulations are employed to obtain related short-term statistics, e.g. Krüger et al. (2004), Daalen et al. (2005) and Spanos and Papanikolaou (2005). However, less time-consuming stochastic procedures have also been suggested. Most of them are based on simplifying, but quite reasonable assumptions, like equivalent linear damping, e.g. Bulian and Francescutto (2004), second- or third-order perturbation procedures, e.g. Neves and Rodriquez (2005), Melnikov functions, e.g. Hsieh et al. (1994) and Spyrou (2000) and moment closure techniques, Ness et al. (1989). More recently, different procedures based on the identification of *critical wave episodes* related to the roll motion have been suggested; see Spyrou and Themelis (2006), Jensen and Pedersen (2006) and Jensen (2007). The present account is largely based on Jensen (2007).

5.7.2 Roll Motion of a Ship

Comprehensive reviews of theoretical-numerical and experimental methods dealing with ship's intact stability can be found in recent reports of the Specialists Committee on Stability of Ships in Waves of ITTC, de Kat (2005). The report by de Kat (2005) discusses various modes of failure, i.e. capsize and the prediction procedures available. The report is partly based on results of a questionnaire distributed to a large number of organisations and thus reflects very well the current status. To cover all modes of failure (static loss of stability, parametric excitation, dynamic rolling, resonance excitation and broaching) a non-linear six-degrees-of-freedom time domain simulation procedure that includes viscous effects and manoeuvring models must be applied. Some commercial codes, e.g. LAMP, France et al. (2003) and Shin et al. (2004), seem to be able to produce valuable results with reasonable accuracy, but they are very time-consuming to run, restricting the application to regular waves or very short stochastic realisations.

Another non-linear six degrees of freedom simulation procedure is GL-SIMPEL, see e.g. Pereira (1988) that is based on a non-linear strip theory formulation. The frequency dependence of the added mass and damping is taken into account using a higher differential equation formulation. FREDYN, see e.g. France et al. (2003), is another non-linear code based on a strip theory formulation. Generally, these codes are much faster than non-linear three-dimensional procedures like LAMP and, as the three-dimensional effects on the roll motion is usually not that important, to be preferred for design work and onboard decision support system.

Other procedures have more limiting capabilities as some of the capsize modes are excluded. An example is the ROLLS procedure, Kröger (1986), where the following non-linear differential equation is used to estimate the roll angle ϕ, (omitting the terms due to wind and fluids in tanks):

$$\ddot{\phi} = \frac{M_\phi + M_{sy} - M_d - \Delta(g - \ddot{w})GZ(\phi) - I_{xz}[(\ddot{\theta} + \theta\dot{\phi}^2)\sin\phi - (\ddot{\psi} + \psi\dot{\phi}^2)\cos\phi]}{I_{xx} - I_{xz}(\psi\sin\phi + \theta\cos\phi)} \tag{5.23}$$

Here M_ϕ, M_{sy} and M_d are the roll moments due to waves, sway and yaw, and hydrodynamic damping, respectively. Furthermore, I_{xx} and I_{xz} are the mass moment of inertia about the longitudinal axis and the cross term mass moment of inertia. The displacement of the ship is denoted by Δ and g is the acceleration of gravity. The instantaneous value of the righting arm GZ is in irregular waves calculated approximately using the so-called *Grim's effective wave*. The heave w, pitch θ and yaw ψ motions are determined by standard strip theory formulations, whereas the surge motion is calculated from the incident wave pressure distribution. The advantage of this formulation compared to full non-linear calculations is the much faster computational speed, still retaining a coupling between all six- degrees-of-freedom, Krüger et al. (2004). The model can, however, not deal with broaching due to the assumption of a linear yaw motion. Both the ROLLS and the GL-SIMBEL procedures are described and validated in the IMO-SLF submission by Germany (2007).

Here a simplified version of Eq. (5.23) is considered. Both the heave motion w and the wave-induced roll moment M_ϕ are taken to be linear functions of the wave elevation, and some closed-form expressions given by Jensen et al. (2004) are applied. The cross term mass moment of inertia is assumed to be small, and pitch is thus only included through the static balancing of the vessel in waves in the calculation of the GZ curve. Furthermore, the sway, yaw and surge motions are ignored as the vertical motions have the largest influence on the instantaneous GZ curve. The damping term M_d is modelled by a standard combination of a linear, a quadratic and a cubic variation in the roll velocity. With these simplifications Eq. (5.23) reads

$$\dot{\phi} = -2\beta_1\omega_\phi\dot{\phi} - \beta_2\dot{\phi}|\dot{\phi}| - \frac{\beta_3\dot{\phi}^3}{\omega_\phi} - \frac{(g-\ddot{w})GZ(\phi)}{r_x^2} + \frac{M_\phi}{I_{xx}} \tag{5.24}$$

where r_x is the roll radius of gyration. The roll frequency ω_ϕ is given by the metacentric height GM_{sw} in still water:

$$\omega_\phi = \frac{\sqrt{gGM_{sw}}}{r_s} \tag{5.25}$$

It is clear that this model is very simplistic, but it is well suited to illustrate the proposed stochastic procedure as it can model parametric rolling, resonance excitation and forced rolling. Hence, it is possible to identify which mode is the most probable for a given combination of sea state, speed and heading. As broaching and dynamic rolling (where a strong coupling to surge exists) cannot be modelled by Eq. (5.25) following and stern quartering seas will be excluded from the present analysis and only heading angles ψ in the range from 60 to 180 degrees (head sea) will be considered.

The instantaneous GZ curve in irregular waves will here be estimated from numerical results for a regular wave with a wavelength equal to the length L of the vessel and a wave height equal to $0.05L$. These numerical results are fitted with analytical approximations of the form

$$\begin{aligned} GZ(\phi,x_c) = {} & (C_0\sin\phi + C_1\phi + C_3\phi^3 + C_5\phi^5)\cos^4\left(\frac{\pi x_c}{L_e}\right) + \\ & (D_0\sin\phi + D_1\phi + D_3\phi^3 + D_5\phi^5)\sin\left(\frac{\pi x_c}{L_e}\right) \end{aligned} \tag{5.26}$$

where the wave crest position x_c is measured relative to the aft end of the vessel. Similarly, the GZ curve in still water is fitted by

$$GZ_{sw}(\phi) = (GM_{sw} - A_1)\sin\phi + A_1\phi + A_3\phi^3 + A_5\phi^5 \tag{5.27}$$

The coefficients $(A_1, A_3, A_5, C_0, C_1, C_3, C_5, D_0, D_1, D_3, D_5, L_e)$ in Eqs. (5.26) and (5.27) are found by the least square method. Other polynomial or Fourier series representations have been suggested, e.g. Spyrou (2000) and Bulian (2005), and generally a very good fit can be achieved for the range of roll angles of interest.

In a stochastic seaway the following approximation of the instantaneous value of the righting arm $GZ(t)$ is then applied:

$$GZ(\phi,t) = GZ_{sw}(\phi) + \frac{h(t)}{0.05L}\left(GZ\left(\phi,x_c(t)\right) - GZ_{sw}\left(\phi\right)\right) \tag{5.28}$$

The instantaneous wave height $h(t)$ along the length of the vessel and the position of the crest x_c are determined by an equivalent wave procedure somewhat similar to the one used by Kröger (1986):

$$
\begin{aligned}
& a(t) = \frac{2}{L_e}\int_0^{L_e} H\left(X\left(x,t\right),t\right)\cos\left(\frac{2\pi x}{L_e}\right)dx; \quad b(t) = \frac{2}{L_e}\int_0^{L_e} H\left(X\left(x,t\right),t\right)\sin\left(\frac{2\pi x}{L_e}\right)dx \\
& X\left(x,t\right) = \left(x+Vt\right)\cos\psi \\
& h(t) = 2\sqrt{a^2(t)+b^2(t)} \\
& x_c(t) = \begin{cases} \dfrac{L_e}{2\pi}\arccos\left(\dfrac{2a(t)}{h(t)}\right) & \text{if } b(t) > 0 \\ L_e - \dfrac{L_e}{2\pi}\arccos\left(\dfrac{2a(t)}{h(t)}\right) & \text{if } b(t) < 0 \end{cases}
\end{aligned}
\tag{5.29}
$$

Note than in beam sea $h(t) = 0$ such that $GZ(\phi,t) = GZ_{sw}(\phi)$. Stationary sea conditions are assumed and specified by a JONSWAP wave spectrum with significant wave height H_s and zero-crossing period T_z. The frequency range is taken to be $\pi \leq \omega T_z \leq 3\pi$ covering the main part of the JONSWAP spectrum.

The next step in the solution procedure is to account for the stochastic behavior of the sea. The straight forward procedure is to generate time series of random waves and use them as input to the ship motion code and then extract extreme values by simple counting and subsequent fitting to a proper extreme value distribution, e.g. the Gumbel distribution. This, however, requires long simulation time and also CPU time to get sufficiently reliable results. A solution is to use clusters of computers. Other methods seek to identify the most probable wave episodes leading to a specified large roll angle. Spyrou and Themelis (2006) describe such an approach in which a specific ship motion parameter, e.g. a large roll angle, is calculated for a range of wave heights, wave periods and number of adjacent high waves. Thereafter, the probabilities of encountering these wave groups are determined and used to estimate the corresponding probability of exceeding the prescribed ship motion response. The feasibility of the method has been documented in Spyrou and Themelis (2006) and Themelis et al. (2007).

A related procedure for the calculation of exceedance probabilities and associated critical wave episodes has been developed in Jensen and Pedersen (2006) for parametric roll in head sea and extended in Jensen (2007) to cover other types of roll motions. This procedure uses the First-Order Reliability Method (FORM) to determine the mean out-crossing rate of the ship response considered. The procedure also identifies a design point with a corresponding most probably wave episode leading to the prescribed response value. Thereby, the tedious task to identify critical wave episodes is done automatically by the procedure and the user (i.e. the designer) only has to select or program a proper time-domain procedure able to model the ship response in question. All the statistical estimates are then done within a standard First-Order Reliability Method (FORM). In the present treatment, the time domain simulation routine, Eq. (5.24), has been linked to the FORM software of *PROBAN* (Det Norske Veritas 2003). It is clear that Eq. (5.24) has a rather limited accuracy, but anyway contains the main features needed to model parametric rolling, roll resonance in near beam sea and forced roll. It is straightforward to replace Eq. (5.24) with e.g. Eq. (5.23). The FORM procedure has also been applied recently in a concept for an onboard decision support system, Spanos et al. (2008).

In the following, the FORM procedure is first described in general terms and then results for a container ship are presented and discussed.

5.7.3 First-Order Reliability Method Applied Wave Loads

5.7.3.1 Design Point and Reliability Index

In the First-Order Reliability Method (FORM), the excitation or input process is a stationary stochastic process. Considering in general wave loads on marine structures, the input process is the wave elevation and the associated wave kinematics. For moderate sea states the wave elevation can be considered as Gaussian distributed, whereas for severer wave conditions corrections for non-linearities must be incorporated. Such corrections are discussed and accounted for by using a second-order wave theory in a FORM analysis of a jack-up platform Jensen and Pedersen (2006). In the present paper dealing with the roll motion of a ship, linear, long-crested waves are assumed and hence the normal distributed wave elevation *H(X,t)* as a function of space X and time t can be written

$$H(X,t) = \sum_{i=1}^{n} \left(u_i c_i(X,t) + \bar{u}_i \bar{c}_i(X,t) \right) \tag{5.30}$$

where the variables $u_i, \bar{u}_i$ are uncorrelated, standard normal distributed variables to be determined by the stochastic procedure and with the deterministic coefficients given by

$$\begin{aligned} c_i(x,t) &= \sigma_i \cos(\omega_i t - k_i X) \\ \bar{c}_i(x,t) &= -\sigma_i \sin(\omega_i t - k_i X) \\ \sigma_i^2 &= S(\omega_i) d\omega_i \end{aligned} \tag{5.31}$$

where ω_i, $k_i = \omega_i^2/g$ are the n discrete frequencies and wave numbers applied. Furthermore, $S(\omega)$ is the wave spectrum and $d\omega_i$ the increment between the discrete frequencies. It is easily seen that the expected value $E[H^2] = \int S(\omega) d\omega$, thus the wave energy in the stationary sea is preserved. Short-crested waves could be incorporated, if needed, but require more unknown variables $u_i, \bar{u}_i$.

From the wave elevation, Eqs. (5.30) and (5.31), and the associated wave kinematics, any non-linear wave-induced response $\phi(t)$ of a marine structure can in principle be determined by a time domain analysis using a proper hydrodynamic model:

$$\phi = \phi(t \,|u_1, \bar{u}_1, u_2, \bar{u}_2, \ldots, u_n, \bar{u}_n) \tag{5.32}$$

Each of these realisations represents the response for a possible wave scenario. The realisation which exceeds a given threshold ϕ_0 at time $t = t_0$ with the highest probability is sought. This problem can be formulated as a limit state problem, well-known within time-invariant reliability theory (Der Kiureghian 2000):

$$g(u_1,\bar{u}_1,u_2,\bar{u}_2,\ldots,u_n,\bar{u}_n) \equiv \phi_0 - \phi(t_0\,|u_1,\bar{u}_1,u_2,\bar{u}_2,\ldots,u_n,\bar{u}_n) = 0 \qquad (5.33)$$

An approximate solution can be obtained by use of the First-Order Reliability Method (FORM). The limit state surface g is given in terms of the uncorrelated standard normal distributed variables $\{u_i,\bar{u}_i\}$, and hence determination of the design point $\{u_i^*,\bar{u}_i^*\}$, defined as the point on the failure surface $g = 0$ with the shortest distance to the origin, is rather straightforward. A linearization around this point replaces Eq. (5.33) with a hyperplane in 2n space. The distance β_{FORM}

$$\beta_{FORM} = \min \sqrt{\sum_{i=1}^{n} \left(u_i^2 + \bar{u}_i^2\right)} \qquad (5.34)$$

from the hyperplane to the origin is denoted the (FORM) *reliability index*. The calculation of the design point $\{u_i^*,\bar{u}_i^*\}$ and the associated value of β_{FORM} can be performed by standard reliability codes (e.g. *PROBAN*, Det Norske Veritas 2003). Alternatively, standard optimisation codes using Eq. (5.34) as the objective function and Eq. (5.33) as the constraint can be applied.

The integration in Eq. (5.33) must cover a sufficient time period $\{0,t_0\}$ to avoid any influence on $\phi(t_0)$ of the initial conditions at $t = 0$, i.e. to be longer than the memory in the system. Proper values of t_0 would usually be 1–3 minutes, depending on the damping in the system. Hence, to avoid repetition in the wave system and for accurate representation of typical wave spectra $n = 15$–50 would be needed.

The deterministic wave profile

$$H^*(X,t) = \sum_{i=1}^{n} \left(u_i^* c_i(X,t) + \bar{u}_i^* \bar{c}_i(X,t)\right) \qquad (5.35)$$

can be considered as a design wave or a critical wave episode. It is the wave scenario with the highest probability of occurrence that leads to the exceedance of the specified response level ϕ_0. For linear systems the result reduces to the standard *Slepian* model, see e.g. Lindgren (1970), Tromans et al. (1991), Adegeest et al. (1998) and Dietz et al. (2004). The critical wave episode is a useful result as it can be used as input in more elaborate time domain simulations to correct for assumptions made in the hydrodynamic code, Eq. (5.32), applied in the FORM calculations. Such a model correction factor approach provides an effective tool of accounting for even very complicated non-linear effects (Ditlevsen and Arnbjerg-Nielsen 1994).

It should be noted that other definitions of design waves based on a suitable non-uniform distribution of phase angles have been applied, especially for experimental applications in model basins. The selection of the phase angle distribution is, however, not obvious, see e.g. Alford et al. (2005).

5.7.3.2 Mean Out-Crossing Rates and Exceedance Probabilities

The time-invariant peak distribution follows from the mean out-crossing rates. Within a FORM approximation the mean out-crossing rate can be written as follows, (Jensen and Capul 2006):

$$\nu(\phi_0) = \frac{1}{2\pi\beta_{FORM}} e^{-\frac{1}{2}\beta_{FORM}^2} \sqrt{\sum_{i=1}^{n} \left(u_i^{*2} + \bar{u}_i^{*2}\right) \omega_i^2} \tag{5.36}$$

based on a general formula given by Koo et al. (2005). Thus, the mean out-crossing rate is expressed analytically in terms of the design point and the reliability index. For linear processes it reduces to the standard Rayleigh distribution. Often the gradient vector $\{\alpha_i^*, \bar{\alpha}_i^*\} = \{u_i^*, \bar{u}_i^*\} / \beta_{FORM}$ to the design point does not vary much with exceedance level ϕ_0. Hence, Eq. (5.36) reduces to

$$\nu(\phi_0) = \nu_0 e^{-\frac{1}{2}\beta_{FORM}^2} \tag{5.37}$$

where ν_0 can be viewed as an effective mean zero out-crossing rate. Finally, on the assumption of statistically independent peaks and, hence, a Poisson distributed process, the number of exceedance of the level ϕ_0 in a given time T can be calculated from the mean out-crossing rate $\nu(\phi_0)$:

$$P\left[\max_T \phi > \phi_0\right] = 1 - e^{-\nu(\phi_0)T} \tag{5.38}$$

The present procedure can be considered as an alternative to the random constrained simulation, see e.g. Dietz et al. (2004). The present method has, however, the advantage that the number of time domain simulations is much smaller due to the very efficient optimisation procedures within FORM, and that it does not require the curve fitting of lines of constant probabilities needed in the other procedure. Furthermore, the present procedure does not rely on a mean wave conditional on a linear response and can hence be applied also to bifurcation types of problems like parametric roll. In such cases the optimisation procedure used in the FORM analysis must be chosen appropriately, i.e. of the non-gradient type. In the present case a circle step approach is used, Det Norske Veritas (2003). Furthermore, to facilitate the convergence of the optimisation procedure, the limit state surface, Eq. (5.33), is replaced by a logarithm transformation:

$$\begin{aligned}
&\tilde{g}(u_1, \bar{u}_1, u_2, \bar{u}_2, \ldots, u_n, \bar{u}_n) \equiv \\
&\text{logt}(\phi_0) - \text{logt}(\phi(t_0 \,|u_1, \bar{u}_1, u_2, \bar{u}_2, \ldots, u_n, \bar{u}_n)) = 0 \\
&\text{logt}(y) \equiv \begin{cases} -1 - \log(-y); y < -1 \\ y; \quad -1 \leq y \leq 1 \\ 1 + \log(y); \qquad 1 < y \end{cases}
\end{aligned} \tag{5.39}$$

Finally, an arbitrary starting point different from zero is used.

The FORM is significantly faster than direct Monte Carlo simulations, while mostly very accurate. In a study Jensen and Pedersen (2006) dealing exclusively with parametric rolling of ships in head sea the FORM approach was found to be two orders of magnitude faster than direct simulation for realistic exceedance levels and with results deviating less than 0.1 in the reliability index. The difference in effort between Monte Carlo and FORM simulations might be even much larger, as shown in a recent seakeeping assessment study of Spanos et al. (2008). Similar observations are noted also in the present study.

It should be mentioned that the present procedure bears some resemblance to the approach adopted by Søborg and Friis-Hansen (2004). The difference is basically in the excitation process, where the present continuous wave excitation in Søborg and Friis-Hansen (2004) is replaced by a discrete excitation in time. The advantage of the present procedure is that it can directly represent the shape of actual wave spectra and that it provides an analytical formula, Eq. (5.36), for the mean out-crossing rate.

5.7.4 Numerical Example

A container ship with main particulars given in Table 5.9 is considered. The damping coefficients, β_1–β_3, are taken, quite arbitrarily, from a different study vessel, Bulian (2005), but reasonably correspond to about 0.05 in equivalent linear damping.

The coefficients in Eqs. (5.26) and (5.27) are given in Table 5.10.

The units of the coefficients are metres with the roll angle given in radians. The approximations are accurate for roll angles up to 0.9 radians, Jensen and Pedersen (2006). It is noted that L_e is slightly shorter than the length of the ship. The GZ curves are shown in Fig. 5.32 and it is clear that a significant reduction in righting lever occurs when the wave crest moves from AP to 0.25L forward of AP. This is quite typical for ships with fine hull forms like container ships.

By use of the closed-form expressions given in Jensen et al. (2004) for the heave w and the wave-induced roll moment M_ϕ, all pertinent data for calculation of the

Table 5.9 Main particulars of a container ship

Length L	Breadth B	Draught D	Block coeff. C_b	β_1	β_2	β_3	GM_{sw}	Radius of gyr. r_x	Speed V
284 m	32.2 m	10.5 m	0.61	0.012	0.40	0.42	0.89 m	0.4B	6 m/s

Table 5.10 Coefficients in the analytical approximations for the GZ curves

A_1	A_3	A_5	C_0, D_0	C_1, D_1	C_3, D_3	C_5, D_5	L_e
10.7964	2.30187	−2.97748	2.96515, −0.40240	2.06522, 0.83103	−3.6616, 1.66807	0.83496, −1.40701	259.2 m

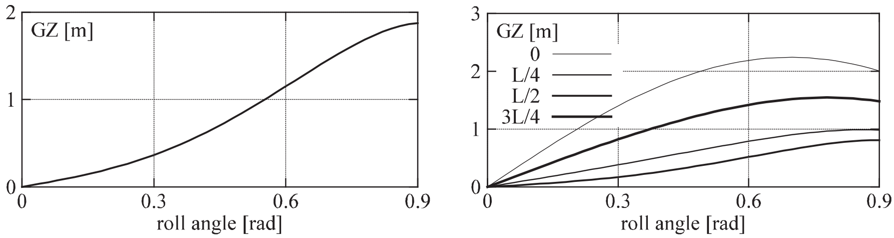


Fig. 5.32 *Top*: GZ curve in still water. *Bottom*: GZ curves in regular waves with wave length equal to the ship length L and a wave height equal to $0.05L$. Wave crest positions at $x_c = 0, 0.25L, 0.5L, 0.75L$ and L

roll angle as function of time are defined. In order to show that Eq. (5.24) can model parametric roll, calculations have been performed with a regular wave with an encounter frequency close to twice the roll frequency, Jensen and Pedersen (2006). Two wave heights are used: one (3.65 m) where parametric roll is not triggered and one slightly higher (3.7 m) where parametric roll develops. The roll motions for the two wave heights are shown in Fig. 5.33. The onset of parametric roll and its saturation level are clearly noticed.

The regular wave height needed to trigger parametric roll is thus about 3.7 m for the present vessel. If the wave height is increased above this value, parametric roll develops faster and to a higher saturation level. These results are consistent with both model test results and numerical calculations using more elaborate hydrodynamic codes, France et al. (2003).

In the following, results are shown for parametric roll motions in head sea. Results for other heading can be found in Jensen (2007).

The reference sea state has a significant wave height $H_s = 12$ m and zero-crossing wave period $T_z = 11.7$ s. The zero-crossing period is chosen such that parametric roll can be expected due to occurrence of encounter frequencies in the range of twice

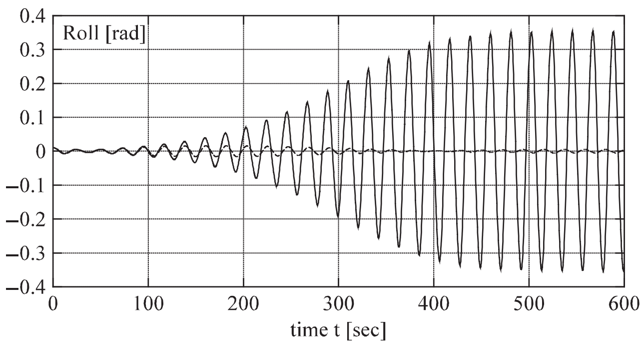


Fig. 5.33 Parametric roll in a regular wave (*solid line*) and the roll response for a slightly smaller regular wave (*dashed line*), Jensen and Pedersen (2006)

the roll frequency. Note, however, that neither the encounter frequency nor the roll frequency is constant in irregular waves.

The time simulations are carried out from $t = 0$ to $t = t_0 = 300$ s. The effect of the initial condition ($\phi(t = 0) = 0.01$ radians) is negligible after about 50 s, but in order to build up parametric roll a longer duration is needed. With $n = 50$ equidistant frequencies, the wave repetition period relative to the ship is about 400 s depending on the forward speed.

5.7.4.1 Parametric Roll in Head Sea in a Stochastic Seaway

A detailed analysis using the present approach is given in Jensen and Pedersen (2006). As an example the most probable roll response and the associated critical wave episode, Eq. (5.35), corresponding to exceedance of a roll angle of 0.5 radians, are given in Fig. 5.34.

The interesting observation is as stated in Jensen and Pedersen (2006): "The critical wave episode is basically a sum of two contributions: firstly, a "regular" wave with encounter frequency close to twice the roll frequency and a wave height just triggering parametric roll and, secondly, a "transient" wave with magnitude depending on the prescribed roll response ϕ_0". The last part resembles the critical wave episodes as obtained from quasi-static response analyses (e.g. Adegeest et al. 1998) and has basically the shape of the autocorrelation function. The first term, which is independent of the prescribed response level, is unique for parametric roll, but is needed to initiate parametric roll. After the peak in roll angle has been reached (i.e. for t > 300 s) the first part is seen to disappear. This is consistent with an unconditional mean wave equal to zero.

A parameter study has been made to quantify the sensitivity of the reliability index β_{FORM} to the sea state parameters H_s, T_z and the forward speed V. As the wave spectrum does not change shape with H_s the critical wave episode, Eq. (5.35), becomes independent of H_s. A change of H_s by a factor μ will then just change the design point and hence also β_{FORM} by a factor $1/\mu$. This behaviour has previously been noted by Tonguć and Söding (1986) and is also mentioned and discussed in the IMO-SLF submission by Germany (2007). Clearly this property greatly facilitates the long-term convolution of the heeling angle.

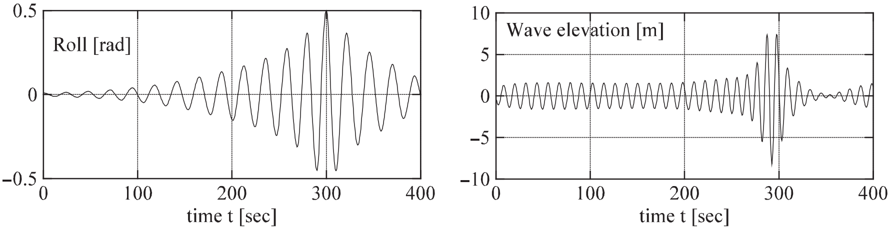
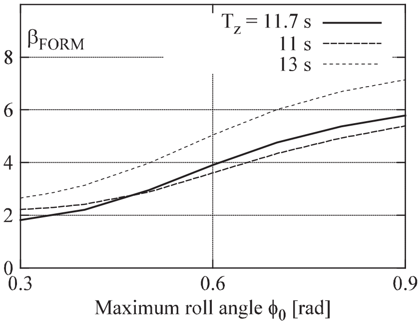


Fig. 5.34 *Top*: Most probable roll response yielding $\phi_0 = 0.5$ radians at $t_0 = 300$ s. *Bottom*: Corresponding critical wave episode



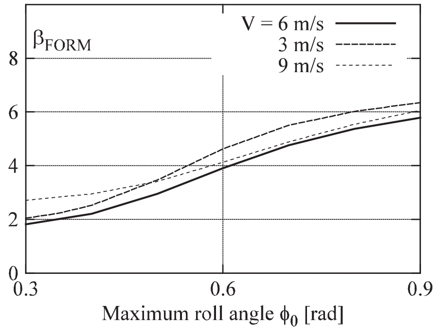


Fig. 5.35 Reliability index β_{FORM} as function of limiting roll angle ϕ_0 for different zero-crossing periods T_z and ship speeds V. Reference case: Head sea, $H_s = 12\,\mathrm{m}$, $T_z = 11.7\,\mathrm{s}$, $V = 6\,\mathrm{m/s}$, $n = 50$ and $t_0 = 300\,\mathrm{s}$

The variation with the zero-crossing period T_z is more complex, as shown in Fig. 5.35. Increasing T_z moves the two-to-one resonance condition away from the dominant encounter wave and roll resonance periods and hence increases β_{FORM}. By lowering T_z an increase in β_{FORM} is seen for smaller roll angles whereas a decrease is noted for higher roll angles. This is due to the GZ dependence of the roll frequency, which implies that the roll resonance period decreases with increasing roll angle.

The variation with ship speed V, Fig. 5.35, shows that the probability of parametric roll decreases, if the speed is either lowered or increased for the present example. For lower limiting roll angles it is seen to be better to increase the speed than to reduce it, assuming that sufficient powering for the ship is available.

Finally, it is noted that for a linear system the reliability index β_{FORM} would be linearly dependent on the limiting roll angle ϕ_0 (with the standard deviation as scale parameter), but this is clearly not the case here.

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5.8 Mustering, Evacuation and Rescue

The process of evacuating a passenger ship is a very complex one, not least because it involves the management of a large number of people on a complex moving platform, of which they normally have very little knowledge. These characteristics make ship evacuation quite different to evacuation from airplanes and buildings as the first only involve relatively simple geometries, whilst the second imply steady platforms, normally with no need for assistance to be given to its occupants during an evacuation and no need for their preparation to survive a harsh environment following a successful evacuation. These inherent problems, coupled to limitations in time to the extent that evacuation may often be untenable, render decision making during a crisis a key to successful evacuation and any passive or active support encompassing design for ease of evacuation, crew training, evacuation plans/procedures and intelligent systems onboard critically important.

Following the *Herald of Free Enterprise* and the *Estonia* ferry disasters, work at the IMO Marine Safety Committee (MSC) focused on the development of recommendations and guidelines to ensure safe and efficient evacuation procedures for passenger ships. This has led to the definition of guidelines for the numerical simulation and analysis of the evacuation processes of passenger ships, as laid down in the interim guidelines MSC/Circ.909 (IMO 1999), later superseded by MSC/Circ.1033 (IMO 2002) and lastly updated MSC/Circ.1238 (IMO 2007). It is noted, however, that the recommended analysis is only mandatory for newly built Ro-Ro passenger ships in compliance with SOLAS reg. II-/28-1.3 and reg. II-2/13.7.4 (which entered into force on July 1, 2002), whereas for other existing or newly built passenger vessels (cruise ships) the IMO recommends the analysis acc. to the guidelines on a voluntary basis. More stringent recommendations are likely to follow in the future, when a variety of issues related to large passenger ship safety have been settled at IMO.

5.8.1 The Shipboard Evacuation Problem

Before proceeding with the intricacies of the evacuation analysis and the description of related simulation tools, it is important to define the problem we try to solve and the degree to which this problem is defined adequately for any evacuation analysis to be meaningful.

In general, the ability to evacuate a ship environment within a given time and for given initial conditions (Evacuability) may be defined as follows Vassalos et al. (2001a,b, 2002, 2003 and 2004) (Fig. 5.36):

$$E = f\{env, d, r(t),\ s[evacplan,\ crew\ functionality,\ mobility\ impairment\ index];\ t\}$$

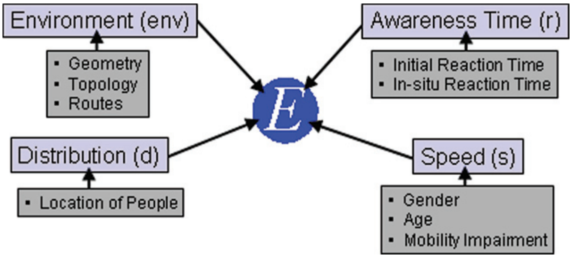

Fig. 5.36 The concept of Evacuability (E)

Based on this expression, the following needs to be explained and emphasised:

- *Initial Conditions (IC): env, d, r(t)*

  env: Ship environment model, pertaining to geometry, topology and domain semantics. For any comparisons to be meaningful we need to assume a time invariant environment for evacuation simulations. An environment changing with time (e.g., blocking doors and exits online) could not easily allow for quantifiable assessment of these effects, as it would be very difficult to repeat any such action in precisely the same state of the simulation model. However, the ability to change the environment online could offer a strong basis for crew training and for decision support in crisis management.

  d: Initial conditions of the evacuation problem, pertaining to spatial and temporal demographics of the people onboard. The actual demographics will actually be randomly distributed with the possibility of fixing some initial values, e.g., placing handicapped people on the embarkation decks and/or near an exit. As such, the initial distribution of people's demographics ought to be sampled to identify its effect on evacuability. The latter could be avoided if the distribution is known with sufficient accuracy (confidence) that a specific spatial distribution in a given time is taken to define a specific scenario for evacuation notation (or indeed any other operational or design) purposes.

  r(t): Response time, assumed to follow a uniform random distribution and hence it has to be sampled for various distributions in order to evaluate its effect on evacuability.

  IC should be defined and remain fixed during the execution of the simulation. Guidance notes/rules could be devised as part of the evacuation notation to ensure that such conditions are defined correctly and uniformly. Once the initial conditions are defined, simulation could then begin.

- *Evacuation Dynamics (ED)*: s [evacplan, crew functionality, mobility impairment index]

  s(ni): Walking *speed* of individual flow units, constituting the main motion variable of evacuation dynamics. The fact that each person onboard is dealt with as an individual flow unit and that every procedural (evacplan)/functional(crew assistance)/behavioural(microscopic) parameter could be accounted for as a multiplicative factor in ascertaining walking speed, provides for a unique and relatively easy way in simulating evacuation, essentially being able to deal with the effect of all of these parameters by simply following a given evacuation plan, accounting for crew assistance in some agreed quantifiable way and then sample walking speed for each individual flow unit from a corresponding distribution (see Figs. 5.1–5.10). Using the relevant Mobility Impairment Index (MII) the walking speed in each case can straightforwardly be calculated. From a development of realistic simulation of evacuation point of view, a great deal of effort may have to be expended to accurately quantify MII for all the pertinent microscopic behaviour as well as for specific crew assistance.

It should be noted that though there are common elements in the simulation of passenger evacuation equally applicable to ships, buildings or aircrafts, there exist critical differences between them which are likely to have a significant (and hence crucially important) effect on the outcome that ought to be addressed at the outset. These include the following:

5.8.1.1 Modeling the Ship (Virtual) Environment

Geometry: The complexity of ship geometry needs to be properly modeled and to account for a great variety of possible escape routes. The difference between an innovative VR model and brute-force modeling could be an order of magnitude in the time taken to produce a virtual ship model and a similar margin is expected concerning the size of data set.

Topology: Closely related to ship geometry and hence unique to ships are topological issues and schemas of evacuation "flows", for example multiple configuration layouts that could lead to disorientation and confusion of passengers.

Semantics: Most semantic specific information is crucially affecting evacuation, mainly because of the geometric complexity but also due to adversity of the sea-ship environment, reinforced by uncertainties in the time available, distance to land, functionality of Life Saving Apparatus, etc.

Platform: Ships move, on occasions severely, which further exacerbates disorientation and reduces mobility, whilst other contributing factors more often than not worsen this situation further, e.g., progressive flooding that may also curtail evacuation time to the extent that evacuating thousands of people in situations that may include restricted access became untenable.

Sea environment: Evacuation pertaining to dry land-based scenarios, means escaping to safety. In ships, it usually means escaping to sea, where rescue is far from being settled.

5.8.1.2 Modeling Human Behaviour

Passenger numbers: In the majority of other cases, evacuation from enclosed spaces does not involve very large numbers of people. This is, however, not so with passenger ships and especially ultra large cruise ships. This in itself presents modeling problems in terms of macroscopic and microscopic movement of people, processing capacity and information handling. These, in turn, give rise to needs of multi-threaded programming and parallel processing, particularly for use in immersive technology and/or employing the navigation interface of a virtual reality integrated environment.

Way-finding and path selection problems: Deriving from the ships' geometric complexity, these problems are exacerbated by the moving base, often severe time constraints and the anticipation of an awaiting unfriendly environment, thus complicating most aspects of human behaviour.

Uncertainty modeling: This derives from the unpredictability of human behaviour as well as the inherent structural instabilities associated with the passenger ship evacuation problem.

5.8.1.3 Passenger Mustering/Evacuation Process Modeling

Procedures: Evacuation strategies, procedures and decision support systems are likely to affect drastically the success of passenger evacuation in ships, more so than in other enclosed spaces, again primarily because of the plethora of parameters likely to affect evacuation in such a complex environment with so many people.

Evacuation scenarios: In addition to evacuation strategies that may be considered (abandon ship, transfer to refuge centres or a combination of the two) and the range of possible incidents (fire, collision, progressive flooding, cargo shift, foundering), it is in the multitude of scenarios that innovative thinking is imperative.

Holistic approach: It would be sub-optimal to model the various procedures (assembly, embarkation, launching of life boats, etc) separately or indeed sequentially. A holistic approach is necessary to understand the evacuation process in ships and to properly model and analyse it for design, operational and regulatory purposes.

Ship abandonment: When transfer to refuge centres is not an option, ship abandonment is most important aspect of passenger evacuation and wholly ship specific (albeit there is strong similarity with offshore platforms) involving such aspects as ship and LSA dynamics and LSA functionality issues whilst accounting for human behaviour.

5.8.1.4 Multi-Agent Modeling

The lowest common denominator of the many definitions of "agent" is an encapsulation of code and data, which has its own thread of control and is capable of executing independently the appropriate piece of code depending on its *own state* (the encapsulated data), the *observables* (the environment) and the *stimuli* (messages from other parts of the system or interactively provided). The agent's action model is essentially a "sense-decide-act" loop. The sense and decide steps may be coalesced, as the sensing is nothing more than the interface of the agent with the data structures representing the environment. The decision process requires access to the perceived information, thus perception is not a complex process but rather a simple access interface between the environment and the agents. Notably, the actions of agents may also change the environment, giving rise to what is called *interactive fiction*.

Multi-agent is a further generalisation of process-based modeling methods where the environment is very well defined and the agents may communicate in a fairly versatile manner. In natural systems, all component parts "live" in some sort of topological space (predators and prey may live on a two dimensional forest floor, data packages traverse a network graph and the evacuees move around on a 2D deck or offshore installation layout). An *environment* is defined to be an artificial representation of this space. Autonomous agents can perform the activities defined by a computer program in this environment. This strong sense of environment does not exist in a process-based simulation. Processes are only aware of themselves and the resources they wish to acquire.

In the implementation the environment is an appropriate collection of data structures in the computer. Communication in multi-agent simulation describes all interaction between real-life entities. This makes multi-agent simulation an extremely powerful tool but also one, which is hard to verify in the context of known mathematical theory. The essence of using agents requires a rigorous definition and full implementation of the environment and its interfaces with the agents as well as an inter-agent communication protocol, as described next.

Modeling the environment model is one of the most important aspects of multi-agent modeling. In the whole, this consists of three aspects - geometry, topology and domain semantics. The perception model for the agents will be able to use the information in these three abstractions at different levels of the decision processes. The whole ship layout is segmented into Euclidian convex regions (simple rectangles in Evi 3.0) with a structure of a linear space, directly connected if they have a common gate. This connectivity topology, for all computation and analysis purposes can be represented by a graph.

In ship layout terms regions are defined as cabins, corridors, public areas (or subsets of these), each with its own connectivity, defined by the gates (these may be actual or artificial doors). Figures 5.37, 5.38 and 5.39 next illustrate schematically these ideas. The path of the agents leading to the embarkation station is determined by searching the connectivity graph of the doors. Currently, the length of the path is taken as the criterion of optimality for network flow.

A minimal description of the ship layout will enable designers to modify the layout easily (add a new corridor or a staircase in virtually no time without having to draft the details of it using an elaborate CAD tool), hence obtaining evacuation performance faster, and thereby making simulation an ideal design tool.

The contrary can be also easily achieved - by simply blocking areas, regions or whole fire zones one can easily examine the effect of these changes and therefore the sensitivity of each different part of the vessel on evacuation capability.

Furthermore, the availability of $2^1/_2$D and 3D models allows for real time visualisation, in which the complete geometric details of the ship and human agents may be utilised to provide an extremely realistic representation. As an alternative,

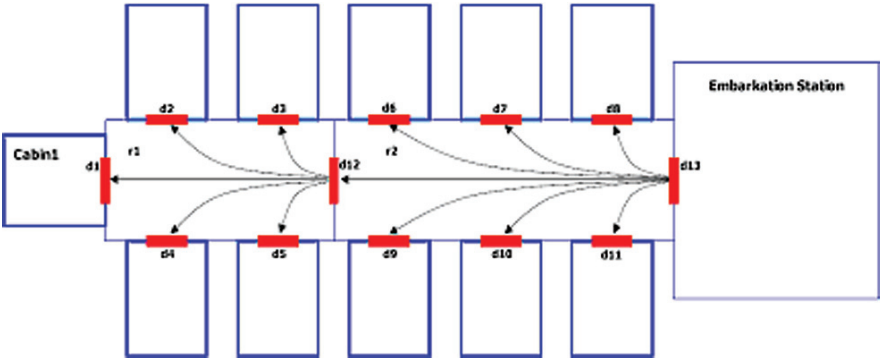

Fig. 5.37 Simple illustration of the path-planning algorithm

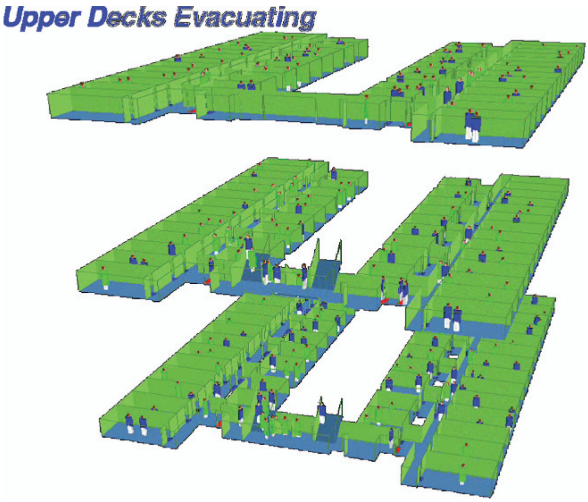

Fig. 5.38 Simulation of evacuation by the EVI v.3.1 software (http://www.safety-at-sea.co.uk/evi)

the code can also be executed separately, allowing a much faster evaluation of a simulation and leaving visualization as a post-processing alternative.

5.8.1.5 Mesoscopic Modeling

The evacuation objective moving a large number of passengers from one area of the ship to another requires two levels of modeling. At the high level, there is the planning and development of routing information which will guide an agent through the environment topology. At the low level, the agent is required to travel between the entrance and exits of the geometry, and to avoid the walls, obstacles and other agents moving the surrounding environment. This combination of macroscopic and microscopic detail is termed Mesoscopic modeling.

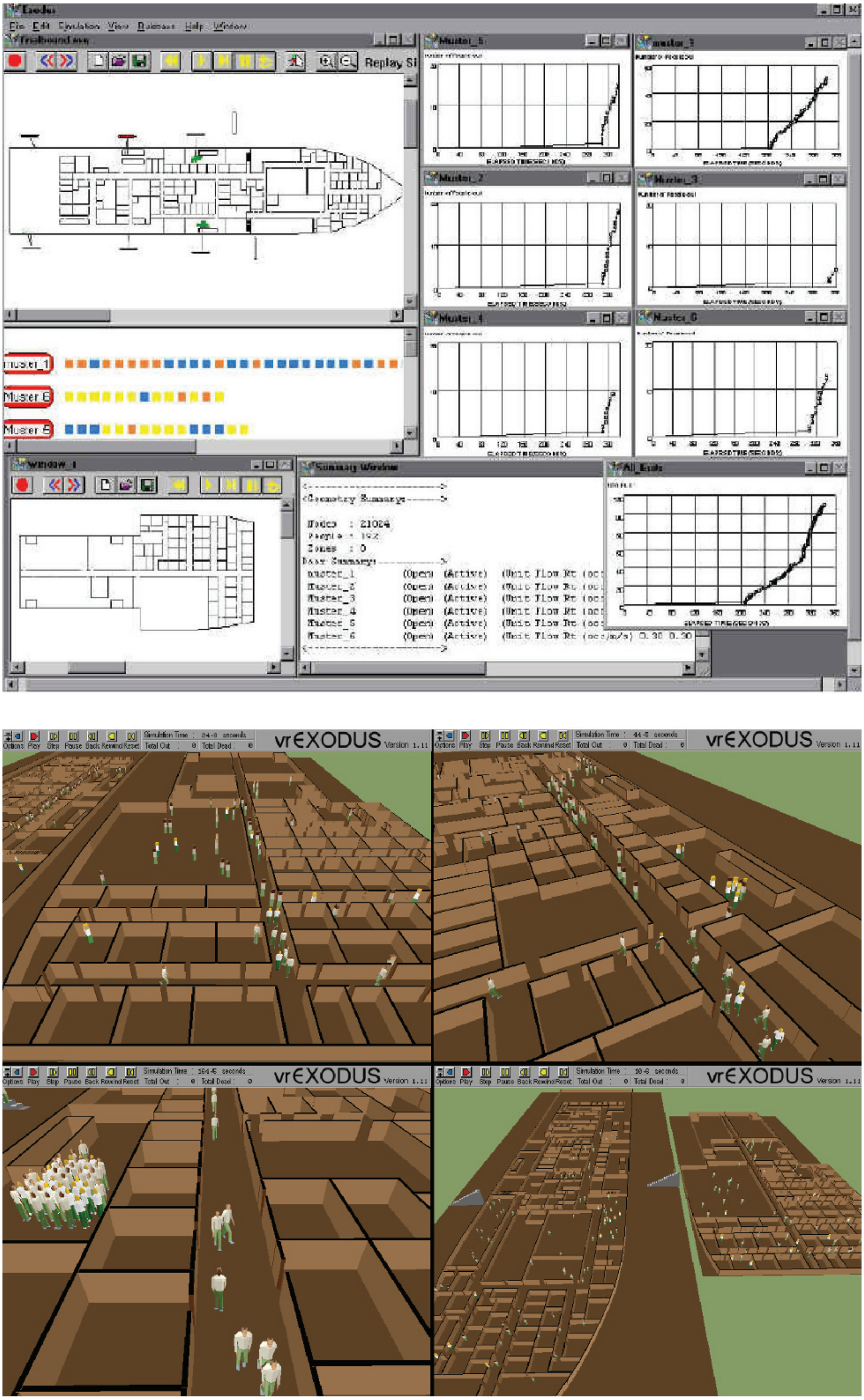

Fig. 5.39 Snapshot of simulation of the evacuation of a Ro-Ro ferry by vrEXODUS v 1.11 (www-fseg.gre.ac.uk/exodus/)

5.8.1.6 Macroscopic Modeling – High Level: Path Planning and Graph Search

With increasing complexity of the minimal geometry of the ship to thousands of doors and regions, it is very important to have an efficient path-planning process. The path-planning algorithm adopted is illustrated in Fig. 5.37, explaining how only the distance information from each door to the embarkation station needs to be left with the door's id. When an agent is located in a region, the distance information from each door of the region can be obtained, thus allowing the agent to simply head to the shortest path leading to the destination area. Re-planning during evacuation is also possible if, for example, there is a dense crowd "blocking" the path or a blackout in the presence of fire or smoke.

5.8.1.7 Microscopic Modeling – Steering of Agents

Given that environment is modeled as small discrete convex geometric elements, the process of moving from one door (gate) to another becomes a process of the pursuit of a static target. However, with additional complexities such as other agents and obstacles, the process of steering becomes significantly more complex. The decision of how to approach this specific problem is one which determines the entire design of the simulation architecture. The key issue is the identification of a technique which will allow enough information to be retrieved from the surrounding locality to enable a decision to be made on a course of action. Consequently, the choice of solution depends on matching the efficiency of the technique for obtaining information from the locality to the desired range of decisions (capability) of the agent. There are several solutions to this problem.

Grid based techniques: Grid based techniques simplify the problem of obtaining information from the surrounding locality by dividing the space up into a grid. Consequently, it is then very easy for an agent to search neighbouring squares. This approach makes for a very rapid simulation tool. However, due to relationship between the size of the square and the size of agents there is only a relatively low number of decisions that can be taken. Furthermore, discrete grid bases approaches are severely limited on variety of geometries that can be represented.

Social Force Methods: Social force methods can be see as the exact opposite to the grid based approach. These methods aim to model the interaction between agents and obstacles in great detail. A force based system is used, controlled by the distances between, to obtain a technique can provide continuous decisions. In accordance with the force based approach, agents operate in a continuous space which allows for a maximum range of flexibility in the geometric environment. However, the continuous space approach is very expensive when it comes to determining information around the locality of an agent. Consequently, this approach is not particularly effective for tools operating in a practical engineering environment.

Hybrid approaches: Evi uses a hybrid approach which aims to take the advantages from the other two techniques. It represents an approach which aims to utilise the effectiveness of grid based technique with the flexibility of social force methods.

In order to simplify calculation, a range of discrete decisions are established around the agent with the objective of identifying the one which will allow the agent to travel the greatest distance toward the local target. In addition, a continuous local (social/personal) space is established around each agent which other agent will aim to avoid. This space is use to prevent deadlock situation when the number of agents in an area become dense. The agent makes a decision of the best use of its personal space to resolve any conflicts that may arise. As a result, this approach allows the evacuation process to be modelled in sufficient detail and still run in real time.

5.8.2 Tools for Simulation and Analysis of Passenger Mustering and Evacuation of Ships

There are a variety of ways to scientifically and practically address this topic. Regression models, queuing models, route-choice models, gas-kinetic and macroscopic models, microscopic models, have all been used as different approaches to the problem of the evacuation analysis Schreckenberg and Sharma (2002). Nevertheless the most impressive and promising approach is that of application of simplified or more advanced Virtual Reality Simulators (Kostas, 2006). Such tools have been introduced in the past solely as navigation or maneuvering simulators requiring sophisticated hardware and significant investments. The most known software systems that are nowadays applied to the assessment of the shipboard evacuation are briefly described and comparatively assessed in the following.

5.8.2.1 EVI (http://www.safety-at-sea.co.uk/evi)

EVI (**Ev**acuability *I*ndex) is a multi-agent evacuation simulation software package developed in compliance with the requirements of IMO's interim guidelines MSC/Circ.1033 (IMO 2002). For a detailed coverage of the employed methods and the underlying research work embedded in EVI, the reader can consult the EVI related publications: Dogliani et al. (2004) and Vassalos et al. (2001a,b, 2002, 2003 and 2004).

EVI was originally developed at the Ship Stability Research Centre (SSRC) of the Universities of Glasgow and Strathclyde; the software was further refined and is now marketed by Safety at Sea. It is one of the few evacuation simulation tools developed specifically to address shipboard evacuation in the marine environment. It is also one of the few tools to use continuous space modelling allowing any ship accommodation layout to be accepted. The simulation can be visualized in a *3*D *virtual reality-like* environment allowing the progress of the evacuation to be reviewed. Any congestion or locations of bottlenecks can be thus rather easily identified. Furthermore, the tool features full telemetry and playback so that the user can review and replay at any time during the simulation. The latest release, EVI 3.1, addresses, as stated by its developers, ship evacuation issues beyond the IMO guidelines by introducing features which can give through-life support in the design, operational and training requirements of a passenger vessel.

A central issue of the research work supporting the EVI package is the *mesoscopic modeling*. As stated by its developers:

> The evacuation objective of moving a large number of passengers from one area of the ship to another requires two levels of modelling. At the high level, there is the planning and development of routing information which will guide an agent through the environment topology. At the low level, the agent is required to travel between the entrance and exits of the geometry, and to avoid the walls, obstacles and other agents moving the surrounding environment. This combination of macroscopic and microscopic detail is termed mesoscopic modelling.

The crowd modelling methodology of EVI follows a rather top-down approach. Specifically, EVI combines grid based techniques and social force methods to arrive to a real-time (grid-based techniques are generally very fast but rather simplistic) and at the same time natural looking simulation outcomes.

5.8.2.2 EXODUS (http://fseg.gre.ac.uk/exodus/)

EXODUS is a software platform developed at the Fire Safety Engineering Group of the School of Computing & Mathematical Sciences of the University of Greenwich. For a detailed coverage of the theoretical background and the main features of EXODUS, see its main related publications: Caldeira-Saraiva et al. (2004) and Galea et al. (2004). EXODUS consists of several software products targeting a variety of evacuation environments. These products are:

- airEXODUS: for applications involving aircrafts.
- buildingEXODUS: for all type of buildings (hospitals, sport facilities, airport terminals etc).
- maritimeEXODUS: for ship evacuation.
- railEXODUS: for train simulations.

Furthermore vrEXODUS, when coupled with one of the above products, enables the generation of animation sequences of computed simulations.

Specifically, *maritimeEXODUS* has the following features and capabilities:

1. Recognition by passengers of the need for emergency action i.e. response to alarm.
2. Preparatory actions e.g. collect life jacket, reunite family, deploy crew, etc.
3. Progressive evacuation to place of relative safety i.e. refuge or assembly station.
4. Preparation/deployment of escape system e.g. prepare lifeboats, deploy Marine Evacuation System (MES).
5. Abandoning the vessel e.g. boarding and lowering lifeboats etc.

Depending on the nature of the “what if” conditions being simulated, all of the above features may be included, while other, more focused scenarios, may only require some of these components. For performing the required simulation scenarios reliably, the evacuation model is equipped with the appropriate set of functionalities and access to the necessary data sets. Furthermore, the scenario under consideration may target situations occurring in calm sea conditions or involve situations with list or roll and may be evaluated at day or night. Naturally, this diversity imposes a requirement for a variety on the data sets and the modelling capabilities.

maritimeEXODUS makes use of marine specific data for the simulation of the performance of passengers under conditions of ship's list and heel. These data sets have been collected by partners of the developer's group at FSEG. As the model has the flexibility to allow the user to alter all of the pre-set default values, it is easily adaptable when new data becomes available. Furthermore, the abandonment component of *maritimeEXODUS* permits, as its name implies, the simulation of the abandonment phase. This includes the use of most currently available escape systems such as MES, davit launched lifeboats, life rafts, etc. In maritimeEXODUS V4.0, new capabilities for handling vertical ladders, 60 degree stairs, water tight doors and hatches have been included.

5.8.2.3 AENEAS

(http://www.gl-group.com/maritime/newbuilding/shipsafety/aeneas/)

AENEAS is a similar software package used for passenger evacuation analysis; it has been developed in close cooperation between *Germanischer Lloyd* and *TraffGo*. It is, as EVI, in full compliance with the specifications of IMO MSC/Circ.1033 and the latest MSC/Circ.1238 (IMO 2007). The underlying modelling and the methodological approach are presented in Meyer-König et al. (2007) and Valanto (2006). AENEAS follows a rather bottom-up per-person agent modeling approach. Although its agent modeling and behavioral scheme is rather simplistic, it has been shown to deliver realistic results.

In brief AENEAS uses the ship's general arrangement plan and automatically divides it into a grid of square cells that are used both for agents and space representation. Software agents model the individual persons with properties ranging from simple walking speed up to "equations of motion" of considerable complexity. AENEAS is a fast-performing simulation tool that allows frequent simulation repetitions even for large crowd populations (3000–4000 persons).

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5.9 Concluding Remarks

This chapter has presented a number of recently developed numerical methods and software tools to predict the probability of occurrence and the consequences of various accidental scenarios for ships. Some of the methods and tools seem quite mature and have been validated with experiments, whereas others still are subjected to significant research and development efforts.

The tools should give the ship designer valuable help when optimizing and assessing the layout and safety of innovative ships. In addition the tools are important for rule-making bodies and maritime safety authorities as they are needed in the process of changing from prescriptive to rational, performance-based rules and design procedures.

Chapter 6
Applications

Dag McGeorge, Bjørn Høyning, Henrik Nordhammar, Apostolos Papanikolaou, Andrzej Jasionowski and Esa Pöyliö

In this chapter, three applications of risk-based approaches to ship design are elaborated, namely the development and design of a lightweight composite sandwich superstructure of a RoPax vessel, the risk-based optimisation of cargo block of an AFRAMAX tanker for enhanced capacity and reduced environmental impact and the development and design of a fast displacement RoPax vessel of enhanced survivability and performance.

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6.1 Lightweight Composite Sandwich RoPax Superstructure

Dag McGeorge, Bjørn Høyning and Henrik Nordhammar

Abstract Lightweight composite materials have a long and successful track record in demanding and weight-critical applications. The benefits of lightweight composite materials have so far not been available to the merchant ship designer because international regulations require that the structure shall be made of non-combustible materials. However, these regulations allow alternative arrangements that deviate from such prescriptive requirements provided that adequate safety is demonstrated by an engineering analysis. For a RoPax ship this method has shown that a weight saving of about 60% can be achieved for the superstructure if the traditional steel superstructure is replaced by a lightweight composite design. This estimate accounts for structural fire protection and other risk control measures. An acceptable level of safety was documented for the new risk-based composite design. This demonstrates the feasibility of significant weight saving in superstructures of merchant ships by using composite materials and gives promise for more efficient and profitable merchant ship designs in the future.

6.1.1 Introduction

Fibre reinforced plastic (FRP) composite materials offer high strength at low weight. A particularly effective form of construction is obtained by using sandwich panels where two light and strong FRP laminates are separated by a lightweight core as illustrated in Fig. 6.1. Such sandwich structures provide both high stiffness and strength at low weight compared to other common forms of construction. For this reason, FRP sandwich structures have been used extensively in such demanding maritime applications as high speed craft and naval ships.

Although weight is more critical in high speed craft than in other merchant ships and composites offer additional advantages in some types of naval ships, weight saving is attractive also for merchant ships. The application of composite materials to merchant ships has, however, been very limited because the International Convention for the Safety of Life at Sea (SOLAS) (IMO 1974) requires that "the hull, superstructures, structural bulkheads, decks and deckhouses shall be constructed of steel or other equivalent material" (Ch II-2 Reg. 11), the latter being defined as non-combustible materials (Ch II-2 Reg. 3.33). This has till now prevented the use of combustible composite materials in the main load-bearing structure of ships approved according to SOLAS.

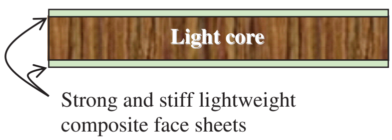

Fig. 6.1 The sandwich form of construction

SOLAS was recently amended with the new Regulation 17 in Ch II-2 allowing for approval of alternative designs and arrangements provided that the safety of the alternative arrangement is documented by an engineering analysis. A composite design may be regarded such an alternative arrangement and, provided that adequate fire safety can be documented, the SOLAS convention provides an opening for approval of such designs. In what follows, the benefits of using this opening to introduce light-weight composite structures to shipbuilding are demonstrated.

6.1.2 Developing the Novel Risk-Based Design

The initial design case selected for this work was an existing RoPax passenger vessel with roughly a length of 200 m, a deadweight capacity of about 7,500 tonnes, a tonnage of about 33,000 GT, 3,100 lane meters and 500 passengers. A so-called base design for the superstructure module of this ship was developed according to the current state of the art composite sandwich technology. The major features of that base design are described in the next sub-section. Through a risk based design process described in the subsequent sub-sections the design was further improved by a number of cost effective risk control options (RCOs). The risk assessment supporting the design process is described briefly. The cost effective RCOs that distinguish the final risk based design from the base design are summarized. They proved the feasibility of the concept. In a next step, a new vessel design of *Stena Rederi AB* was considered and the risk assessment was adapted to cover also the new design. The superstructure modules considered in the study are shown in Fig.6.2.

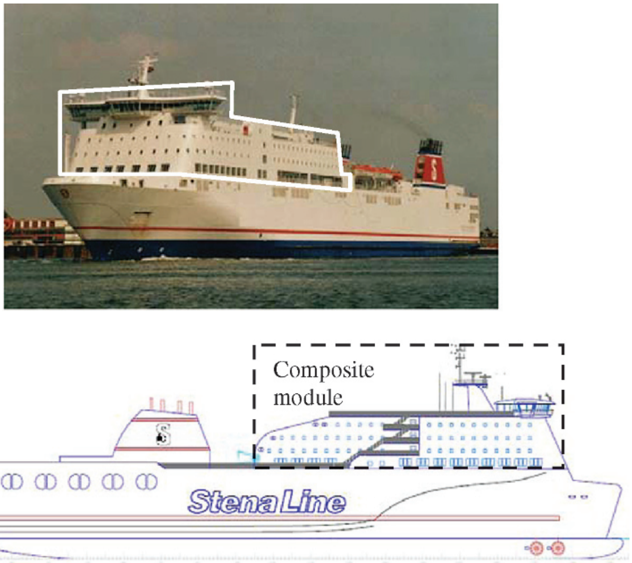

Fig. 6.2 The composite superstructure modules considered in the SAFEDOR study

6.1.2.1 The Base Design

The sandwich concept illustrated in Fig. 6.1 was used to obtain a light-weight design of the superstructure module. Composite face sheets of vinyl ester thermosetting polymeric material reinforced with glass fibers were used. The core material should be light but stiff in shear. Common core materials include balsa wood and polymeric foams usually made of rigid PVC.

All interiors such as cabin modules, decorative surface panels etc were chosen to be of standard commercial types that fulfil the SOLAS requirements to such items and are in use onboard steel designs and are hence approved for use in ships.

Both the face and core materials are combustible. If directly exposed to a fire, these materials would contribute to the fire and the fire could also spread on the exposed surfaces. That could compromise the ship's fire safety. Therefore all the surfaces inside the super-structure were protected by a suitable fire protection system. Structural panels that are hidden behind standard elements, e.g. decks and bulkheads in accommodation areas, would have standard low cost fire protection systems typically of mineral wool. Other structural panels such as bulkheads facing corridors are protected with dedicated fire protection systems that have a decorative and robust surface. Some systems of this type have been earlier described and characterized by Gutierrez et al. (2005) and McGeorge and Høyning (2002). All the surfaces satisfy the fire reaction requirements specified in the IMO HSC Code (IMO 2000). These requirements are stricter than those of the SOLAS convention.

This ensures that, as long as the fire protection capacity is not exceeded, the behaviour of the composite superstructure in a fire will be at least as favourable as that of a traditional steel design. The critical question for equivalence with prescriptive steel designs is the risk contributions associated with the rare events of fires that last longer than the fire protection time of the FRP structure such that the combustible structural material is exposed. This is addressed herein by the risk assessment.

The weight of the lightweight module was only about 40% of that of the existing traditional steel design. This weight comparison includes all fire and thermal insulation and represents the real weight difference of the two arrangements as installed onboard. The cost of this weight saving was estimated to about 5 € per kg. Whether this is commercially attractive depends on the intended trade of the vessel, but plausible examples were identified where the cost increase would be expected to pay back in one to two years of service.

6.1.2.2 The Risk Based Design Process

A risk based design process was performed involving the usual steps of a risk assessment: hazard identification, ranking of risks using a qualitative risk assessment, identification of risk control options (RCOs), quantitative risk assessment with focus on the most critical risks and a decision process where the most effective risk control options were adopted. To ensure that the most critical risks and the best RCOs were identified and that the most appropriate methods were used to assess risks;

26 experts were involved in the risk based assessment and design process. These 26 experts covered all relevant areas of expertise and represented all stakeholders. Several design iterations were performed. In the first iteration, focus was placed on identifying design solutions that were effective in meeting the design objectives. Then focus was gradually shifted towards identifying effective ways of controlling the risks associated with the novel design. To support this process, each expert was involved at the most appropriate stage in the design process.

The estimated risks were compared to the risk acceptance criteria given in Table 6.1. The criteria were derived from a set of recommended risk acceptance criteria suggested by Skjong et al. (2005) considering that the total risk will be dominated by the more severe risks due to collision and grounding such that the superstructure fire risk should only represent a small fraction of the total acceptable risk. Hence, the criteria used for superstructure fires are much stricter than the criteria suggested by Skjong et al. (2005) and correspond to the difference between those and the historic risks from collisions, grounding and engine room fires as reported by Vanem and Skjong (2004a, 2004b). The individual risk acceptance criteria cover individual risks to passengers and crew. If the individual risks exceed any of those criteria, the level of risk is unacceptable and must be reduced. Furthermore a societal risk criterion was specified in terms of the potential loss of lives (PLL). This number represents the statistical expectation of the number of fatalities per year of operation of an average ship. Exceeding the societal risk criterion implies that the risk level is too high and that the risk must be reduced irrespective of costs. Finally, a cost effectiveness criterion is specified in terms of the cost of averting a fatality (CAF). This criterion need not be used if one can show that the societal risks are negligible. However, the historic collision and grounding risks are themselves significant. They were not aimed to be reduced in the present work. Therefore, irrespective of the new design, the total risk could not be regarded negligible and the CAF criterion would have to be used. This criterion does not apply to the design itself, but to identified RCOs. It implies that, after all the other risk criteria are met, RCOs having a CAF less than the given CAF criterion should be implemented to further reduce risk such as to become *As Low As Reasonably Practicable* (ALARP).

Table 6.1 Acceptance criteria for superstructure fires

Limit for intolerable individual superstructure fire risk for passengers	$8.2\ 10^{-5}$ per ship year
Limit for intolerable individual superstructure fire risk for crew	$7.5\ 10^{-4}$ per ship year
Limit for intolerable societal superstructure fire risk expressed as PLL	0.0005
Cost of averting a fatality (CAF) used for evaluation of RCOs (to be used as indicator including also serious and less serious injuries).	3 million USD

6.1.2.3 Major Features of the Risk Based Design

The risk assessment showed that, for the base design, the fire risk associated with the superstructure was much less than other risks (e.g. risks associated with grounding and collision), but nevertheless that the risk was indeed significant, above the target level and higher than that associated with a traditional steel design. Furthermore, assessment of RCOs identified through the risk based design process showed that there were a number of cost effective RCOs. The results of the risk assessment are summarized below. The RCOs considered cost effective on the basis of the risk assessment were:

- The use of a drencher system that is able to sprinkle water on the external surfaces of the superstructure. The aim of this RCO is to cool the external surfaces of the superstructure in the event of a fire so as to prevent the propagation of a fire via the external surfaces should external windows or doors fail to contain the fire.
- The use of windows and doors in external bulkheads that are rated to survive for at least 60 min in the standard fire. The aim of this RCO is to prevent flames and smoke from a fire inside the superstructure to escape to the outside and potentially cause fire propagation and a threat to the passengers that have escaped from the fire zone.
- The use of an emergency control station away from the bridge allowing controlling the fire-fighting and escape operations as well as navigating towards a safe refuge even if the bridge has had to be abandoned.

These RCOs had only a small impact on the weight and cost of the lightweight composite design and are unlikely to compromise the profitability of the novel design.

6.1.3 Fire Risk Assessment

A fire onset onboard a ship is not a particularly uncommon occurrence. However, due to effective fire safety measures, almost all fire onsets are safely extinguished before becoming a threat to passengers or crew. In rare cases, however, the fires develop and become a threat. Whether this happens or not depends on factors such as whether detection and active fire fighting systems function as intended, the precise location of the fire onset, the presence of persons nearby, their training and state of mind, whether fuel for the fire exists near the fire onset, the precise nature of the surface of these fuel items, local ventilation condition etc. These factors and their consequences do not lend themselves easily to theoretical predictions from first principles. For this reason, every fire risk assessment faces the challenge that the probabilities and initial development of relevant fire scenarios can currently not be predicted with theoretical models.

A solution to this problem is to *define* a limited set of design fire scenarios that, based on service experience and expert judgment, are *deemed* to contain the major risk contributions and assign probabilities to each scenario based on experience, judgment and available fire statistics. This simplified approach is acceptable according to international standards and guidelines (ISO, 1999, SFPE 2000). A more rational approach was chosen in the present case. The design solutions that were considered for the alternative design were restricted to those options that would not change the probability of ignition and the initial development of a fire compared to that implied by the prescriptive fire requirements of SOLAS. How this was done was explained before. This ensures that the occurrence probability of a significant fire would be the same as that of traditional steel designs. This probability can be estimated from available fire accident statistics for ships and therefore need not be predicted from theoretical models or assigned based on judgment.

With this approach, an initial event being the occurrence of a significant fire could be defined with a probability that can be estimated from historic records. Furthermore because the composite superstructure model is located in the fore ship far away from the engine room, one can assume that the novel design would not affect engine room fire scenarios. Hence, only a subset of the fire accident statistics needs to be considered.

Statistics for historic fires can be established from *Lloyd's Register – Fairplay* (online). Such statistics were compiled and reported by Vanem and Skjong (2004a). According to their results the probability of a significant superstructure fire for this ship type is $5.6\ 10^{-4}$ per ship year. This probability is dominated by accidents that occurred before the latest amendments to the fire safety regulations where e.g. sprinkler systems became mandatory. Taking account of the reliability of sprinkler systems (Hall 2006), an improved estimate of this probability for current ships of $5\ 10^{-5}$ per ship year was established and used for the risk assessment.

From the initial event (occurrence of a significant superstructure fire), a range of 25 distinct fire scenarios were developed and together formed an event tree representing all the fire scenarios considered relevant. In this way, the risk model accounted for all fires from the small ones making little damage to uncontrolled fires that, due to the effectiveness of the adopted RCOs are very rare indeed, but if occurring would lead to severe consequences. Escape simulations were performed to estimate the required safe egress time. Small scale fire tests (Fig. 6.3) were performed

Fig. 6.3 Small scale tests performed at SP (Sweden) to provide inputs to fire simulations

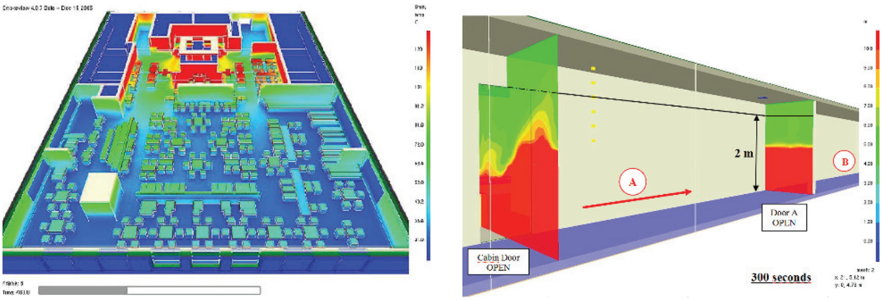

Fig. 6.4 Results from unpublished simulations performed by CETENA of fires in the cafeteria and a corridor

to obtain input data for fire simulations. Fire simulations (Fig. 6.4) predicted the development of significant fires and the propagation of heat and smoke in the specified fire scenarios. This could be compared to the results from the escape simulations to establish the risks associated with escape from the fire zone. Full scale fire test trials established the fire resistance of structural components such as decks and bulkheads (Fig. 6.5) including cable, pipe and duct penetrations (Fig. 6.6) and the effectiveness of fire rated windows and doors and external drencher system (Fig. 6.7) as RCOs. All fire tests were continued beyond the intended survival time thus providing information about the true capacity that was used in the risk modeling. Furthermore, the effects of human decisions such as the captain's decision to abandon ship were included in the risk model. On that basis also the risks associated with the later stages of escalating fires were estimated. Making use of advice from the group of experts, this produced the conditional probabilities and consequences of all

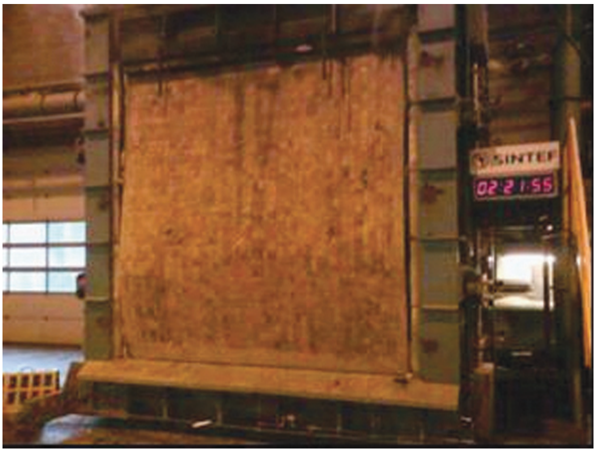

Fig. 6.5 Fire resistance test performed at Sintef (Norway) of a balsa-cored bulkhead that survived 2 h 20 min

Fig. 6.6 Fire resistance test performed at SP (Sweden) of bulkhead with cable, pipe and AC duct penetrations

the events in the event tree. This allowed to estimate the consequences in terms of expected number of fatalities both among those nearby the initial fire being exposed to risk on their escape from the fire zone and those safely mustered that would be exposed to risks in the unlikely event of an escalating fire getting out of control. The risk contributions were updated for the RCOs such that the effect of adopting the RCO on risk could be quantified.

Fig. 6.7 Full scale fire test trial performed at SP (Sweden) demonstrating the efficiency of a drencher system in preventing external fire propagation when an internal fire exits through a broken window

6.1.4 Results of Fire Risk Assessment

Application of the fire risk model to the base design provided an estimate of the superstructure fire risk associated with it. All individual risk criteria were met. A superstructure fire PLL of 0.016 was estimated. This is above the limit specified for societal risk and may be regarded unacceptable. The effects of a range of RCOs were estimated using the risk model. Figure 6.8 shows the estimated effects of the most promising RCOs. For comparison, the historic PLL from collision and grounding as well as fire are shown. The historic fire PLL includes contributions from all fires, also those that would not be caused by the superstructure fire (e.g. engine room fires) and is dominated by accidents that occurred before the latest amendments to the fire safety regulations. An attempt was made at correcting these two factors producing a lower and an upper bound estimate of the PLL due to superstructure fires in current steel designs. These estimates are also shown in Fig. 6.8. The upper bound coincides with the target PLL defined in Table 6.1. Figure 6.8 shows that the risk of the base design is above the specified acceptable societal risk (PLL) but that implementation of the most effective RCOs brings the PLL below the target such that it compares favourably with that of traditional steel designs.

The main reason why the risk of the composite superstructure is less than that estimated for steel superstructures is that the use of fire rated windows and doors increases the probability that a fire inside the superstructure will be contained inside and thus not expose passengers and crew.

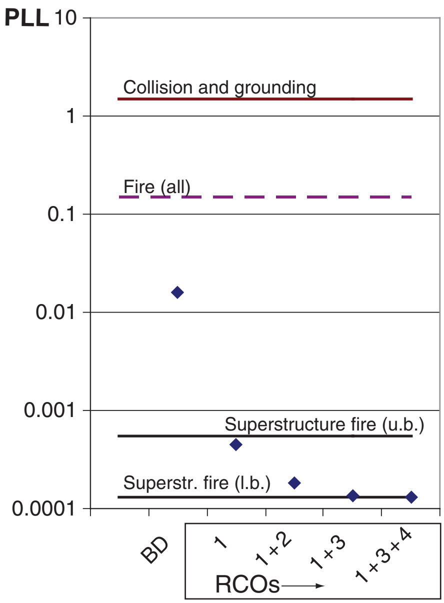

Fig. 6.8 Estimated effect of the four most promising RCOs on societal risk of superstructure fires

6.1.5 Benefits of the Risk Based Design

The composite design offers considerable weight-saving. Table 6.2 shows a comparison of weights and new-build costs of a steel design compared with two alternative composite designs for the case used in the first step of the study. About 60% weight saving compared to the steel superstructure was estimated for the second composite design. The costs and weights include all the differences between the steel and composite designs such as fire insulation and deck coverings and can thus be compared directly. The estimated weight saving is likely to be attractive at the estimated cost if increased payload can be achieved for the particular project considered.

Table 6.2 Summary of weights and new-build costs of a steel design compared with two alternative composite designs for the case used in the first step of this study

	Weight (tonnes)		New-build cost (mill USD)	
	Superstructure	Saving	Superstructure	Increase
Steel reference design	950	0	4	0
Composite design 1	440	510	7,1	3,1
Composite design 2	360	590	6,9	2,9

6.1.6 Discussion

Simplifying assumptions were made in the risk assessment. One may replace some of these assumptions with more detailed simulations or test trials to provide more accurate estimates of conditional probabilities or consequences in the various fire scenarios and hence also more accurate risk estimates. However, the risk contributions from the various fire scenarios are all conditional upon the occurrence of a significant superstructure fire. The historic occurrence frequency of significant superstructure fires is indeed quite small. Hence one may conclude that that the sensitivity of the fire risk estimates to uncertainties in the conditional probabilities or consequences of the subsequent events is limited for alternative designs where the deviation from the prescriptive fire safety requirements do not alter the occurrence probability of significant superstructure fires. This implies that it would not be cost effective for such designs to invest a great effort at improving the fire risk estimates. If shipping safety is the concern, it would certainly be more useful to spend those resources on improving the understanding of more significant risks such as those due to collisions and groundings. This suggests that the level of rigor employed in the risk assessment is sufficient for the intended purpose.

The IMO guidelines on alternative design and arrangements for fire safety (IMO 2001) require that the effects of the uncertainties and limitations of the input parameters are determined by a sensitivity analysis. In the present case a probabilistic analysis was used. It explicitly includes uncertainties in the input parameters used to characterise the design fire scenarios and quantifies the effects of these uncertainties. Therefore, the probabilistic approach provides a direct and rational way of satisfying the requirement to perform a sensitivity analysis. However, simplifying assumptions and simplified models were needed to complete the assessment within reasonable budgets and time limits even with the probabilistic approach. Therefore, it is important also to assess the sensitivity of the conclusions to the uncertainties introduced by those simplifications. This was done by changing the best available estimates of probabilities and consequences with values that were considered obviously pessimistic. This did neither raise the individual or societal risk estimates into the intolerable region nor did it make additional RCOs cost effective. Therefore, it is considered that the reported conclusions are robust with regard to uncertainties and limitations of the input parameters.

All the RCOs that were cost effective according to the CAF criterion were adopted. In addition, some RCOs that were somewhat less cost effective were adopted although that would not strictly be required. Those RCOs were inexpensive and did not significantly affect the cost of the superstructure module. They were adopted because they were considered to provide the margin necessary to ensure safe use of the new technology also for other slightly different design cases. Hence, the technology described herein is likely to have wider application than the design cases studied and could provide a useful basis for a possible future risk-based standard for composites in passenger ship superstructures should the ongoing work with the international regulatory regime allow that in the future. Under the current regulations, however, the fire risks would have to be assessed in each individual case.

6.1.7 Conclusions

Current state of the art composite sandwich technology was used to develop a base design for a large superstructure module for a RoPax passenger ship. The weight of this light-weight design proved to be only about 40% of that of a traditional steel design. However, a risk assessment showed that, although individual risks were acceptable, the societal risk was not. A risk based design process was performed leading to the identification of a set of risk control options deemed cost effective. Adopting these risk control options reduced the risk to acceptable levels that compare favourably with steel designs compliant with current prescriptive SOLAS requirements. Such a lightweight design could be regarded an alternative arrangement as defined in SOLAS and could therefore be approved according to SOLAS Ch II-2 Reg. 17. This gives promise for more efficient and profitable merchant ship designs in the future. Furthermore, the present work provides a useful basis for a possible future risk-based standard for composites in passenger ship superstructures should the ongoing work with the international regulatory regime allow that in the future.

Acknowledgments Tommy Hertzberg and Jesper Axelsson of SP, Sweden, provided valuable advice on fire testing and simulations and managed many of the tests trials and simulations from which the results were used to estimate risks. Federica Devoto of CETENA, Italy, performed a large amount of fire simulations used in the risk assessment. Arnulf Aa of Brødrene Aa, Norway, assisted with weight and cost estimates and making of test objects. The success of the risk based design process depended on the contributions also from many experts within all the relevant fields of expertise, too many to be mentioned individually here. The valuable contributions of all these persons are gratefully acknowledged.

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6.2 RBD Application: AFRAMAX Tanker Design

Apostolos Papanikolaou

Abstract Following a series of catastrophic single hull tanker accidents, currently in force IMO regulations (and long before U.S. OPA90, National Research Council, 1991) recognize double hull tanker designs as the only acceptable solution for the safe carriage of oil in tanker ships. The resistance towards the acceptance of alternative double hull tanker designs by the authorities has been limiting creativity within the industry, though currently in force MARPOL requirements appear challengeable without increasing the risk of negative environmental impact.

The herein presented study refers to a risk-based parametric optimization of a double hull AFRAMAX tanker within a holistic design optimization concept aiming to achieve innovative designs with increased cargo carrying capacity and improved environmental protection, while challenging the cargo tank size limitations imposed by the existing IMO-MARPOL regulations.

6.2.1 Introduction

The main objective of the presented work is the introduction of an innovative tanker design that challenges some MARPOL requirements (IMO, 2003) and promises significant economical advantage as well as lower potential of medium to large amount of oil spills.

The study presented herein focused primarily on optimizing only the main cargo area of an AFRAMAX class tanker in order to demonstrate the best performing design in terms of improving both environmental protection from accidental oil outflow and economical competitiveness. However, further development of the introduced methodology to include more optimisation objectives, such as ship's hull form, including main dimensions and other tanker classes appears straightforward.

For the design concept development stage, a full parametric multi-objective design optimisation platform has been developed, implementing interfaces between standard naval architectural software packages and optimization techniques (herein of Genetic Algorithms) and taking into account probabilistic oil outflow calculation methods for side and bottom damages. The resultant Pareto-optimal designs are evaluated in terms of oil outflow consequences, cargo capacity, design feasibility, ship maintainability and ballast water capacity.

The developed alternative designs dispose, compared to a standard AFRAMAX double hull design, increased cargo carrying capability, at a comparable or even slightly reduced risk for oil outflow. Therefore, from the economy and safety point of view, the resulting designs appear very promising compared to existing standard type AFRAMAX double hull designs. A preliminary economic analysis showed that despite the anticipated slightly increased building cost, the developed alternative designs show an appreciable decrease of unit transport cost, making them attractive to the shipping industry.

The presented research study was undertaken in the framework of the EU funded project SAFEDOR (2005–2009).

6.2.2 Introduction to Holistic Ship Design Optimization

Ship design was in the past more art than science, highly dependent on experienced naval architects, with good background in various fundamental and specialized scientific and engineering subjects, next to practice. The design space was practically explored using heuristic methods, namely methods deriving from knowledge gained through a process of trial and error often over the course of decades.

Inherently coupled with the design process is design optimization, namely the selection of the best solution out of many feasible ones on the basis of a criterion, or rather a set of criteria. Considering the ship over her whole life cycle as a system, consisting of the processes/stages of concept/preliminary design – contractual/detailed design – ship construction/production – operation – scrapping/recycling, it is evident that the *optimal* ship with respect to her whole life cycle is the outcome of a *holistic*[1] optimization of the entire, above defined ship system. It is noted that mathematically, every constituent of the above defined life-cycle ship system forms evidently itself a complex nonlinear optimization problem for the design variables, with a variety of constraints and criteria/objective functions to be jointly optimized. Even the simplest component of the above system, namely the 1st loop (conceptual/preliminary design), is complex enough to be simplified (*reduced*[2]) in practice. Also, inherent to ship design optimization are the conflicting requirements resulting from the design constraints and optimization criteria (merit or objective functions), reflecting the interests of the various ship design stake holders: ship owners/operators, ship builders, classification society/coast guard, regulators, insurers, cargo owners/forwarders, port operators etc. Assuming a specific set of requirements (usually the shipowner's requirements), a ship needs to be optimized for lowest construction cost, for highest operational efficiency or lowest Required Freight Rate (RFR), for highest safety of passengers/crew, for satisfactory protection of cargo and the ship herself as hardware and last but not least, particularly for oil carrying ships, for minimum environmental impact. Many of these requirements are clearly conflicting and a decision regarding the optimal ship design needs to be rationally made.

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[1] Principle of holism according to Aristotle (Metaphysics): "The whole is more than the sum of the parts".

[2] Principle of reductionism may be seen as the opposite of holism, implying that a complex system can be approached by reduction to its fundamental parts. However, holism and reductionism should be regarded as complementary approaches, as they are both needed to satisfactorily address complex systems in practice.

Since the middle sixties with the advance of computer hard- and software more and more parts of the design process were taken over by computers, particularly the heavy calculatory and drafting elements of ship design. Simultaneously, the first computer-aided preliminary design software systems were introduced, dealing with the mathematical parametric exploration of the design space on the basis of empirical/simplified ship models for specific ship types or the optimization of design variables for specific economic criteria by gradient based search techniques (Murphy et al. 1965, Nowacki et al. 1970). Also, computer-aided studies on optimization of ship's hull form for least resistance and best seakeeping behavior (hydrodynamic design optimization) or of ship's midship section/structural design for least steel weight (structural design optimization) started being introduced to the naval architectural scientific community until they led to matured results in more recent years (see, e.g., Papanikolaou et al. 1996, Boulougouris and Papanikolaou 2006, 2008).

With the further and faster advance of computer hard- and software tools, along with their integration into powerful hard- and software design systems, the time has come to look at the way ahead in ship design optimization in a *holistic* way, namely by addressing and optimizing several and gradually all aspects of ship's life (or all elements of the entire ship life cycle system), at least the stages of design, construction and operation; within a *holistic* ship design optimization we should herein also understand exhaustive multiobjective and multiconstrained ship design optimisation procedures even for individual stages of ship's life (e.g. conceptual design) with least reduction of the entire real problem. Recently introduced scientific disciplines in the general framework of "design for XXX", namely "design for safety" (SAFEDOR 2005–2009, Vassalos 2007), "design for efficiency", "design for production", "design for operation" etc. indicate the need for approaches and the availability of matured methods and computational tools to address holistically the ship design optimization problem (Papanikolaou 2008).

The use of Genetic Algorithms (GA), combined with gradient based search techniques in micro-scale exploration and with a utility functions technique for the design evaluation, is advanced in the present work as a generic type optimization technique for producing and identifying optimized designs through effective exploration of the large-scale, nonlinear design space and a multitude of evaluation criteria. Several applications of this generic, multi-objective ship design optimization approach by use of NTUA-SDL[3]'s design software system, integrating the naval architectural software package *NAPA*®[4], the optimization software *mode FRONTIER*®[5] and various application software tools, as necessary for the evaluation of stability, resistance, seakeeping etc. may be found in the listed references. For the general concept and details of multi-objective optimisation by use of Genetic Algorithms and alternative procedures reference is made to *C. Lucas (2007), "Practical Multiobjective Optimisation", http://www.calresco.org/lucas/pmo.htm*.

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[3] National Technical University of Athens – Ship Design Laboratory, NTUA-SDL, http://www.naval.ntua.gr/sdl.

[4] NAPA Oy (2005), NAPA software, http://www.NAPA.fi/.

[5] E.STE.CO (2003), "modeFrontier software v.2.5.x", http://www.esteco.it/.

6.2.3 Design Optimisation Procedure

The optimisation of the internal hull space arrangement of a tanker ship requires meeting a set of several different objectives, which are often conflicting and non-commensurable. This problem can be effectively addressed by multi-objective optimization methods, which yield first a family of non-dominated solutions (also named non-inferior or admissible), the so-called *Pareto*-optimal set. The concept of non-dominance refers to the solutions for which no objective can be improved without worsening at least one of the other objectives. Thus, the non-dominated solutions are superior to the others with respect to all objectives, while comparatively good among themselves. Since all the non-dominated solutions in the Pareto set are considered equivalent in dominance, any of them is an acceptable solution. Once such designs are found, it usually requires a ranking based decision-making techniques to choose one of them for further elaboration. The rational choice of one solution over the other *Pareto-Optimal Design Alternatives* (PODAs) entails additional knowledge of the problem such as designer/shipowner preferences or shipyard production experience.

As designers' or other experts' fuzzy opinions, which can be linguistic terms, cannot be taken into account in the optimisation stage because of its crisp nature, ranking or evaluation of PODAs is considered as a fuzzy multi-attributive group decision-making problem. To this effect various solutions can be exercised to arrive in more rational decisions in the final design selection process. A Multi-Criteria Decision Making (MCDM) procedure might be employed to address this effectively, introducing a new single objective function by use of so-called utility functions and enabling the systematic evaluation of the PODAs by a computerized procedure.

In this study in order to test and demonstrate a risk-based design platform for tanker ships, various design concepts are implemented within a tailored-made optimisation platform capable of measuring relative environmental impact of a given set of design variations. A schematic process flow of the implemented tanker design optimisation procedure is given in Fig. 6.9.

Firstly a set of design objectives are defined which are indicative of the performance of a tanker ship in relation to accidental oil spill potential and carrying capacity. The design team has decided on a number of target design parameters to focus on to meet the objectives determined together with the design constrains. The specially developed optimisation platform consists mainly of two parts; a design package and an optimisation package, which are adapted to the problem to produce design alternatives and arrive at a series of PODAs.

The optimisation work-flow is herein modelled in the *modeFRONTIER*® software environment. A parametric and topological *NAPA*® (Naval Architectural Software) model of the AFRAMAX vessel definition is developed so that the reference vessel layout can be developed for each design experiment with respect to the defined optimisation parameters. Therefore, for each design layout (or design experiment), the design package employs the *NAPA*® software suit to produce the desired design from given set of parameters. Then it calculates and checks the design features in relation to the cargo block, to be optimized and the tank capacities.

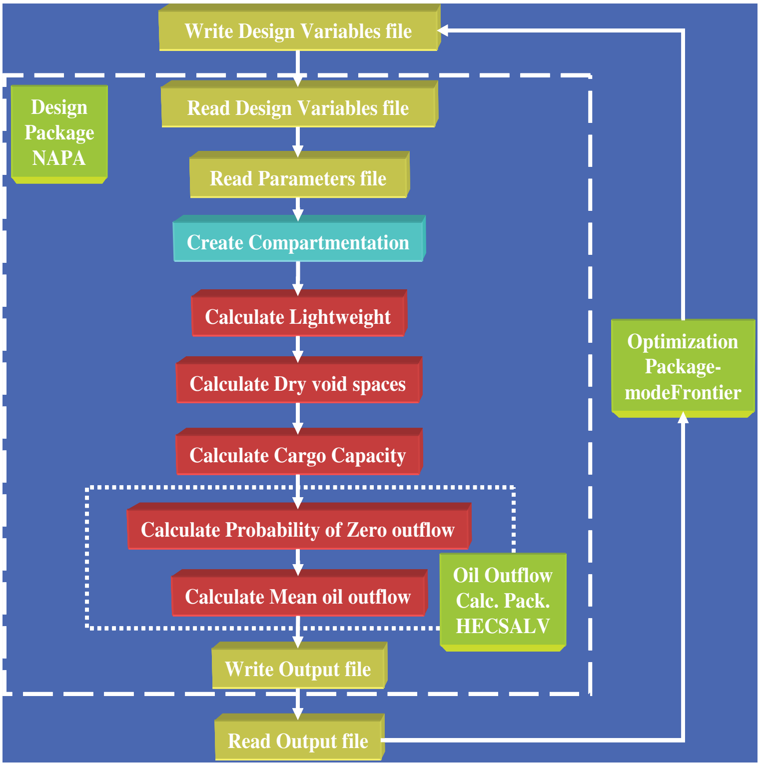

Fig. 6.9 Implemented tanker design optimisation procedure

Following this, the design is evaluated by a specially developed oil outflow module of *HECSALV*®[6] software suite in terms of oil outflow performances. The same calculations can be performed independently within the *NAPA*® software suite.

The optimisation platform utilizes a genetic algorithm based multi-objective optimisation methodology of the *FRONTIER* software suite, namely MOGA, where the solution space is searched for a set of PODAs through a satisfactory number of generations from an initial number of design experiments.

6.2.4 Reference Vessel

The reference vessel, code-named as "Double Venture", is a double hull construction ship of AFRAMAX size. "Double Venture" fully complies with the current regulations and is still in operation. In Table 6.3, the basic characteristics of the vessel are presented.

[6] HECSALV®, http://www.herbertsoftware.com.

Table 6.3 Reference vessel

Length, oa	250.10 m
Length, bp	239.00 m
Breadth, moulded	44.00 m
Depth, moulded (main deck)	21.00 m
Width of double skin sides	2.50 m
Width of double skin bottom	2.50 m
Draught scantling	14.60 m
Deadweight, scantling draught (comparable with design proposed)	109,800 dwt (cargo density $0.868\,\mathrm{T/m^3}$)
Cargo capacity	
Liquid volume,	$122,375\,\mathrm{m^3} + 2,830\,\mathrm{m^3}$ (Slop),
heavy oil, diesel oil,	$3,380\,\mathrm{m^3}, 260\,\mathrm{m^3}$
Water ballast	$41,065\,\mathrm{m^3} + 3,500\,\mathrm{m^3}$ (peaks)
Classification	Lloyds Register
Propeller Diameter	7,200 mm
Number of Cargo tanks	12 plus 2 slop tanks
Cargo Tanks block length	181.44 m

The vessel is single-decked without forecastle. A double skin construction is arranged along the cargo length area, consisting of six (6) pairs of side and bottom tanks for use of water ballast. The cargo tanks area has a longitudinal bulkhead and is subdivided into six pair of tanks for the carriage of crude oil and products, Fig. 6.10. Two slop tanks are also provided, afterwards of main cargo area. Cargo handling is by means of centrifugal pumps installed in a pump room, which is located forward of the machinery space. It is noted that the above reference double hull design disposes an increased double side and bottom clearance of 2.5 m, compared to the minimum 2.0 m required for this size of ship according to MARPOL relevant requirements, thus it does not only comply with but exceeds minimum requirements set by currently in force regulations (IMO, 2003).

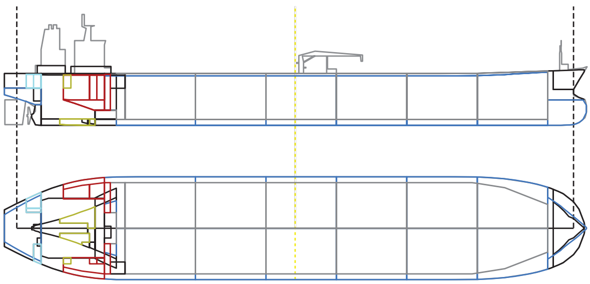

Fig. 6.10 Reference vessel “Double Venture”

Crew accommodation is arranged in a deckhouse above the engine room, separated from the funnel casing to reduce possible noise and vibration problems. The reference vessel “Double Venture” was also used in another EU funded project POP&C (2004). Due to commercial confidentiality, full details of ship’s particulars are not given at this publication

6.2.5 Concept of Design Study

6.2.5.1 Safety Goals

The present design study addressed the following specific safety objectives:

- Reduction of potential of medium to large amount oil spills significantly.
- Eliminate small size oil spills due to operational incidents/accidents
- Significantly reduced ballast water exchange and their effects.
- Zero-fatality and injury rate for tanker operations.
- Prolonged-maintenance-free structural life, and easy inspection and assessment of structure.

6.2.5.2 Challenges in the Proposed Design

In developing a promising design concept for an AFRAMAX tanker that will satisfy the set safety objectives, prove attractive to the maritime industry and be acceptable to regulators, a variety of known design alternatives and hybrids thereof were considered. It was finally decided to consider herein only possible variations of the double hull design concept that is nowadays generally accepted as a tanker industry design standard. The new design will be developed by using principles of risk-based design and will be enhanced with special subdivision considerations for optimal economic and environmental performance. The optimum location, size and configuration of cargo and ballast tanks will be obtained through analysis of oil outflow calculations; mainly considering zero, mean and extreme outflow rates using the probabilistic oil outflow framework, together with economical implications on the design layout.

Several alternatives have been studied and the most significant layouts are presented in the next paragraphs. The main characteristic of the proposed alternatives is the increase of double bottom height in the fore part of the ship, where accidents are more probable (mainly due to groundings), as well as the rational redistribution of transverse bulkheads in order to minimize the oil outflow in case of oil spill.

Considering different design alternatives and possible challenges of existing regulations, it appeared realistic that the proposed design layout should challenge herein only the regulation MARPOL 73/78, Annex I/26, that is related to the limitations of size and arrangement of cargo tanks, namely “maximum length of each cargo tank should not exceed 0.2L”.

The proposed design alternatives should be economically attractive and prove even safer than a conventional one complying with the above mentioned regulation, taking advantage of a more rational distribution of the double skin and double bottom bulkheads, while increasing protection and limiting tank size in the areas most susceptible to suffering damages due to grounding and side collision.

Advantages of New Proposals

1. Improved performance in case of accidental oil outflow.
2. Increase of cargo capacity taking advantage of hull volume in areas where the probability of damage is low.
3. Decreased amount of segregated ballast water when compared to a conventional design, as a result of the cargo capacity increase.

Disadvantages of New Proposals

1. Slightly higher bending moments and shear forces due to capacity changes observed in ballast water and cargo tanks.
2. Partly increased complexity in building some double skin and double bottom bulkheads, leading probably to increase of fabrication costs. Although not studied in details, an increase of steel weight and cost is expected.
3. Some restrictions different from the conventional ones will be imposed to hull form design since aft trimming tendencies were observed by using the hull lines of the reference vessel. To address this issue, modifications of the buoyancy distribution are required and consequently investigation of ship's hydrodynamic behaviour shall be studied in the future. It is likely that shifting the LCB aft will have an adverse impact on the powering and fuel costs.

6.2.6 Overview of Design Problem

The design objectives of the present study can be summarized as follows:

- Increased cargo capacity as much as possible while maintaining the same main vessel characteristic.
- Optimized overall oil outflow performance.
- Reduction of fabrication costs by designing a production-oriented ship structure.

The main design and optimisation characteristics are described below:

Type of vessel: "Double Hull" AFRAMAX tanker.

General Arrangement: An optimized layout is proposed as well as the number of cargo tanks depending on the outflow optimisation study. Water Ballast tanks, Double Bottom and Double Sides dry spaces to be optimized as well.

Initial Main Dimensions	Length 239 m (as reference vessel) Breadth 44 m (as reference vessel) Depth 21 m (as reference vessel) Design draught: around 13.6 m Scantling draught: min. 14.6 m
Width of double skin	Sides clearance to be optimized Double bottom height to be optimized
Deadweight/Tonnage *Design Deadweight*: *Scantling Deadweight*:	(as reference vessel) around 100,000 tonnes according to Lightship weight calculations and a minimum cargo density of $0.855\,\mathrm{t/m^3}$
Cargo/other capacities:	Liquid Cargo Volume: amount to be optimized, reference vessel $(127,444\,\mathrm{m^3})$ Heavy oil: $3,380\,\mathrm{m^3}$ (as ref. vessel) Diesel oil: $260\,\mathrm{m^3}$ (as ref. vessel) Water ballast: amount to be optimized.

6.2.7 Design Optimization Case Study

The reduced environmental impact and increased cargo capacity are sought by determining the best double hull dimensions for the given reference vessel. The hull surface of the reference vessel is taken unchanged and the optimisation procedure is carried out for three models, namely Model 1–3. The tank configuration layouts are given in Figs. 6.11, 6.12 and 6.13 respectively.

Model 1: Basic Double Hull model, with a single longitudinal bulkhead at centre line.
Model 2: Segregated Ballast Tanks-Protectively Located (SBT-PL) model with large side tanks, central cargo tanks and two longitudinal bulkheads.
Model 3: Hybrid model – Basic Double Hull Model, but with two longitudinal bulkheads.

In the initial optimisation search, the cargo block length, which runs from -73.02 to 108.42 m with reference to amidships, is kept constant. Therefore, the aft area of the Cargo Tank 6 is kept unchanged, where the engine room, pump room, slope tanks, service tanks and accommodation spaces are located. The forward area of the Cargo Tank 1 is kept unchanged as well.

Further design search was conducted for a model where cargo block length is varied by moving the aft limit of the Cargo Tank 6. In this case, the engine room area and superstructure need modifications in order to allow for the lengthening of the cargo block. However, the forward area of the Cargo Tank 1 is in all cases kept unaffected.

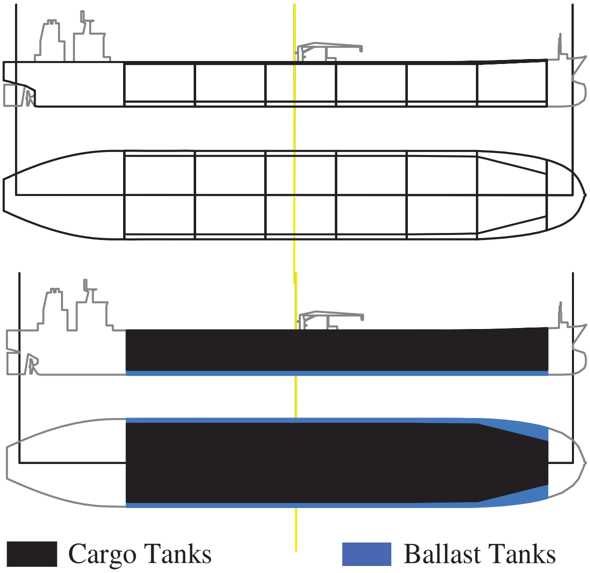

Fig. 6.11 Basic double hull model, 6×2 cargo tanks configuration, Model 1

The basic parametric tank configuration model introduced a sloped double bottom height increase, Fig. 6.14. In a second parametric model alternative (see later results for Long310-01), the deck height increases by a linear sheer, following the slope of the double bottom, thus regaining the lost cargo volume due to the double bottom height increase.

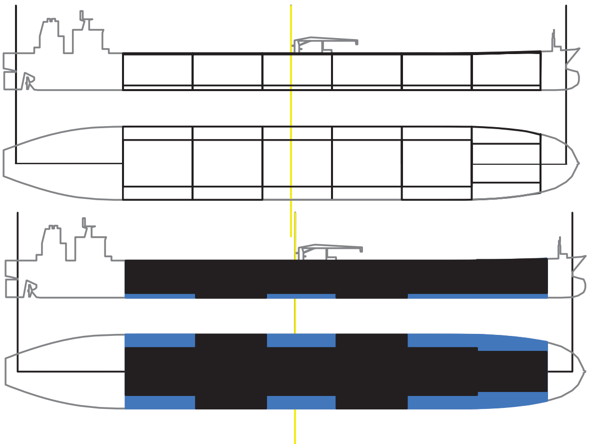

Fig. 6.12 SBT-PL model- Large side tanks and central cargo tanks, $6+4$ cargo tanks configuration, Model 2

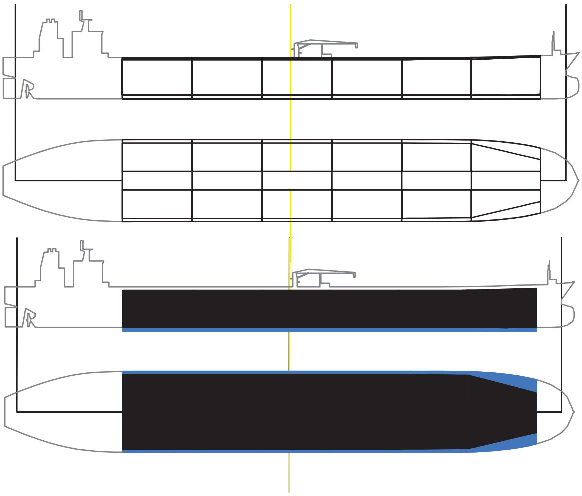

Fig. 6.13 Hybrid model – traditional double skin with two longitudinal bulkheads, 6 × 3 configuration, Model 3

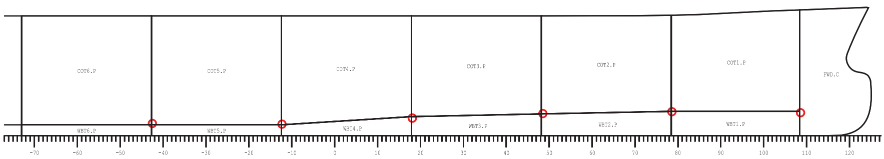

Fig. 6.14 Parameters defining double bottom height for cargo block

With respect to Model 1 and 2, the cargo tanks are bounded by L-shaped wing tanks, Fig. 6.15. In case of Model 2, a longitudinal bulkhead is used instead of double skin construction. Fig. 6.16 demonstrates the parameters controlling the cargo tank lengths. The length values are used as normalized by the total length of the cargo block.

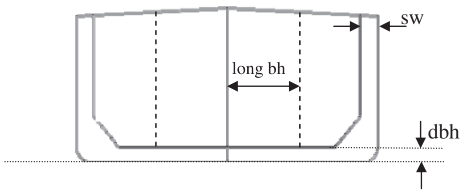

Fig. 6.15 Parameters defining double hull and size of tanks in cargo block

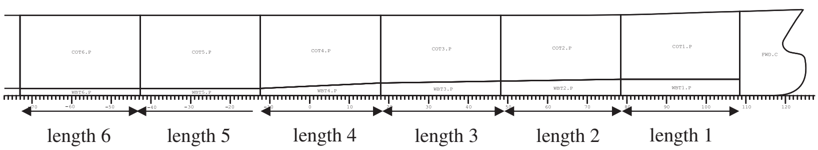

Fig. 6.16 Parameters defining length of the cargo tanks; length 1–6

All the parameters used to control the cargo block configuration are given in Table 6.4 as optimisation variables. For different generation generations, different limit and range values are used in the optimization search; those are given in parenthesis.

6.2.7.1 Implemented Optimisation Objectives

Considering the primary focus of the design concept, the following optimisation objectives were finally implemented:

- Maximization of Cargo Capacity
- Minimization of Mean oil outflow
- Maximization of Probability of Zero outflow
- Minimization of Lightweight
- Maximization of Dry void spaces

6.2.7.2 Implemented Optimization Constraints and Assumptions

In order to perform a reasonably rational design comparison for alternative designs, a series of constraints and assumptions are taken into consideration. Most of the assumptions are taken because although they do not affect the design search and selection process, they reduce the computational efforts significantly. Synoptically, the following constraints and assumptions were implemented:

- The hull shape is kept unchanged for each employed parametric Model with respect to the reference vessel
- All parts are kept as they are in reference vessel except for the cargo block area. In a second stage, the cargo block area is lengthened; therefore the aft part of the vessel is altered.
- The aft and forward spaces are simplified to reduce the calculation time.
- The ship's draught is assumed the same, when considering bottom oil outflow for comparison, but is actually varying to account for cargo capacity and light ship weight increase.
- Cargo oil density was assumed $0.855\,\mathrm{t/m^3}$
- Cargo tanks are fully loaded at 98% of their total capacity.
- Side and bottom damage probability distributions are considered in accordance to MARPOL 73/78 relevant requirements.
- Survivability criteria are determined according to recommended survival s-factor from the new harmonized probabilistic damage stability regulations (IMO 2005, Tuzcu 2004, Moore 2006).
- No tidal effect is introduced.

Table 6.4 Optimisation variables

Variable	Explanation	Type	Lower value	Upper value	Increment
Layout type	0: Double Hull, 1: SBT - PL	Discrete	0	1	–
Long bh	Position of the longitudinal bulkhead from C.L.	Continuous	0 (5) (8)	0 (15) (10)	– (5) (0.25)
dbh 1	Double Bottom height for Cargo Tank 1 Area	Continuous	1.9	5	0.1
sw 1	Side wing tank clearance	Continuous	1.7	3.0	0.1
Length 1	Length of Cargo Tank 1 / Length of the cargo block	Continuous	0.1	0.3	0.05
Centre 1	0: Ballast Tank, 1: Cargo Tank	Discrete	0	1	–
Side 1	0: Ballast Tank, 1: Cargo Tank	Discrete	0	1	–
dbh 2	Double Bottom height for Cargo Tank 2 Area	Continuous	1.9	5	0.1
sw 2	Side wing tank clearance	Continuous	1.7	3.0	0.1
Length 2	Length of Cargo Tank 2 / Length of the cargo block	Continuous	0.1	0.3	0.05
Centre 2	0: Ballast Tank, 1: Cargo Tank	Discrete	0	1	–
Side 2	0: Ballast Tank, 1: Cargo Tank	Discrete	0	1	–
dbh 3	Double Bottom height for Cargo Tank 3 Area	Continuous	1.9	5	0.1
sw 3	Side wing tank clearance	Continuous	1.7	3.0	0.1
Length 3	Length of Cargo Tank 3 / Length of the cargo block	Continuous	0.1	0.3	0.05
Centre 3	0: Ballast Tank, 1: Cargo Tank	Discrete	0	1	–
Side 3	0: Ballast Tank, 1: Cargo Tank	Discrete	0	1	–
dbh 4	Double Bottom height for Cargo Tank 4 Area	Continuous	1.9	5	0.1
sw 4	Side wing tank clearance	Continuous	1.7	3.0	0.1
Length 4	Length of Cargo Tank 4 / Length of the cargo block	Continuous	0.1	0.3	0.05
Centre 4	0: Ballast Tank, 1: Cargo Tank	Discrete	0	1	–
Side 4	0: Ballast Tank, 1: Cargo Tank	Discrete	0	1	–
dbh 5	Double Bottom height for Cargo Tank 5 Area	Continuous	1.9	5	0.1
sw 5	Side wing tank clearance	Continuous	1.7	3.0	0.1
Length 5	Length of Cargo Tank 5 / Length of the cargo block	Continuous	0.1	0.3	0.05
Centre 5	0: Ballast Tank, 1: Cargo Tank	Discrete	0	1	–
Side 5	0: Ballast Tank, 1: Cargo Tank	Discrete	0	1	–
dbh 6	Double Bottom height for Cargo Tank 6 Area	Continuous	1.9	5	0.1
sw 6	Side wing tank clearance	Continuous	1.7	3.0	0.1
Length 6	Length of Cargo Tank 6 / Length of the cargo block	Continuous	0.1	0.3	0.05
Centre 6	0: Ballast Tank, 1: Cargo Tank	Discrete	0	1	–
Side 6	0: Ballast Tank, 1: Cargo Tank	Discrete	0	1	–
Aft limit	Aft limit of Cargo Block	Continues	– (–88.14)	– (–73.02)	– (3.78)
Fwd limit	Forward limit of Cargo Block	Constant	108.42	–	–

Implementation of Optimization Procedure

Figures 6.17 and 6.18 present the implemented risk-based tanker design optimization procedure as flow chart and block diagram.

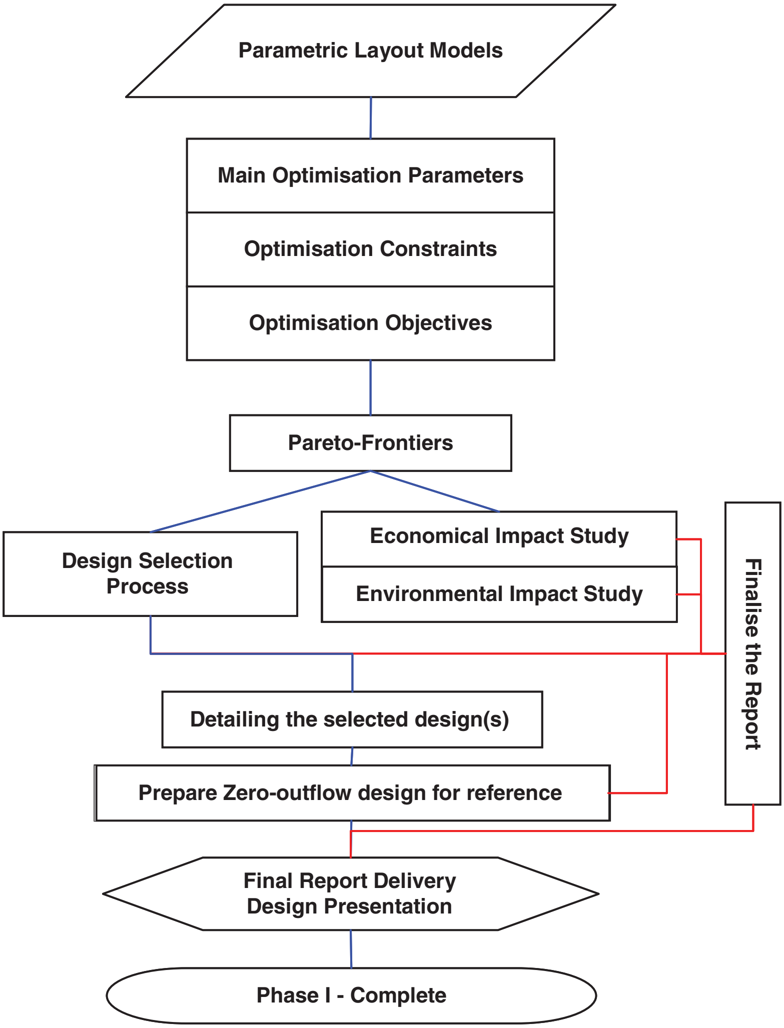

Fig. 6.17 Implementation of optimization procedure

6.2.7.3 Search of Design Resultant Domains

After running the model with respect to the given parameters and objectives, a series of alternative design spaces are obtained. Through filtering of the solution

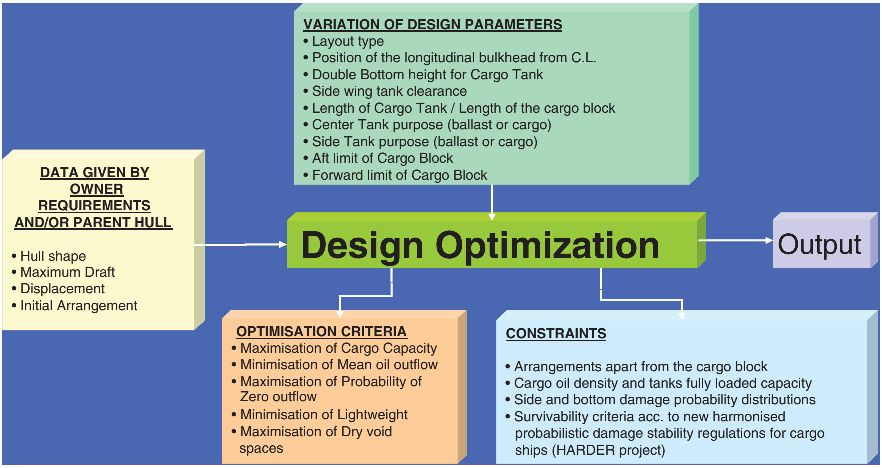

Fig. 6.18 Risk-based tanker design optimization

spaces, several designs are determined as Pareto-optimum designs. It was evident that Model 2 provided the least attractive design solutions due to larger mean oil outflow characteristics despite the potential increase in cargo carrying capacity.

As a result of the optimization process, the best performing design solution space proved to be associated with Model 1. As it is expected, Model 1 provides better side damage performance. Model 2 was characterized as the worst in terms of mean oil outflow due to side damage, resulting in a necessity of increasing the number of tanks to obtain better oil outflow damage for side damage cases. This alternative would increase ship's lightweight significantly and consequently it is not considered herein further. A similar conclusion was obtained for Model 3 where the lightweight increases due to one additional longitudinal bulkhead. Increased cargo and ballast tank surfaces for coating and maintenance are considered as one of the disadvantages of the designs produced by Model 2 and Model 3.

A fairly large design search has been finally carried out with respect to Model 1 which demonstrates better oil outflow performance per capacity, with limited cargo and ballast tank area values. Model 1 is further optimized by increasing the cargo block length as stated before. The research domain initiated by utilizing good designs from the early generations where the cargo block length was fixed. The particular design search domain is presented in Fig. 6.19. The elaboration of the other two basic design models remains to be explored in further studies.

6.2.7.4 Selected Pareto-Optimal Design Alternatives

Further evaluating the design studies, several Pareto-Optimal designs are selected from the solution domains. The particular selected designs are listed in Appendix

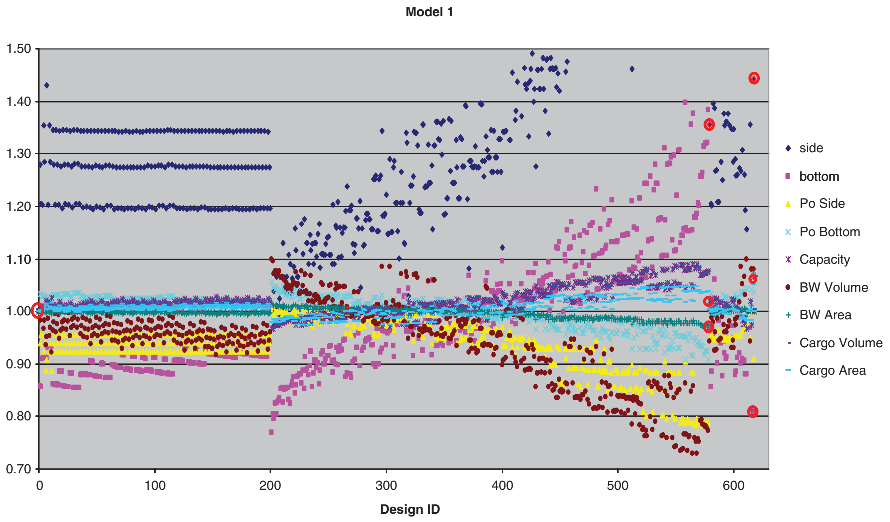

Fig. 6.19 Search domain for Model 1; values are normalized with respect to given reference vessel

A, Table 6.7. The reference vessel is coded as ID 0 in the particular table. The underlined values indicate cases that do not meet the minimum cargo tank length requirement specified by the relevant MARPOL regulations.

After all Pareto-optimal design alternatives have been identified, the next step is to evaluate them in relation to economical, safety and environmental impact considerations in order to select the best design. The selection of the best design should also involve major stake-holders' preferences. A Multi-Criteria Decision Making (MCDM) procedure might be employed to rationalize stake-holders preferences and address the decision making effectively, introducing a new single objective function by use of so-called *utility functions*; they are enabling the systematic evaluation of the PODAs by a computerized procedure and greatly support the decision making.

6.2.7.5 Resulting Design Alternatives

Regarding oil outflow performance, several alternatives have been explored. In this section, the most interesting resulting designs are briefly commented.

Alternative 141

The first selected alternative is the one coded as 141 that features the best oil outflow performance and some improvement of capacities, keeping in parallel most of the other relevant design features such as hull lines, engine room design, location of

Table 6.5 Principle characteristics of alterative 141

Width of double skin sides	2.10 m
Width of double skin bottom	Variable, 2.10 m min.
Draught scantling	14.60 m
DWT, scantling draught (comparable with design proposed)	109,800 dwt (cargo density 0.867 $\mathrm{T/m^3}$)
Cargo capacity	
Liquid volume,	$124,800\,\mathrm{m}^3 + 2,830\,\mathrm{m}^3$ (Slop),
heavy oil, diesel oil,	about $3,380\,\mathrm{m}^3$, $260\,\mathrm{m}^3$
Water ballast	$38,713\,\mathrm{m}^3 + 3,500\,\mathrm{m}^3$ (peaks)
Number of Cargo tanks	12 plus 2 slop tanks
Cargo Tanks block length	181.44 m

accommodation, etc. unchanged. The main particulars for alternative 141 are given in Table 6.5, whereas the basic general arrangement is shown in Fig. 6.20.

In the particular alternative, the arrangement of engine room as well as the fore and aft limit of the cargo block is kept the same as the reference vessel. The difference with respect to the reference vessel is in the distribution of load and ballast inside the cargo block and tanks length. The selected configuration gives more protection to the fore tanks where damages are more probable and also limits the volume of tanks situated in the more "risky areas". Note that the width of double side and depth of double bottom are reduced in relation to the reference design (tanks 5 and 6), allowing to recover the volume lost in the fore part of the ship (tanks 1, 2 and 3), where the double bottom is raised according to the introduced protection philosophy, and even gain some volume with respect the reference design.

Analyzing the changes introduced in the cargo tanks, it is evident that this configuration results to the aftward movement of the longitudinal centre of gravity compared to the reference design.

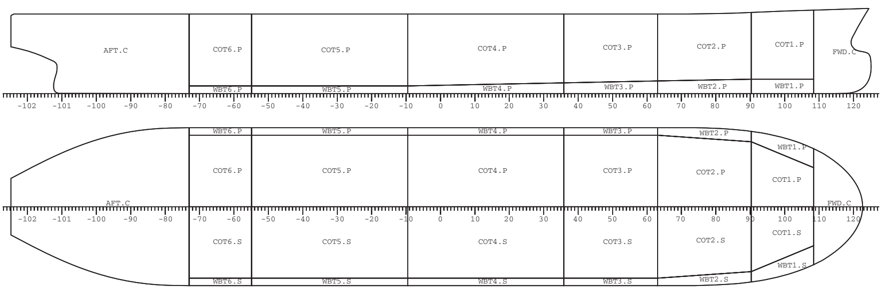

Fig. 6.20 Alternative 141: Cargo block sketch

Alternative Long310

This is one of the alternatives with the largest improvement in terms of cargo capacity, at fully satisfactory oil outflow performance. Due to the shortening of the engine

Table 6.6 Principle characteristics of alterative *Long310*

Width of double skin sides	2.30 m
Width of double skin bottom	Variable
Draught scantling	15.10 m
DWT, scantling draught (comparable with design proposed)	114,200 dwt (cargo density $0.855\,\mathrm{T/m^3}$)
Cargo capacity	
Liquid volume,	$130{,}43\ 0\,\mathrm{m^3} + 2{,}830\,\mathrm{m^3}$ (Slop),
heavy oil, diesel oil,	about $3{,}000\,\mathrm{m^3}, 260\,\mathrm{m^3}$
Water ballast	$44{,}344\,\mathrm{m^3} + 3{,}500\,\mathrm{m^3}$ (peaks)
Number of Cargo tanks	12 plus 2 slop tanks
Cargo Tanks block length	196.56 m

space, this design is associated with a "state of the art" Diesel Electric Drive system, which clearly introduces greater flexibility to arrange design layout while keeping the main dimensions of the tanker the same. The alternative takes advantage of a reduced engine room design offering an important opportunity to increase in cargo capacity. Table 6.6 presents the main characteristics of the particular alternative, whereas the basic general arrangement is given in Fig. 6.21.

The required propulsion for alternative Long310 consists of four medium speed Diesel Engines Driven Alternators of about 4300 kW and two Electric Motors coupled through a shaft line to a reduction gear, Fig. 6.22.

The Lightship weight of Long310 was estimated to be about 21,700 tonnes. The volume of cargo gained is located mainly in the aft part of the cargo block area; consequently in case of future further development of this particular design, a significant change of hull lines will be performed in order to better balance the actual position of longitudinal centre of gravity.

It must be mentioned that the fuel consumption for the current alternative with medium speed engines will be about 7% higher than the consumption of conventional propulsion with a slow diesel engine.

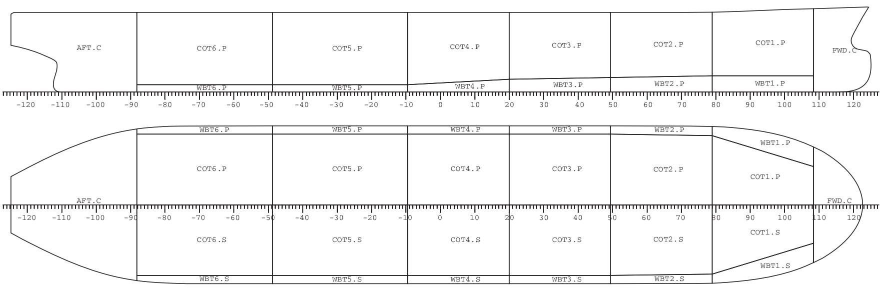

Fig. 6.21 Alternative Long310 Cargo sketch

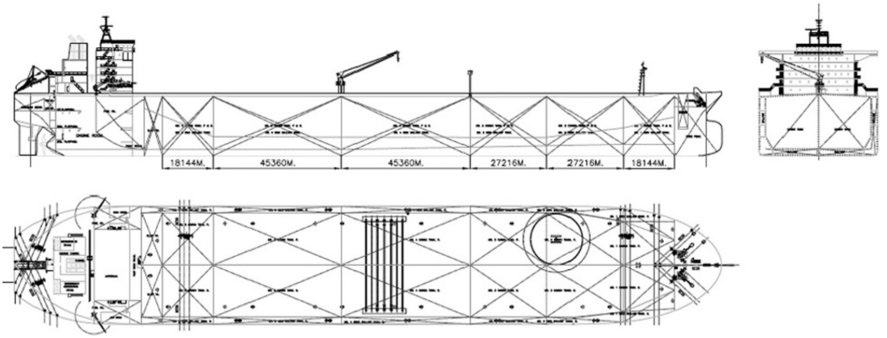

Fig. 6.22 Alternative Long310: Engine room sketch

Furthermore, a redistribution of the accommodation tower would be required to allow the arrangement of some technical spaces on the first deck, such as converter room and engine control room, noting that after the reduction of the engine room length, such spaces could not be located under the main deck. Finally, the strong impact of a diesel electric drive with medium speed diesel engines and high number of cylinders should be considered in the capital and maintenance/repair costs.

Alternative Zero Spill Tanker

Imposing a zero Oil Outflow ("Zero Spill" tanker) as a constraint in the optimization procedure for the cargo block area, a design with the following features is found, Fig. 6.23:

1. Inner bulkhead must be positioned in 13.2 m from side shell, in order to have zero oil outflow in all statistically probable side damages.
2. For survival in the extreme damage cases (0.3L damage extent), the cargo area must be located within a minimum number of wing compartments. Therefore seven (7) wing compartments are needed.
3. Double bottom tank height must be at least 6.3 m from the bottom shell in order to have zero oil outflow due to all statistically probable bottom damages.
4. For survival in the extreme bottom damage cases (0.8L), the assumed damage extent must be limited within the minimum number of possible compartmentation; one double bottom tank would be sufficient; however two (2) double bottom tanks are needed because of the side damage requirements without any restriction of being more than two. The resulted double bottom tanks can be used as dry spaces or for ballasting purposes.

The particular alternative has the obvious disadvantage of having a very poor cargo capacity, of only $46,000\,m^3$. In addition, ballast water must be arranged permanently in order to have adequate immersion of the propeller.

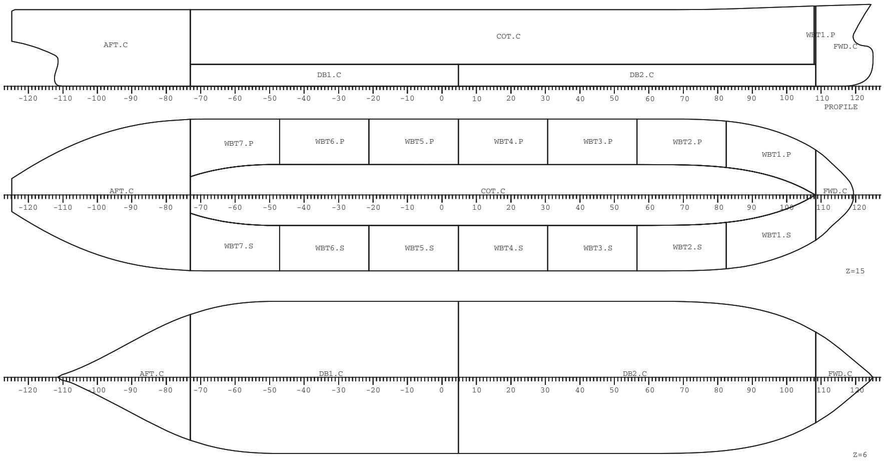

Fig. 6.23 Alternative zero oil outflow Cargo sketch

Design ID 10

Design alternative ID 10 is an example for increased oil outflow performance by raised double bottom height with a forward slope; however the cargo capacity is reduced significantly. The double bottom in the cargo block is raised by 2.5 m towards the forward part of the ship to 4.50 m from 2.0 m at the aft tank. The double side clearance is maintained at 2.5 m throughout the cargo block length which is the same as the reference vessel. Each cargo tank length is also kept the same as the reference vessel. This design is included to demonstrate the sole effect of the raised double bottom height for the forward section of the cargo block (Fig. 6.24).

Design ID Long20

Design alternative ID Long20 is a Double Hull optimized to have the best capacity together with an increased level of oil outflow performance. The cargo block is lengthened by 4 frames which is 15.12 m aftwards. Cargo tanks 5 and 6 fail to meet the formal minimum tank length requirements (MARPOL/Regulation 26). The double bottom in the cargo block is raised by 2.50 m towards the forward end to 4.50 m from 2.0 m at the aft tank. The double side clearance is maintained at 2.5 m throughout the cargo block length (Fig. 6.25).

Although the lengthening options of 1, 2 and 3 frames are included in the search, the best designs were obviously obtained with the maximum possible increase which is 4 frames. The design studies demonstrate an example engine room arrangement for the longer cargo block alternatives.

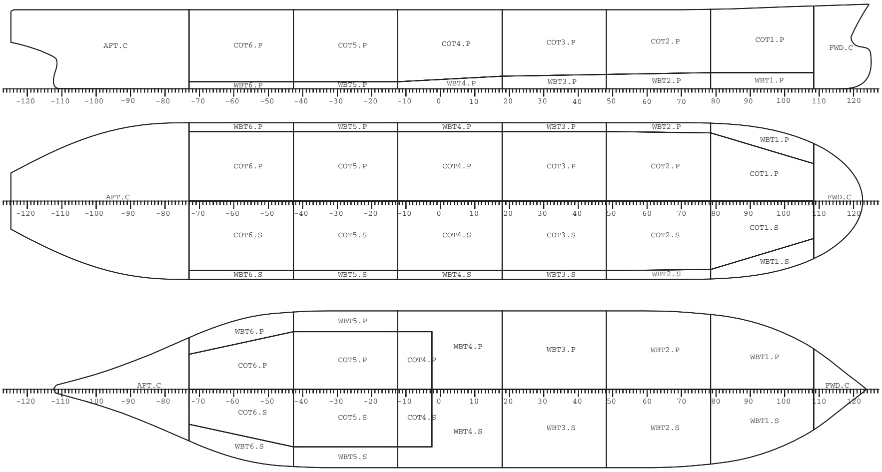

Fig. 6.24 Design ID 10 sketch

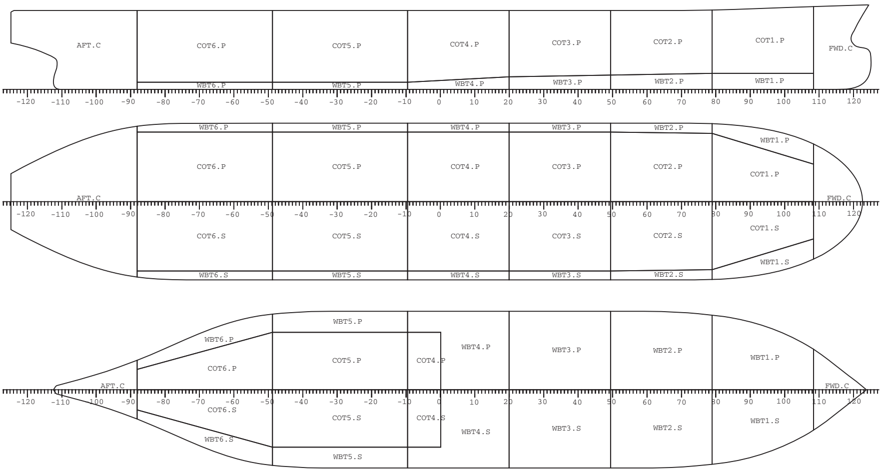

Fig. 6.25 Design ID long 20 sketch

A list of normalized performance values for the Pareto-optimal design alternatives is given in tabular form in Appendix A, Table 6.8 for easy comparison.

6.2.7.6 Comments on the Presented Alternatives

For the selected design alternatives no major technical problems were found. Some adjustments should be made in more detailed design stages in order to harmonize the structural configuration of the ship against common production methods. Also, potential modifications to hull lines are suggested in order to achieve an optimal trimming of the ship.

The selected alternatives show partly improved performances regarding the oil outflow, compared to the reference ship, which is actually in this respect a very good double hull representative, disposing side hull and double bottom clearances in excess of the MARPOL rules marginal values by 25%. This result is considered significant, having in mind that the regulation MARPOL 73/78 Annex I/26 (formerly Regulation 24) related to the maximum length of cargo tanks is not satisfied by the proposed alternatives. Consequently, it is suggested that an actualization of this rule could be considered. Moreover, the current optimisation method has been found effective to systematically assess and to improve the oil outflow performances of a design, generating technically and economically viable alternatives.

6.2.8 Economic Impact Study

Some proposed alternative designs dispose increased oil carrying capability; therefore from the point of view of yearly transport work and income they are clearly superior to existing AFRAMAX double hull designs, thus attractive to the industry. A simplified economic assessment model, which is based on the transport cost per tonne of oil carried, has been applied and results thereof shown in Appendix A, Table 6.9. Note that in this assessment, a roundtrip voyage of 8,000 sm at a service speed of 15 knots has been assumed.

Despite an expected increased building (first investment) cost, the alternative with longer cargo-block, (*Long310*) design shows a decrease of unit transport cost by 3.7% (the *Long 310-01* even by 6.7%!).

The same design proves superior to the basis ship with respect to its environmental impact (reduced oil outflow index E according to MARPOL relevant regulation). Another interesting result of the economic impact study is that that the developed zero outflow design (zero spill tanker) is associated with a unit transport cost of about 2.7 times higher than that of the basis ship.

6.2.9 Environmental Impact Study

Probabilistic oil outflow calculations were carried out for side and bottom damages to determine mean oil outflow values, assuming damages with Loss of Watertight Integrity (LOWI). Zero-oil outflow and extreme oil outflow values were also calculated in the process, assuming simplified cargo block internal details.

The likely amount of yearly oil outflow due to collision and grounding accidents was estimated independently on the basis of historical accidental data for Double Hull tankers (Papanikolaou et al. 2006); results for the environmental impact of the new designs, compared to the basis ship, appear also very promising. It should be however noted, that the number of double hull tanker accidents (post 1990 period) leading to pollution is very limited to allow firm statistical conclusions about the future and the there upon based assessment of the present designs. Other Hazard categories, besides those leading to LOWI, were not considered at this stage of the study.

The performance comparison shows that design alternative *141* and *Long310* are competitive to reference vessel in terms of environmental impact in case of collision or grounding accident, Appendix A, Table 6.8.

6.2.10 Further Investigations

Besides the further elaboration of the presented risk-based design concept and its application to any size of tanker, some further promising and most challenging items relevant to innovative tanker designs and increased safety are addressed below.

a) Main Dimensions and Hull Form: The present optimization study does not include considerations for the possible change of main dimensions and hull form at given deadweight capacity and speed. This is however a straightforward option within the introduced multi-objective optimization method by adding in the objectives the minimization of resistance and powering, along with considerations of optimal trim. The latter is particularly of importance for ballast operating conditions.
b) Structural design: No structural design aspects were introduced in the present optimisation study. This can be however also introduced as an additional feature of the presented holistic optimisation approach. For this, a parametric structural design model referring to the main structural elements needs to be developed and be introduced in the design parameters, whereas longitudinal strength requirements may be introduced as constraint. This may be facilitated by interfacing the present optimisation procedure with known structural design software tools of major classification societies. The objective will be herein (in addition) the minimization of the structural weight. Also, aspects of corrosion and maintenance in relation to cargo and ballast spaces and related areas may be introduced in the objectives, along with the handling of ballast water.
c) Further Safety issues: Some further safety relevant issues may be considered when developing safer and more effective tanker designs.

- Diesel electric propulsion: A diesel-electric powered propulsion system enables the possibility of installing two separate engine rooms providing higher redundancy as well as reduces engine room spaces. Installing also a POD propulsion system will enhance manoeuvrability and reduce port time without need for external tug assistance. It will also help at places of refuge for ships in need of assistance, as the tanker will be self sufficient for most of the small to medium size incidents even if she is left with a single engine room functioning.
- Twin screw propulsion: Twin screw propulsion for tankers is also a relatively simple but effective design feature that will significantly enhance the manoeuvrability and overall safety of tankers. This appears to be also

cost-effective, as shown in conducted preliminary Formal Safety Assessment studies (Dewanney 2008).

- Accommodation location: The possibility of locating the accommodation space and the deckhouse near the forepeak would improve watch keeping, and overall control of the vessel operations. Independently, a separated accommodation block from the control rooms, pump rooms and the bridge structure would also be possible, and would further reduce risk to crew life due to fire and explosion, and would help achieving zero-fatality rate.

6.2.11 Conclusions

An optimization of an AFRAMAX tanker with respect to the cargo block size and configuration has been carried out to arrive at the best design in terms of oil outflow performance whilst keeping the carrying capacity at least the same, but at best even increasing it.

The best oil outflow performance was obtained for the basic double hull configuration (Model 1) without compromising any economical competitiveness as measured here in terms of carrying capacity, cargo and ballast tanks volumes and surface areas.

Raised double bottom height for the forward section of the cargo block provides significant advantage in terms of reducing mean oil outflow as well as increasing zero oil outflow probability for mainly bottom damages. The same actually indirectly results as an effective Risk Control Option for a reduced length of the tanks in the forward cargo block section.

Design alternative 141 attains better overall oil outflow index (0.971), in comparison to reference vessel (1.00). Design alternative Long310 also attains better overall oil outflow index (0.986). Therefore these two design alternatives can be considered for further elaboration and development, Appendix A, Table 6.8.

Considering that these designs were developed by a risk-based procedure, challenging existing MARPOL rules, the route to acceptance by relevant authorities will be an evaluation of the proposed designs on the basis of the employed risk model which enables a direct comparison of a reference MARPOL design with the proposed alternative designs in terms of risk to environment, risk to property and risk to human life. The complete risk model and its evaluation could actually include all types of accidents, like non-accidental structural failure, collision, grounding, contact, fire and explosion. Furthermore, within the introduced holistic ship design optimisation procedure, further design aspects and objectives may be introduced, like optimization of structural design for least weight and maintenance effort, as well as of hull form for least powering.

Eventually, resulting designs should prove to have a reduced oil outflow potential in comparison to the reference design, whereas elements of the risk related to property and human life should also be reduced, at comparable or even increased efficiency and economic performance.

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Appendix

Table 6.7 Pareto Optimal design alternatives

	ID	**0***	**141**	**10**	**Long310**	**Long20**
Capacity	**mt**	104630.7	106642.6	101843.9	111516.2	110,319.8
	m^3	122375.1	124727.9	119115.7	130428.3	129,028.9
aft limit		–73.02	–73.02	–73.02	– 88.14	– 88.14
fwd limit		108.42	108.42	108.42	108.42	108.42
Layout type		0	0	0	0	0
Long bh	m	0	0	0	0	0
dbh	m	2.5	4	4.5	4.5	4.5
sw	m	2.5	2.1	2.5	2.3	2.5
Length	m	0.167	0.1	0.167	0.15	0.15
Centre		1	1	1	1	1
Side		0	0	0	0	0
dbh	m	2.5	4	4.5	4.5	4.5
sw	m	2.5	2.1	2.5	2.3	2.5
Length	m	0.167	0.15	0.167	0.15	0.15
Center		1	1	1	1	1
Side		0	0	0	0	0
dbh	m	2.5	3.5	4	4	4
sw	m	2.5	2.1	2.5	2.3	2.5
Length	m	0.167	0.15	0.167	0.15	0.15
Centre		1	1	1	1	1
Side		0	0	0	0	0
dbh	m	2.5	3	3.5	3.5	3.5
sw	m	2.5	2.1	2.5	2.3	2.5
Length	m	0.167	0.25	0.167	0.15	0.15
Centre		1	1	1	1	1
Side		0	0	0	0	0
dbh	m	2.5	2.1	2	2	2
sw	m	2.5	2.1	2.5	2.3	2.5
Length	m	0.167	0.25	0.167	0.2	0.2
Centre		1	1	1	1	1
Side		0	0	0	0	0
dbh	m	2.5	2.1	2	2	2
sw	m	2.5	2.1	2.5	2.3	2.5
Length	m	0.167	0.1	0.167	0.2	0.2
Centre		1	1	1	1	1
Side		0	0	0	0	0
Tank top raised	m	0	1.90	2.50	2.50	2.50

Table 6.8 Performance comparison of the Pareto-optimal alternative designs

	ID	0	141	10	Long310	Long20
Capacity	mt	104630.7	106642.6	101843.9	111516.2	110,319.8
	m^3	122375.1	124727.9	119115.7	130428.3	129,028.9
Side outflow		1.00	1.3564	1.0008	1.4425	1.2977
Bottom outflow		1.00	0.9694	0.8120	0.8074	0.8065
Po Side	–	1.00	0.9503	1.0003	0.9092	0.9403
Po bottom	–	1.00	1.0140	1.0420	1.0359	1.0365
Capacity	–	1.00	1.0192	0.9734	1.0658	1.0544
BW volume	–	1.00	0.9427	1.0794	1.0798	1.1139
BW area	–	1.00	1.0011	1.0111	1.0724	1.0752
Cargo volume	–	1.00	1.0192	0.9734	1.0658	1.0544
Cargo area	–	1.00	1.0029	0.9827	1.0514	1.0445
E		**1.00**	**0.971**	**1.037**	**0.986**	**1.001**

Note: The values are normalised with respect to the reference vessel, ID0.

Side outflow:	mean oil outflow due to side damage
Bottom outflow:	mean oil outflow due to bottom damage
Po Side:	probability of zero oil outflow for side damage
Po Bottom:	probability of zero oil outflow for bottom damage
Capacity:	total cargo carrying capacity
BW Volume:	total volume of ballast water tanks within cargo block
BW Area:	total surface area of ballast water tanks within cargo block
Cargo Volume:	total volume of cargo tanks within cargo block
Cargo Area:	total surface area of cargo tanks within cargo block

Table 6.9 Economic impact study - voyage roundtrip 8,000 sm, speed 15 knots

ID	Reference vessel	141	Long310	Zero outflow	Long310-01
Vessel DWT	108857	110222	115296	113864	120900
Capital cost					
Cost, $ M	65.00	66.08	66.81	65.00	68.00
CRF at 12% 20 years	0.13	0.13	0.13	0.13	0.13
Annualized Cost	8.70	8.85	8.94	8.70	9.10
Non–voyage optg cost, $ M					
Manning	0.89	0.89	0.89	0.89	0.89
Stores and Lubes	0.27	0.27	0.27	0.27	0.27
M & R	0.58	0.58	0.58	0.58	0.58
Insurance					
H & M	0.58	0.59	0.60	0.58	0.61
P & I	0.09	0.09	0.09	0.09	0.09
Admin and Other	0.23	0.23	0.23	0.23	0.23
Voyage Cost , $ M					
Fuel					
Fuel cons, T/d	45	45.45	46.72	46.17	48.14
Fuel cost $/T	220	220	220	220	220
Fuel cost	3.45	3.49	3.59	3.54	3.70
Port Costs	0.21	0.21	0.21	0.21	0.21
Total costs, $M	15.01	15.20	15.40	15.10	15.68
Cargo Del' d, MT/yr	1.50	1.52	1.59	0.55	1.67
Trans Cost, $/T	10.03	9.97	9.66	27.55	9.36
% Difference in terms of transport cost		***– 0.64%***	***–3.72%***	***+174.70%***	***– 6.65%***

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6.3 Fast Full Displacement Ferry

Andrzej Jasionowski and Esa Pöyliö

6.3.1 Introduction

Provision of safety in a ship design process has been based to date on the compliance with a set o prescriptive regulations, Jasionowski et al. (2006a, b, c). Although alternative means of compliance with safety standards is permitted in the SOLAS rules in principle, the process of developing such alternatives and performing the necessary calculus has never been elaborated or agreed, e.g. with regard to fire related loss scenarios, and was excessively laborious. Thus, the eventual approval by the authorities of alternative means has never been predictable. The project SAFEDOR set to progress this status quo by developing transparent risk modeling techniques as well as by bringing about their common acceptance.

The present study has advanced one main element of such methodology and demonstrated its merits. Its primary objective was to increase payload of a fast displacement ferry by more efficient utilization of space, but which solution could not be readily achieved without compromising safety regulations.

6.3.2 Design Concept

A ship representative of the current market trends was chosen as a starting basis of the design process, Pöyliö E (2006). The state of the art concept, hereafter referred to as Ver A, has length overall of 200 m, speed of 27 knots, passenger capacity of 2,200 and some 4,000 car-lane meters of payload space. The vessel has typical machinery arrangement of two medium speed diesel engines driving two shaft lines through two reduction gears. Electric energy is delivered by three diesel generator sets and two shaft generators.

According to the *ShipPax*® database there are 53 comparable vessels with passenger capacity of over 400 persons, with speed of over 25 knots and overall length of about 180 m. The first 4 fast full displacement ferries were built in late 1970s, in 1980 only two ships were delivered, in 1990s 18 new builds were delivered, and in years 2000–2005, 33 fast full displacement ferries entered trade. There is a clear market demand for such concept, with new operators starting the fast-ferry based trade, e.g. Color Line, Viking Line, etc.

The key design principle conceived as best responding to the objective of increasing payload has been layout referred to as “onion”, as shown in Fig. 6.26 below.

Additionally, alternative arrangement of upper passenger decks as well as means of ship evacuation without life boats has been considered. As was found out during early design iterations, these design choices would compromise the following regulations:

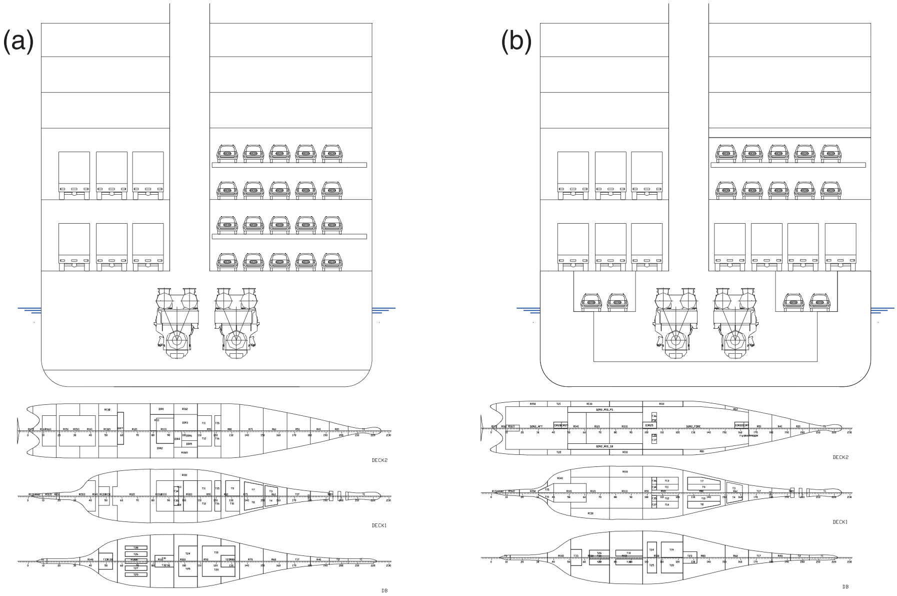

Fig. 6.26 A sketch of the concept designs, (**a**) reference vessel Ver A, *left*, and (**b**) "onion" arrangement, *right*

1. SOLAS II-1, MSC Resolution 216 (82), Regulation 6.1 on the attained index of subdivision.
2. SOLAS II-2, Regulation 9.2.2.1.2 on fire zones.
3. SOLAS III, Regulation 21.1.2.1 on provision of life boats.

Without RBD paradigm, whereby safety provision is based on managing risk, the above choices could not be considered further. The question obviously remained on how to demonstrate adequate safety standard of this rule-breaking design?

6.3.3 Safety Assessment

Safety can be considered in engineering as a "state of acceptable risk", Jasionowski et al. (2006a), which notion is fully compatible with the notion of SOLAS rules, whereby measurable and thus verifiable regulations must be complied with so that "risk" is acceptable, even though "risk" itself is unknown. A case when rules are not met has traditionally implied that risk is no longer acceptable to verifying bodies such as Class Societies or Administrations.

However, risk is neither disclosed explicitly in SOLAS rules, nor is it considered systematically, which is the core reason for the risk-based approach; it can prove advantageous in that risk posed by a design, when disclosed by a systematically constructed model, might prove still acceptable despite lack of compliance with deterministic regulations, which, in terms of risk R, could be expressed as follows:

$$R_{design} \leq R_{acceptable} \tag{6.1}$$

The key challenge is of course the mentioned explicit disclosure of the risk. As a first step in response to this challenge the risk must be defined. It is proposed that the risk is understood as a “chance of a loss”, whereby the “chance” is quantified by means of various statistics of the loss, and “the loss” is measured by an integer number of fatalities, N (no injury of any type is considered), in case of offering a route for demonstration of a safety alternative to regulations for the prevention of loss of life SOLAS. Also, at this stage no explicitly defined acceptable risk $R_{acceptable}$ is available and, therefore, a traditional approach has considered it sufficient to demonstrate that a new design would not give rise to higher risk than risk posed by a comparative and rules-compliant alternative. In this case the safety objective is to demonstrate that:

$$R_{design} \leq R_{VerA} \tag{6.2}$$

To re-iterate, it is obviously implicit that R_{VerA} is acceptable, since Ver A does comply with safety regulations, which are considered acceptable by all verifying bodies and thus society.

The next step is the exact and verifiable quantification of risk R. Here the risk has been quantified by an “expected number of fatalities” which can occur, should an accident of collision and flooding take place, as shown below.

$$R = \sum_{i=1}^{N_{\max}} i \cdot fr_N(i) = \sum_{i=1}^{N_{\max}} F_N(i) \tag{6.3}$$

$$F_N(N) = \sum_{i=N}^{N_{\max}} fr_N(i) \tag{6.4}$$

Where: $F_N(N)$: cumulative distribution of frequency for occurrence of N or more number of fatalities per ship per year, known as an “F-N curve” $N_{\max}$ is the total number of persons considered (e.g. number of crew, or number of passengers, or both, onboard the ship), and $fr_N(N)$ is the frequency of occurrence of exactly N number of fatalities per ship per year, given by Eq. (6.5).

$$fr_N(N) = \sum_{j=1}^{n_{hz}} fr_{HZ}(hz_j) \cdot p_{N|HZ}\left(N \middle| hz_j\right) \tag{6.5}$$

Where n_{hz} is the total number of loss scenarios considered as “exhaustively” contributing to risk to life, and hz_j represents an event of the occurrence of a chain of events HZ, (a loss scenario), identifiable by any of the following principal hazards (Table 6.10):

Furthermore, $fr_{HZ}(hz_j)$ is the frequency of occurrence of a scenario $HZ = hz_j$ per ship per year, and $p_{N|HZ}\left(N \middle| hz_j\right)$ is the marginal probability of occurrence of exactly N fatalities, given loss scenario hz_j occurred. The nature of the Eq. (6.5) is what allows for straightforward yet consistent and arbitrarily comprehensive

Table 6.10 Principal hazards

j	Principal hazards, hz_j	Average historical frequency of its occurrence, $fr_{HZ}(hz_j)$
1	Collision and flooding	2.58E-03 Vanem et al. (2004)
2	Grounding and flooding	
3	Fire	
4	Intact Stability Loss	N/A in this exercise
5	… etc	

accommodation for any conceivable loss scenario contributing to risk to life, and for which reason the risk model of Eq. (6.3) or (6.4) can be referred to as "holistic".

In this design exercise only one loss scenario of a ship-to-ship collision, denoted as $HZ = hz_1$, is considered for quantification of risk to life. The frequency of occurrence of this loss scenario, $fr_{HZ}(hz_1)$, in this discussion will be based on historical data, according to which such scenario takes place 2.58E-03 times per RoPax ship per year Vanem et al. (2004).

Finally, the model for assigning of marginal probability mass distribution $p_{N|HZ}(N|hz_1)$ for a number of fatalities N that can occur as a result of scenario of flooding due to a collision and subsequent loss of stability, hz_1, can be presented in a numerically disclosed form, Jasionowski et al. (2006a, b, c), Jasionowski et al. (2007) as follows:

$$p_{N|HZ}(N|hz_1) = \sum_{i}^{3} \sum_{j}^{n_{flood}} \sum_{k}^{n_{Hs}} w_i \cdot p_j \cdot e_k \cdot c_{i,j,k}(N) \tag{6.6}$$

The terms w_i and p_j are the probability mass functions of the 3 specific loading conditions and n_{flood} number of flooding extents, respectively, calculated according to the harmonized probabilistic rules for ship subdivision, MSC 216 (82). The term e_k is the probability mass function given by Eq. (6.7), where k denotes a successive environmental condition (sign. wave height) Hs_k, *where* $0 < Hs_k \leq 4m$, $Hs_k = k \cdot 4 \cdot n_{Hs}^{-1}$.

$$e_k = \begin{cases} 0.3093 & if\ Hs_k = 0 \\ 1.2 \cdot e^{\left(-e^{0.16-1.2\cdot Hs_k} + (0.16-1.2\cdot Hs_k)\right)} \cdot \left(4 \cdot n_{Hs}^{-1}\right) & if\ Hs_k > 0 \end{cases} \tag{6.7}$$

$$c_{i,j,k}(N) = \left(-\ln\left(\varepsilon_{i,j,k}\right) \cdot \left(\varepsilon_{i,j,k}\right)^{\frac{t_{fail}(N)}{t_0}}\right) \cdot \frac{\left|\partial t_{fail}(N)\right|}{t_0} \tag{6.8}$$

$$\varepsilon_{i,j,k} = 1 - \Phi\left(\frac{Hs_k - Hs_{crit}(s_{ij})}{\sigma_r\left(Hs_{crit}(s_{ij})\right)}\right) \tag{6.9}$$

$$\sigma_r(Hs_{crit}) = 0.039 \cdot Hs_{crit} + 0.049 \tag{6.10}$$

$$Hs_{crit}(s) = \begin{cases} 0 & if\ s \leq 0.3093 \\ \dfrac{0.16 - \ln(-\ln(s))}{1.2} & if\ s > 0.3093 \end{cases} \quad (6.11)$$

Equation (6.8) associates the time it takes the ship to capsize with the number of persons that can loose their life, should the ship capsize within this time, through the following relations.

$$\partial t_{fail}(N) = t_{fail}(N) - t_{fail}(N-1) \quad (6.12)$$

$$t_{fail}(N) = N_{fail}^{-1}(t) \quad (6.13)$$

$$N_{fail}(t) = N_{\max} - N_{evac}(t) \quad (6.14)$$

Where the term $N_{evac}(t)$ is the number of passengers evacuated within time t, referred to as an "evacuation completion curve", see Fig. 6.27 below.

Since no readily available tools to model the whole process of evacuation were available, the relation $N_{evac}(t)$ was considered in terms of its two main elements, namely the mustering (assembly at muster stations) and abandonment (use of life boats or MES), through the IMO principle shown in Fig. 6.28 below.

The process of assembly at muster stations is affected by the geometry of passenger spaces, and hence the commonly used method of its assessment has been based on numerical Monte-Carlo simulations, such as shown in the following Fig. 6.29 for two basic versions of accommodation spaces considered.

The result of such a simulation is the relation between the number of persons reaching muster stations and the time, see Fig. 6.30.

The speed of assembling $N_{assembley}(t)$ will be affected by the angle of heel, and in this project this was accounted for through a speed reduction relation with an angle of equilibrium in damaged condition as follows.

$$t\left(N_{assembley|\varphi}\right) = \frac{t\left(N_{assembley|\varphi=0\deg}\right)}{r(\varphi)} \quad (6.15)$$

$$r(\varphi) = \frac{e - e^{\frac{\varphi}{35}}}{e-1} \quad (6.16)$$

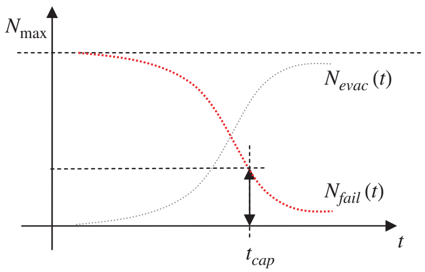

Fig. 6.27 Evacuation completion curve

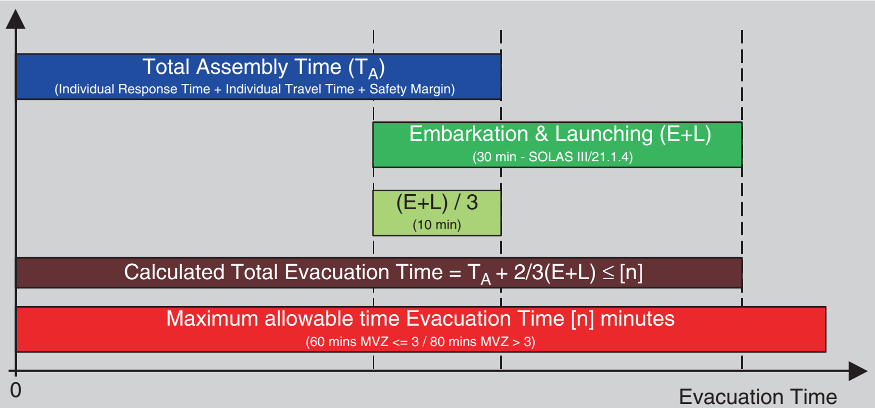

Fig. 6.28 Recommendation on the abandoning process assessment, 30 min, SOLAS III/21.1.4

Finally, the abandoning is considered to commence 10 min prior to last person arriving at muster stations for each damage case, see Fig. 6.28, and take in total 30 minutes in case of use of life boats, as suggested by SOLAS III/21.1.4, see Figs. 6.31 and 6.32 below.

When an MES system is considered, it is assumed that it takes on average 26 seconds per person per shoot to abandon the ship, see Figs. 6.33 and 6.34.

6.3.4 Design Studies

Conducted design studies entailed a number of iterations with subsequent assessment of risk as well as impact on environment and economic performance of each of the design variants. Design iterations were made through brain-storming sessions among the design team members, leading to 10 alternatives, as summarized in the following Tables 6.11 and 6.12 and Figs. 6.35 and 6.36.

6.3.5 Discussion of Results

As can be seen from Fig. 6.35, provision of a MES system only for passenger abandonment on the basis ship, Ver A, leads to about 4% increase in risk to life. This results from the fact that abandonment through shoots assumed in this study is slower, see Fig. 6.34. Provision of no LSA for the ship increases risk by 11%. All other design iterations E, E+ (increased GM), J and K seem to lead to risk to life higher than on the basis design Ver A, this despite the fact that these solutions provide with better protection of ship vital systems in way of the machinery spaces (some 30 or 55% lower probability of systems loss after collision in case of implementing longitudinal bulkhead at B/10 or B/5, respectively), see Fig. 6.37, as well as a better superstructure arrangement allowing for swifter assembly at muster stations,

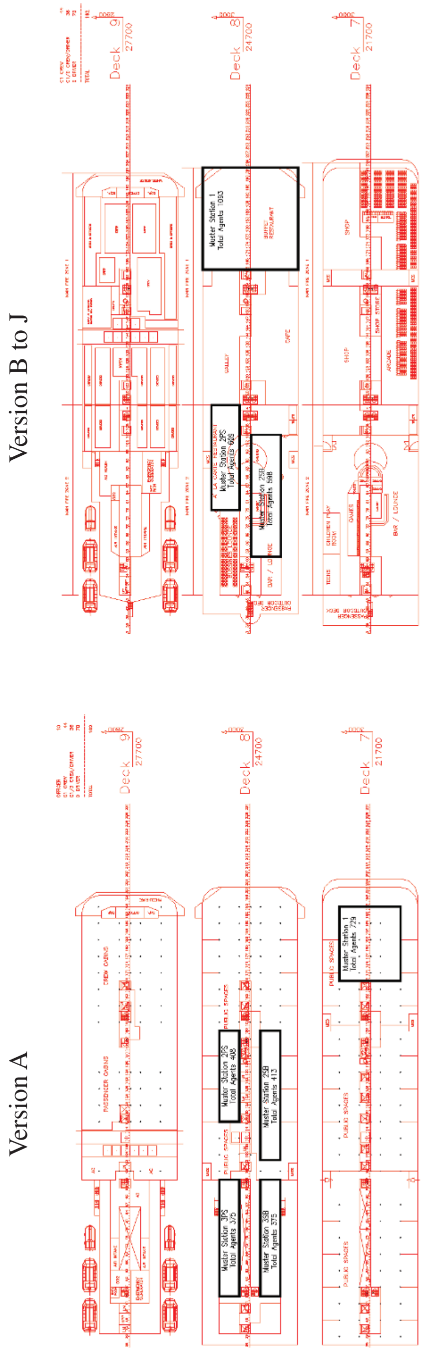

Fig. 6.29 Geometry of passenger spaces on upper decks with clearly marked mustering stations. Two versions of the arrangements simulated

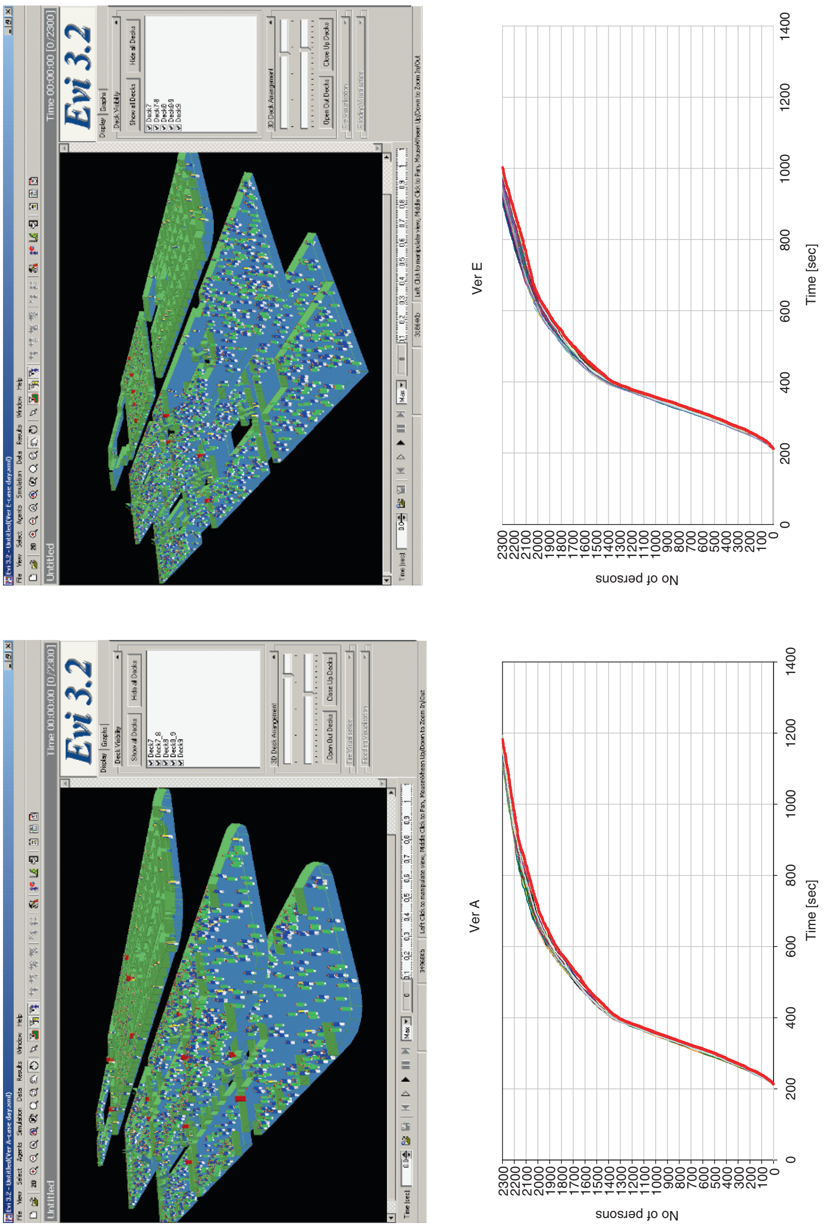

Fig. 6.30 Numerical simulation of assembly process, $N_{assembley}(t)$, for two alternative arrangements of upper decks. The slowest assembly (marked in red) in the Monte-Carlo simulation is considered further

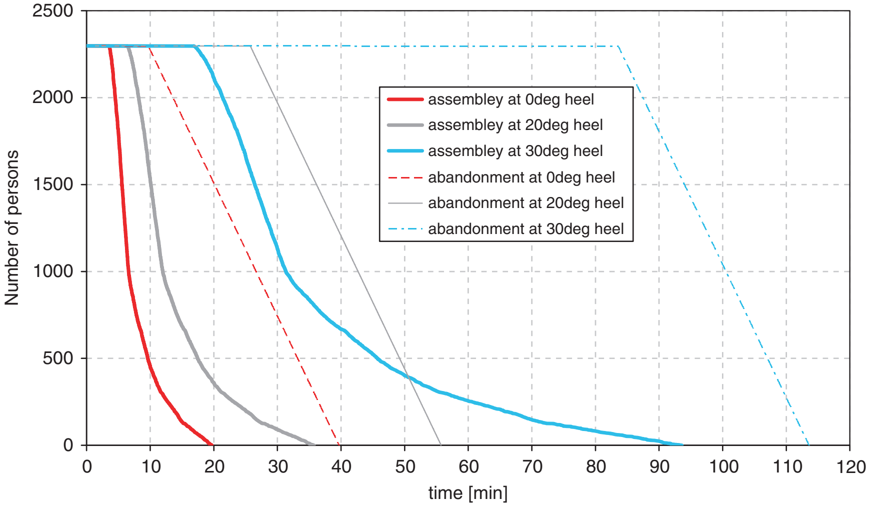

Fig. 6.31 Relationship between time and the complement of number of persons assembling in muster stations and eventually abandoning the vessel by life boats $N_{fail}(t) = N_{\max} - N_{assembley|\varphi}(t)$. Case of three heel angles assumed as attained in equilibrium after flooding. Abandonment is assumed to always take 30 min, according to IMO guidelines

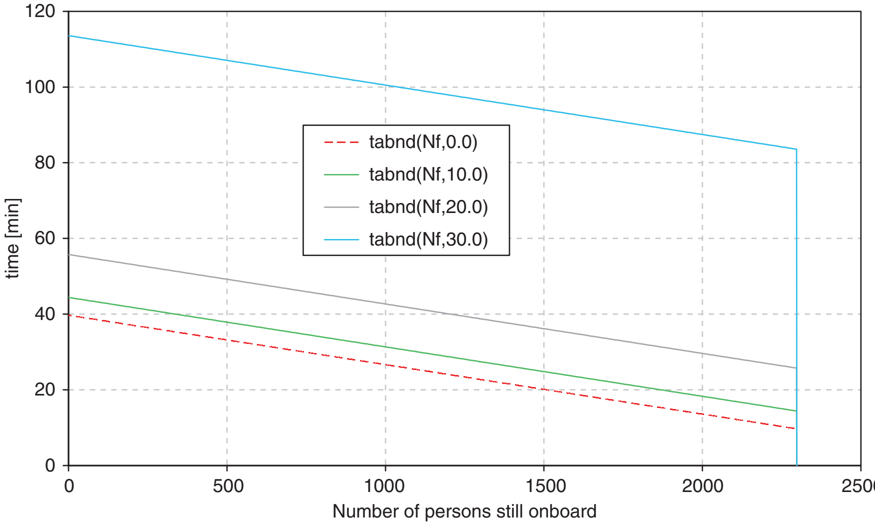

Fig. 6.32 Inverse relationship between the number of persons abandoning the vessel by life boats and the time, $t_{fail}(N) = N_{fail}^{-1}(t)$. Case of four heel angles of 0, 10, 20 and 30°, assumed as attained in equilibrium after flooding

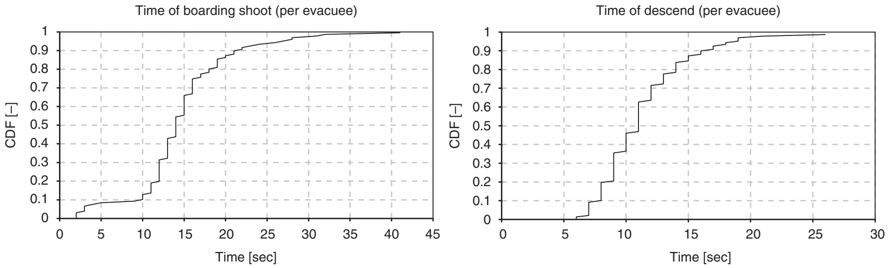

Fig. 6.33 Experimental data on boarding a shoot and descend within the shoot, with average abandonment rate of 26 s per person per shoot

see Fig. 6.30. Simply, there is higher number of extensive damage cases, where the vessel is lost fast with few or no passengers capable of abandoning the ship.

The high risk to life on the design solution "Ver E blister 1 row" seemed a surprise initially; however upon inspection of a number of time-domain simulations it became clear that the buoyancy was provided too high, as by the time heeling reached some 20–30°, i.e. where the buoyant blisters become effective, the flooding of car deck and upper spaces was too extensive and thus the vessel would still capsize. Thus, the solution "Ver E blister 2 row" was conceived, adding one more row of inflatable buoyancy near the deep draft line. The effect has surpassed the expectation, as the risk to life has been reduced by some 90% in comparison to *Ver A*.

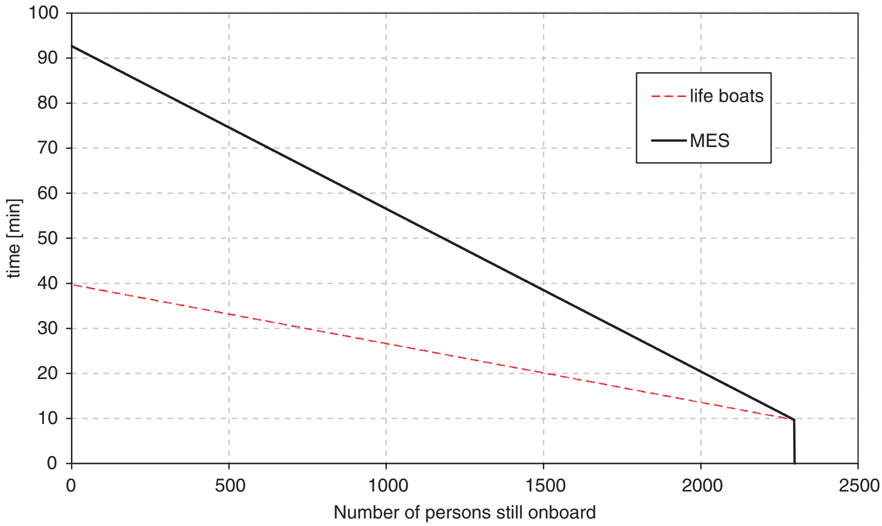

Fig. 6.34 Inverse relationship between the number of persons abandoning the vessel by life boats or MES, and the time, $t_{fail}(N) = N_{fail}^{-1}(t)$. Case of up-right equilibrium after flooding. The 2298 passengers will abandon the vessel in about **83 min** through 6 MES stations, with 2 shoots each

Table 6.11 Description of study cases. Notation: (l.boats – life boats considered, no.LSA – no life saving appliances considered)

Study Case	Ship version and LSA	A (digits in blue color correspond to cases with inflatable blisters)	1– A	Probability of ship capsizing within 3 h after events of collision and flooding	Risk (PLL) Expected value of the number of fatalities per ship per year, conditional on occurrence of collision and flooding loss scenario
1	Ver A (l.boats)	0.8082	0.1918	0.1771	0.951
2	Ver A (MES)	0.8082	0.1918	0.1771	0.991
3	Ver A (no.LSA)	0.8082	0.1918	0.1771	1.069
4	Ver E (l.boats)	0.7488	0.2512	0.2496	1.363
5	Ver E+ (l.boats)	0.8033	0.1967	0.1979	1.070
6	Ver E blister 1 row (l.boats)	0.7488 (0.7754)	0.1918	0.1944	1.045
7	Ver E blister 2 rows (l.boats)	0.7488 (0.9527)	0.1918	0.0140	0.071
8	Ver E blister 2 rows (no.LSA)	0.7488 (0.9527)	0.1918	0.0140	0.085
9	Ver J (l.boats)	0.7750	0.225	0.1928	1.059
10	Ver K (l.boats)	0.7965	0.2035	0.1807	0.989

l.boats – life boats considered, no.LSA – no life saving appliances considered.

It became clear that such solution for the provision of survivability, based on inflatable buoyancy blisters, can be extremely effective, to the extent, that even when no LSA are provided, the risk remains extremely low. Obviously since the size and location of these blisters impacts upon the risk so much, there is a lot of room for optimisation of this arrangement. Note, however, that there is room for improvements of solutions based on the "onion structure" only.

Since this project has only concentrated on the design of ship internal arrangement for better utilisation of the space, the environmental impact has been assessed on the bases of annual savings in CO_2 emissions which would be achieved through the increased ratio of (cargo carried)/(energy expenditure). The results are shown in Fig. 6.38 below. The increased ratio of payload to propulsive power, allows for reduction of annual CO_2 emissions by some 8% or more.

Table 6.12 Description of economic performance of various design alternatives Mammes (2006)

Annual earning capacity increase w.r.t. basis design		Amortisation time for additional investment and operational costs		Net annual earning capacity increase w.r.t. basis design	
E	13,9%	E	1,1 years	E	6,8%
EE	15,9%	EE	0,6 years	EE	6.8%
E + blister	13,9%	E + blister*	N/A	E + blister*	6.8%
EE + blister	15,9%	EE + blister*	N/A	EE + blister*	6.8*%
J	12,8%	J	1,4 years	J	6,4%
JJ	14,4%	JJ	0,8 years	JJ	5.7%
K	13%	K	1,3 years	K	7.0%
KK	14,5%	KK	0,7 years	KK	5.8%

* note that the cost of installation and maintenance of the inflatable blisters is unknown at this stage, and hence has not been accounted for in this study.

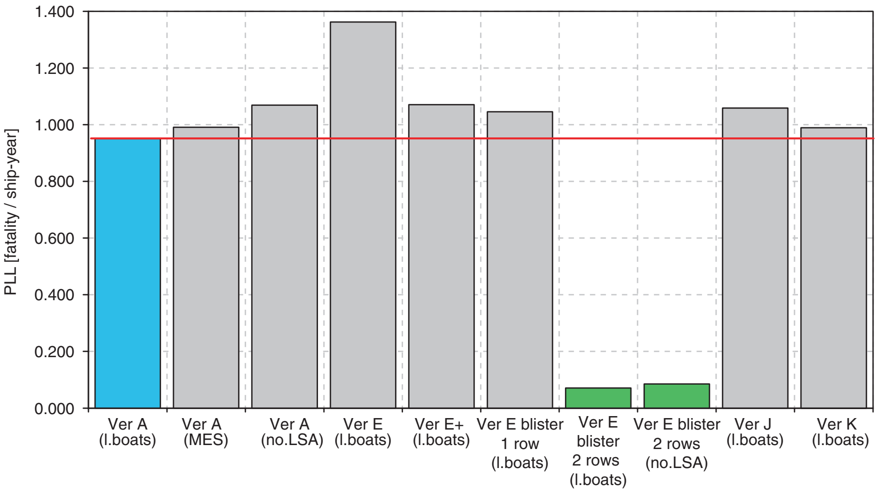

Fig. 6.35 The risk to life due to loss scenario of "collision ∩ flooding" for the series of ship design alternatives considered. The impact of inflatable buoyancy, Ver E2B, is immense, with over 90% risk reduction in comparison to the basis Ver A. Note the level of "acceptable risk", referred to in Eq. (6.2)

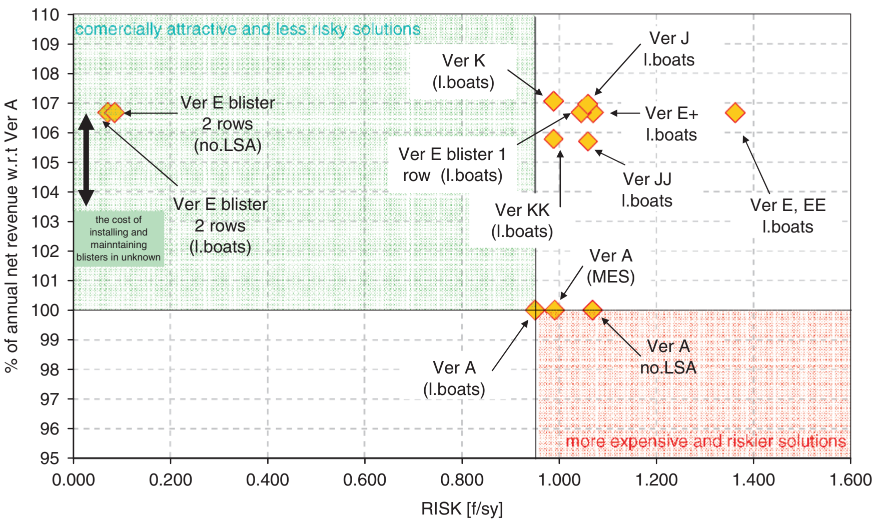

Fig. 6.36 Economic performance as a function of risk for design variations considered. Note the level of "acceptable risk", referred to in Eq. (6.2)

The proposed concept of an onion structure and changed superstructure allows for increase of the number of passengers up to 2,298 and the payload to between 4,300–4,800 car lane meters, i.e. the payload increases by 8–20%, respectively, though the 20% car lane payload increase cannot be realized due to limitation on number of persons on board, and thus trailer-based usage is considered.

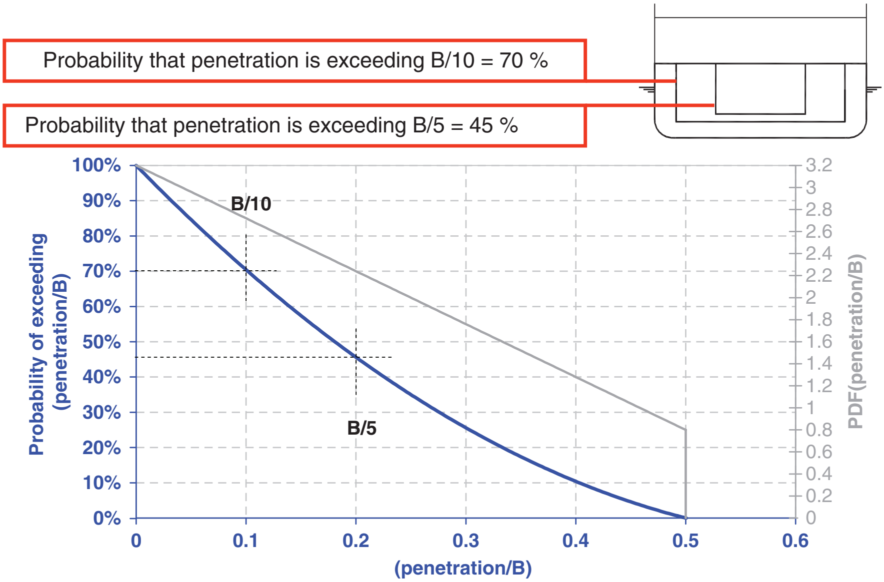

Fig. 6.37 Probability distribution for penetration depth

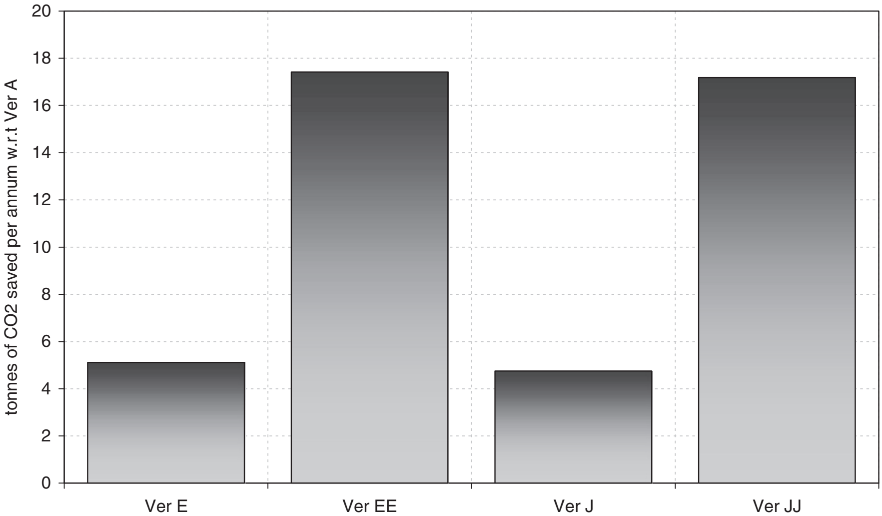

Fig. 6.38 Annual savings in CO_2 emissions with respect to the basis vessel

The period for payback on additional investments above those envisaged for the basis ship, of between 0.6 to 1.4 years has been estimated for various alternatives considered.

In terms of feasibility of the solutions, it is clear that the watertight arrangement is feasible, as it is simply a variation on the long-lower hold concept. The provision of inflatable buoyancy is, however, not yet established. An airbag installed for improved protection from deceleration impact seems a standard feature of nearly every car on the market today. Hence it is considered feasible that similar mechanism for stability provision, triggered by a sensor of heel, could in future effectively protect ships from capsizing.

6.3.6 Further Work

Further work would involve inclusion of more loss scenarios from Table 6.10, such as grounding, fire, intact stability and others. Each of these implies development of appropriate models for predictions of the occurrence of loss (in case of e.g. loss of life the task involves development of models for both the frequency of occurrence of each of these scenarios fr_{HZ} as well as distribution of the loss $p_{N|HZ}$). More comprehensive models should be considered, whereby design and operational variables such as e.g. structural arrangement, abandoning systems, crew performance, bridge systems, impact of systems availability see Fig. 6.39 and Eq. (6.17), or the whole organization of rescue operations are all included. The risk or economic modeling should allow for flexible extensions for bespoke solutions, such as the "blisters" considered in this study, this would imply that an advanced and dedicated computer aided design system needs to be developed, allowing for interaction at any level of detail and optimization.

Moreover, proper quantification of uncertainties in modeling should be considered.

$$t_{fail|j}(N) = \frac{t_{fail}(N)}{1 - p\left(lsa\_systems\_fail \,\middle|\, damage_j\right)} \tag{6.17}$$

Last but not least, the professional community and authorities?! should develop explicit numerals for the acceptable risk, so that any design can be developed without reference to existing concepts.

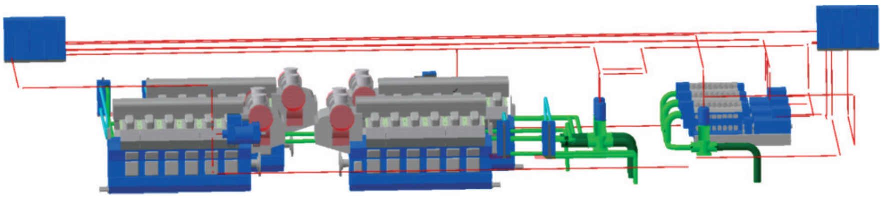

Fig. 6.39 Assessment of systems availability could be included in risk modelling

6.3.7 Conclusions

This study has demonstrated that risk-based design of RoPax ships is possible and that it can lead to very effective and safe design solutions. A series of design solutions, inconceivable when the creativity space is restrained by the prescriptive safety codes and regulations, but enabled through the new philosophy of risk-based design, have been explored. A design which is substantially more attractive commercially, more environment-friendly and yet is dramatically less risky with respect to potential loss of life, has been developed.

It seems that the key for risk-based-design to become reality is the disposal of a robust risk model, which is validated and accepted by the authorities.

Elements of the concept of a holistic view of safety have been explored through implementation of a comprehensive model of risk. It was found that despite more efficient superstructure arrangement in terms of the evacuability, the design as a "whole" was more risky.

Acknowledgments This report is a summary of work undertaken in a close partnership of the following organizations:

- Color Line, Norway
- Deltamarin Ltd, Finland
- Det Norske Veritas, Norway
- Meyer Werft, Germany
- Safety at Sea Ltd, United Kingdom

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Acronyms and Glossary

Acronyms

A, A-Index	Attained subdivision index
AIS	Automatic Identification System
ALARP	As Low As Reasonably Practicable
ANN	Artificial Neural Network
ARPA	Automatic Radar Plotting Aids
ASET	Available Safe Egress Time
BDDs	Binary Decision Diagrams
CAF	Cost of Averting a Fatality
CATS	Cost to Avert one Tonne of Spilt Oil
CEN	Comité Européen de Normalisation/European Committee for Standardization
CFD	Computational Fluid Dynamics
CLIA	Cruise Lines International Association, http://www.cruising.org/
COMSAR	Communication and Search and Rescue (IMO sub-committee)
DALY	Disability Adjusted Life Year
DE	Design and Equipment (IMO sub-committee)
DNV	Det Norske Veritas
DOF	Degrees of freedom
ECDIS	Electronic Chart Display and Information System
EU	European Union
FEC	Fractional Effective Concentration
FED	Fractional Effective Dose
FEM	Finite Element Method
FMEA	Failure Mode and Effects Analysis
FORM	First-Order Reliability Method
FRP	Fibre Reinforced Plastics
FSA	Formal Safety Assessment
FTA	Fault Tree Analysis
FTS	Fault Tree Synthesis
GA	Genetic Algorithms

GBS	Goal Based Standards
GCAF	Gross Cost of Averting A Fatality
GL	Germanischer Lloyd
GRP	Glass fibre Reinforced Plastics
GUI	Graphical User Interface
HazId	Hazard Identification
HAZOP	Hazard and Operability Studies
HiP-HOPS	Hierarchically Performed Hazard Origin and Propagation Studies
HLA	Helicopter Landing Area
HSC	High-Speed Craft
HSE	Health & Safety Executive (UK), http://www.hse.gov.uk/
IACS	International Association of Classification Societies, http://www.iacs.org.uk/
ICAF	Implied Costs of Averting a statistical Fatality (term now replaced by NCAF)
ICCL	International Council of Cruise Lines (now CLIA)
IMF	International Monetary Fund
IMO	International Maritime Organization (IMO), http://www.imo.org/
INTERCARGO	International Association of Dry Cargo Shipowners, http://www.intercargo.org
ISM	International Safety Management (ISM) Code
ISO	International Organization for Standardization
ISPSC	International Ship and Port Security Code
ITTC	International Towing Tank Conference
LMIS	Lloyds Maritime Information Systems
MCA	Maritime and Coastguard Agency (UK)
MCDM	Multi-Criteria Decision Making
MEPC	Marine Environment Protection Committee (IMO committee)
MES	Marine Evacuation System
MFZ	Main Fire Zone
MSC	Maritime Safety Committee (IMO committee)
MVZ	Main Vertical Zone
NCAF	Net Costs of Averting a Fatality
NRC	Nuclear Regulatory Commission (US)
OECD	Organization for Economic Co-operation and Development
OFM	Operator Function Model
OPA	Oil Pollution Act (US)
PLL	Potential Loss of Life
PoE	Panel of Experts (Appointed provisional sub-committee for assessing ship's damage stability, IMO-MSC, 1994–1995)
PSA	Probabilistic Safety Assessment
PSC	Port State Control
PVC	Polyvinylchloride
QRA	Quantitative Risk Analysis

QRD	Qualitative Design Review
R, R-Index	Required subdivision index
RBD	Risk-Based Design
RCO	Risk Control Option
RFR	Required Freight Rate
RID	Regulatory Impact Diagrams
RINA	Registro Italiano NAvale
RO	Recognized Organizations
RPN	Risk Priority Number
RSET	Required Safe Egress Time
SAVANT	Systems AVailability ANalysis Tool
SCF	Ship Construction File
SLA	Safety Level Approach
SLF	Sub-committee on Stability and Load lines and on Fishing vessels (IMO sub-committee)
SMS	Safety Management System
SRA	Structural Reliability Analysis
UN	United Nations
VOF	Volume of Fluid (CFD numerical method)
WB	World Bank
WIG	Wing-In-Ground effect craft

Glossary*

Accident An unintended event involving fatality, injury, ship loss or damage, other property loss or damage, or environmental damage.

Accident category A designation of accidents reported in statistical tables according to their nature, e.g. fire, collision, grounding, etc.

Accident scenario A sequence of events from the initiating event to one of the final stages.

Consequence The outcome of an accident.

Frequency The number of occurrences per unit time (e.g. per year).

Generic model A set of functions common to all ships or areas under consideration.

Hazard A potential to threaten human life, health, property or the environment.

Initiating event The first of a sequence of events leading to a hazardous situation or accident.

Risk The combination of the frequency and the severity of the consequence.

*(Reference: International Maritime Organization, MSC 83/INF.2)

Risk contribution tree (RCT) The combination of all fault trees and event trees that constitute the (RCT)

Risk control measure A means of controlling a single element of risk

Risk control option (RCO) A combination of risk control measures

Risk evaluation criteria Criteria used to evaluate the acceptability/tolerability of risk.

Main Maritime International Conventions – IMO

MARPOL Convention

The MARPOL Convention (International Convention for the Prevention of Pollution from Ships) is the main international convention covering the prevention of pollution of the marine environment by ships from operational or accidental causes. It is a combination of two treaties adopted at IMO in 1973 and 1978 respectively. MARPOL was continuously updated by amendments through the years (http://www.imo.org/Conventions/).

SOLAS Convention

The SOLAS Convention (International Convention for the Safety of Life at Sea) in its successive forms is generally regarded as the most important of all international treaties concerning the safety of merchant ships. The first version was internationally adopted in 1914, in response to the Titanic disaster, the second in 1929, the third in 1948, and the fourth in 1960. The 1960 Convention was the first major task for IMO after the Organization's creation. SOLAS was continually updated by amendments through the years (http://www.imo.org/Conventions/).

ICLL Convention

The first ICLL Convention (International Convention on Load Lines), adopted in 1930, was based on the principle of reserve buoyancy, although it was recognized then that the freeboard should also ensure adequate stability and avoid excessive stress on the ship's hull as a result of overloading. Thus, limitations on the draught to which a ship may be loaded make a significant contribution to her safety. These limits are given in the form of freeboards, which constitute, besides external weathertight and watertight integrity, the main objective of this Convention. As other conventions, it was continually updated at IMO by amendments through the years (http://www.imo.org/Conventions/).

STCW Convention

The International Convention on Standards of Training, Certification and Watch-keeping for Seafarers (STCW), 1978, as amended, sets qualification standards for masters, officers and watch personnel on seagoing merchant ships. STCW was adopted in 1978 by conference at the International Maritime Organization (IMO) in London, and entered into force in 1984. The Convention was significantly amended in 1995.

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Mr. Dag McGeorge qualified as a naval architect from NTNU in Norway in 1989 and now holds the position of Principal Engineer at Det Norske Veritas. He has 15 years of working experience in project management, research and development, innovation and consultancy mainly related to maritime, naval and offshore activities with focus on the use of advanced and lightweight materials in load-bearing structural applications. He was project manager and technical coordinator of a large collaborative European R&D project on composites in superstructures of naval ships (EUCLID RTP3.21) and is now leading SAFEDOR's subproject on risk based design of composite superstructures.

Apostolos D. Papanikolaou studied Naval Architecture & Marine Engineering at the Technical University of Berlin, where he also received his Dr.-Ing. and Habilitation degrees. He is Professor of Ship Design in the School of Naval Architecture and Marine Engineering of the National Technical University of Athens and Director of the Ship Design Laboratory. His educational, research and professional activities cover a broad area of Naval Architecture and Ocean Engineering and are documented in about 400 technical publications. He was and is Principal Investigator of a long series of EU or nationally funded research projects regarding the design and optimization of conventional and unconventional ships, the hydrodynamic analysis and assessment of the calm water performance and the seakeeping behavior of ships, the stability and safety of ships and regulatory developments.

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