Risk-Based Ship Design
Apostolos Papanikolaou (Ed.)

Risk-Based Ship Design
Methods, Tools and Applications

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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
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 81/245. 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 work-
ing 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 truly 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:

\[ R_{\text{Design}} \leq R_{\text{acceptable}} \]  \hspace{1cm} (1.1)

with \( R_{\text{Design}} \) the risk of the considered ship or system and \( R_{\text{acceptable}} \) 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 $R_{\text{Design}}$ 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 $R_{\text{acceptable}}$ 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.

References

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Related Research Projects

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, undemanned 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
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,
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.
• To mitigate the consequences of grounding: double bottom extent and height, etc.
• To mitigate the consequences of a fire: fire rating → 1 h fire protection \(\Delta T_{\text{max}} = 180^\circ\text{C}, \text{etc.}\), 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](image-url)