Chapter 3
On the History of Ship Design for the Life Cycle

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Contents

Abstract Maritime transport in its history after two world wars has developed an increasing significance in securing our welfare and prosperity in a global world. At the same time, the world has become aware of growing risks involved in marine transport technology by a number of shipping disasters, catastrophic losses and damages to the maritime environment. The maritime community has responded to these challenges by intensified research and developments. New ship types, new design methodologies and tightened safety standards and regulations have been introduced and are in further development. This chapter deals with the driving forces in this new situation and describes new achievements and current trends in the methodologies of ship design for safer, cleaner and more economical ships.

Keywords Lifecycle ship modelling · Holistic ship design
Multiobjective optimization · Genetic algorithms

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3.1 Introduction

Design is a decision process. Design aims at finding a solution within a set of possible alternatives. This process may be informal by plain trial and error. Modern rational design, however, is usually based on a formalized model of the decision process. Such models are generally built on the basis of modern decision theory (Chernoff and Moses 1986).

Design can be modelled as a formal decision process in mathematical and hence computational terms if a specific design paradigm is adopted. A rather generic paradigm models the design process by means of the following elements (Fig. 3.1).

D = design variables, free decision variables.

P = parameters, state variables of the design, usually a function of the free variables, but not under the designer's control.

M = M (D, P) = measure of merit function (also objective function), determined by the designer's preference. A design may be stated to have several objectives.

C = C (D, P) = constraint functions. The state variables of the design are usually subject to constraints (of equality or inequality type), i.e. functional, technical, physical, regulatory, safety, environmental, aesthetic and other side conditions. They serve to define the permissible range of variation in the design, thus to recognize the feasible space.

The criteria **M** and **C** may contain probabilistic elements in their definitions so that the whole model may have distributions of probabilistic results, e.g. different values for different lifecycle stages. These influences of uncertainties will be taken into account statistically according to their frequency of occurrence.

The elements **R** and **S** contain input information to the design process, while the variables of design assessment and of ship properties are outputs.

R contains design requirements by the owner and by authorities.

S denotes the given bounds on variable search ranges and the like. It also includes databases for fuel and material costs and other information about the market. The outputs denote all information that is needed to evaluate the ship by the chosen criteria, but in addition they contain many other design features which will help to evaluate ship performance as a by-product of assessing many systems in the ship.

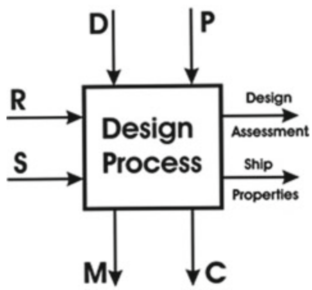

Fig. 3.1 Elements of the design process (Nowacki 2009)

In this chapter, the historical development of design decision modelling will be reviewed from its early beginnings in manual design practice, but mainly during the computer era, when elaborate lifecycle assessment became feasible in early design stages. The story will demonstrate how in the course of time more and more relevant elements of the design process of ships were included in design, production and operational decisions under the aspects of the whole life cycle of ships.

3.2 Ship Design Decision Models

3.2.1 Ship Design as Optimization

Figure 3.1 describes the elements of a design process and at the same time of Systems Analysis. Systems Analysis and ship design are special cases of a decision process.

Systems Analysis deals with the task of finding a *best* solution within a set of feasible alternative systems under given constraints. The systems may be *products* at a given time or time-dependent *processes*. *The existence of a measure of merit for the system calls for and permits optimization*.

Ship Design, i.e. the design of ship characteristics, ship production processes and ship operations, in fact, of all lifecycle phases of ships, is a special case of Systems Analysis. Accordingly, the design task is also modelled as an optimization problem with constraints. This was recognized very early, e.g. in 1968 by Woodward et al. (1968).

The common denominator of these types of modelling applications is essentially the following problem statement:

> Minimize (or maximize) a measure of merit function $\mathbf{M}$ $(\mathbf{D}, \mathbf{P})$ of a system subject to constraints $\mathbf{C}$ $(\mathbf{D}, \mathbf{P})$, i.e. equalities $\mathbf{h} = \mathbf{h}$ $(\mathbf{D}, \mathbf{P}) = \mathbf{0}$ and inequalities $\mathbf{g} = \mathbf{g}$ $(\mathbf{D}, \mathbf{P}) \geq \mathbf{0}$.

If at least one constraint function and/or the measure of merit is a nonlinear function of the free design variables, which is common in ship design, then this problem type is known as "*nonlinear programming*" (*NLP*) (Fiacco and McCormick 1968). Thus, the integrated overall ship design problem and a great variety of ship design subproblems can be treated as nonlinear optimization problems with constraints (NLP).

3.2.2 The Stagewise Structure of the Ship Design Process

The development of a ship product model, i.e. the description of the entire ship with all its features and systems, goes through many decision stages as shown for ship product design in Fig. 3.2.

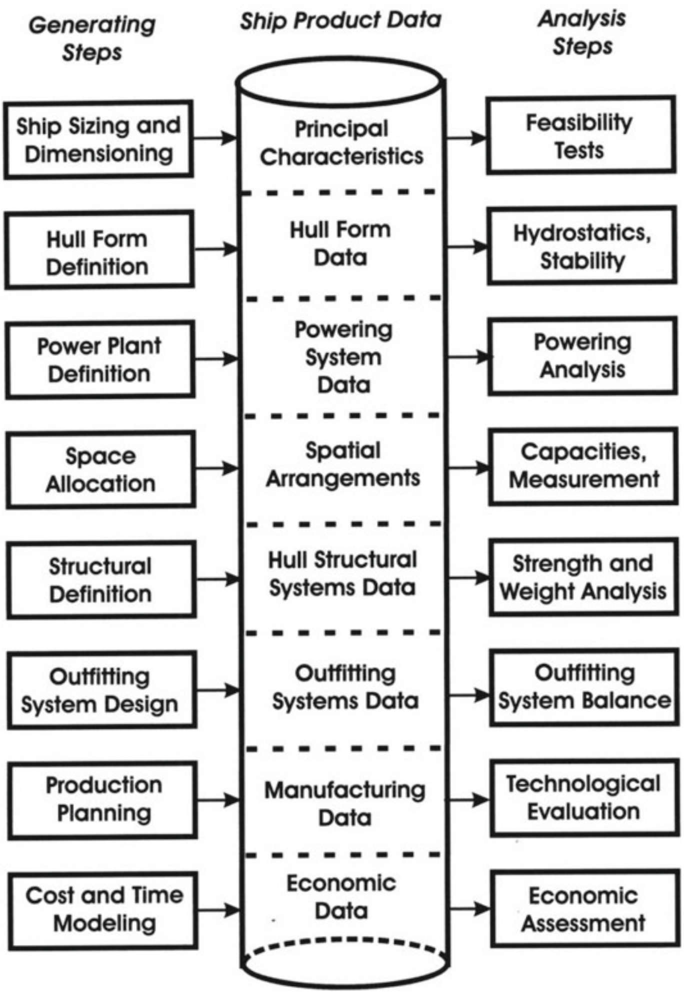

Fig. 3.2 Stages of the ship product modelling process (Nowacki 2009)

Ship design includes the following stages:

- Principal characteristics
- Hull form
- Speed and powering
- Spatial arrangements
- Structural design (strength and weight)
- Hydrostatics and stability
- Outfitting
- Damage stability and control

- Ship safety
- Ship environmental impact
- Cost and time

Each part of the product model is derived by a *synthesis* step from its requirements and constraints, and is then checked by an *analysis* step for compliance with requirements and constraints. Feasible and infeasible solutions are reported and corrected if necessary. This is an iterative process because the results from certain stages have effects on other stages. The sequence of steps need not be prescribed, but is flexible and problem dependent. In the end, when the process has converged and all constraints are met, one achieves at least a *stagewise* optimal and permissible result. To optimize all stages together in the end, one must apply a global measure of merit to the set of stages. The global optimum does not have to coincide with the sum of the stage optima.

While stagewise optimization was common practice in the past, current trends are towards integrated optimization of all relevant stages.

3.2.3 The Generic Ship Design Model

In the context of ship design, the elements of the optimization model are as follows (Nowacki 2009).

D = design variables, free variables of the design: Hull form principal dimensions (L, L/B, B/T, L/D, C_B), speed when free, free spatial arrangements, structural and outfitting variables.

P = parameters, dependent variables, i.e. state variables not under the designer's control: owner's functional requirements, available water depth and width, speed when limited, weather and seaway conditions, port and cargo-handling conditions, environmental conditions, safety conditions.

M = M (D, P) = measure of merit, measure of the quality of the design, one or several indicators, based on the interests of the stakeholders (builder, operator, safety and environmental authority, the public).

C = C (D, P) = constraints (permissibility conditions), depending on ship type and functions, applied to size and speed, safety and environmental hazards, upper and lower bounds on design and state variables.

The NLP format accommodates in practice any combination or subset of these modelling elements. Depending on the aims of the design optimization study in practice, most design investigations have dealt only with special cases of this generic ship design model depending on the purpose of the study and the interests of the stakeholders. Examples will be discussed in Sect. 3.3.

3.3 Specific Cases of Ship Design Optimization Studies

3.3.1 Generations of Ship Design Models

The history of ship design optimization has developed continuously and rather rapidly from simple beginnings to more and more elaborate formulations. This was largely driven by advances in modelling ship safety and environmental regulations. Table 3.1 shows a succession of design methodologies in computer-aided ship design studies.

Engineering design optimization based on physical principles and mathematical models has had a fairly long history and has involved some famous scientists. In the context of fluid dynamics and later ship design, the following may be claimed to be precursors of hydrodynamic and structural optimization, applicable or applied to ships: Newton (1726), Bouguer (1746), Euler (1749), Chapman (1775), J. S. Russell and I. Brunel (the builder and designer of the famous *SS Great Eastern* in 1858, respectively), Froude (1868, see, Duckworth 1955), Michell (1898), Weinblum (1932), Wigley (1935), Taylor (1943). However, these early precursors of ship design optimization confined their activities to special features of ship design, such as powering requirements or structural weights. The effort of manually computing ship properties at the early design stage was simply too prohibitive for a comprehensive layout and analysis of the whole design, and essential data were missing. A serious attempt at coping with the full complexity of early stage ship design, although it might have contributed many benefits, was not made feasible before the advent of computers in the design office and the spreading of Systems Analysis techniques for design. Lifecycle evaluations of engineering products and operations were foremost requirements in engineering design and in ship design.

I would date the modest beginnings of such design applications around 1960. The extended scope of ship design to the full life cycle was an important added value to the design process. An economic analysis justifying the investment in a ship cannot be performed without looking at the cost and benefits of the vessel for the whole life cycle from early and detailed design through the operating phase to the final disposal of the vessel.

Such a view has to take into account the vested interests of all parties involved in the ship's lifetime, i.e. the builder's and operator's goals and criteria, as well as those of the suppliers, classification societies, legal authorities, insurance companies and the general public as customers for transportation of passengers and cargo. There is also a general public interest in safe and environmentally clean ships. All of this now belongs to a lifecycle evaluation of a new design, which is continually widening the scope of modern design studies. The results of course are not unique, but depend on the viewpoints taken by the parties.

During the decades since 1960, the scope and depth of the lifecycle evaluation of ship design have grown systematically so that one can recognize four distinct generations of lifecycle ship design models (Table 3.1).

Table 3.1 Generations of ship design optimization models

Model type	Ship type	Design variables	No. of functions	No. of constraints	Optim. approach	Measure of merit	References	Years
Synthesis model	Tanker, bulker, general cargo ships	Principal dimensions, size, speed	1	Few	NPL: penalty Fct, gradient methods, SLP, direct search	LCC, RFR, NPV, CRF	Murphy et al. (1965), Mandel and Leopold (1966), Kuniyasu (1968), Nowacki et al. (1970), Söding and Poulsen (1974), Nowacki and Lessenich (1976), Nowacki et al. (1990)	1965 until ca.1990
Multiobjective model	Tanker and any other ship types	Principal dimensions, size, speed	Multiple, some probabilistic	Many	NPL: Pareto optimization, utility Fcts., graphical visualization	Economics, safety, environment, etc.	Papanikolaou et al. (2011), Papanikolaou et al. (2010b)	2010 and forward
Holistic design model	Merchant and naval ships	Geometry, safety environmental impact, etc.	Multiple, some probabilistic	Many	NPL: Pareto optimization, utility Fcts., graphical visualization	Economics, safety, naval criteria, environment, etc.	Papanikolaou (2011a), Papanikolaou (2010a), Boulougouris et al. (2011), Köpke et al. (2014)	2010 and forward
Risk-based design model	Cruise ships, RoPax, tankers, bulkers, etc.	Geometry, safety environmental impact, etc.	Multiple, some probabilistic	Many	NPL: Pareto optimization, utility Fcts., graphical visualization	Economics, safety, naval criteria, environment, etc.	Boulougouris et al. (2004), Vassalos (2009), Papanikolaou (2009a, 2009b)	2004 and forward

Where *NLP* nonlinear programming, *NPV* net present value, *LCC* lifecycle cost, *RFR* required freight rate, *CRF* capital recovery factor, *SLP* sequential linear programming

Table 3.2 Synthesis models

Authors	Year	Ship type	Measure of merit	Approach	References
Murphy, Sabat and Taylor	1965	General cargo ship	Lifecycle cost	Systematic variation, interpolation	Murphy et al. (1965)
Mandel and Leopold	1966	Tanker and general cargo ship	Lifecycle cost, NPV	Exponential random search, unconstrained	Mandel and Leopold (1966)
Kuniyasu	1968	Tanker, bulk carrier	Capital recovery factor	Parametric studies	Kuniyasu (1968)
Nowacki, Brusis and Swift	1970	Tanker	RFR	NLP: penalty Fcts. and direct search	Nowacki et al. (1970)
Söding and Poulsen	1974	Bulk carrier	Average annual cost	NPL with slack variables	Söding and Poulsen (1974)
Nowacki and Lessenich	1976	Tanker, bulk carrier, general cargo ship	RFR	NLP: penalty Fcts., feasible directions	Nowacki and Lessenich (1976)
Nowacki, Papanikolaou, Holbach and Zaraphonitis	1990	SWATH ferry	RFR, NPV	NLP: penalty Fcts., feasible directions	Nowacki et al. (1990)

where *RFR*—required freight rate = (mean annual operating cost plus capital cost discounted to first investment date)/(annual transport capacity) in \$/ton, *NPV*—net present value = all in and out cash flows, discounted back with current and estimated future interest rates to the investment date. NPV is more speculative depending on future income and loss estimates, but may account for future profits and losses more directly than RFR

3.3.2 Synthesis Models

Synthesis models (see Table 3.2), the first generation of design models, assume a single measure of merit, usually a measure of the economy of the design (lifecycle cost, required freight rate, net present value, cost-benefit ratios). All other design requirements are treated as constraints: owner's requirements, legal and statutory requirements and classification rules. In particular all safety requirements (stability, freeboard, fire, collision and grounding, etc.) are represented as inequalities denoting the borders between feasible and infeasible design spaces.

The goal of the design process, then, is finding the economically best design, which does not violate any constraint. The result is usually unique unless some designs have identical measures of merit.

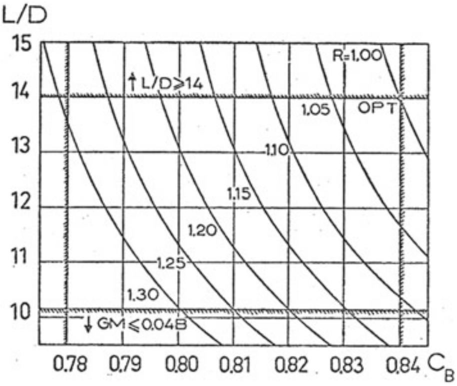

Fig. 3.3 Tanker dimensionless required freight rate *R* as a function of *L*/*D* and C_B for optimum values of *T*, *B*/*T*, *L*/*B*, dwt and speed (Nowacki et al. 1970)

As an application example, let us look at an early case study, a VLCC or ULCC tanker of 1970 vintage, designed by Nowacki et al. (1970). The ship is designed for crude oil transport from the Persian Gulf around the Cape of Good Hope to Rotterdam for a draft limit in the access to the port of Rotterdam of $T_{\text{MAX}} \leq 20.0$ m. There are further constraints imposed on $L/D_{\text{MAX}} \leq 14.0$ for strength and stiffness purposes, $C_B \leq 0.84$ for hydrodynamic reasons and on GM ≥ 0.4 B for intact stability. The available cargo and the permissible speed in full load were considered unlimited as was common in crude oil trades. No further constraints were imposed for other risks such as damage stability, environmental damages, fire, collision and grounding. This was before safety and environmental rules were later much stiffened. This situation tends to yield the ship of the greatest permissible size, determined by the draft constraint and the limit on C_B, while the economic speed is determined by the fuel price.

The optimization problem is of nonlinear programming type. The solution is governed by two or more constraints, here by those on T_{MAX}, GM, C_B and L/D_{MAX}. Figure 3.3 shows a planar intersection through the multidimensional design space in the plane of the optimum. The optimum in this synthesis model is unique. The constraints are linear functions of the design variables. Here the single optimum is located in a corner of the feasible space.

Synthesis models were relatively successful whenever a single purpose was served by the ship and a few constraints were dominant (Table 3.2). It is remarkable that an economic orientation for the measure of merit for the whole life cycle (lifecycle cost) was present in the earliest optimization studies of 1965 (and before) although the details became more refined later. However, the number of constraints grew with the increasing complexity of the design applications so that such requirements were expressed by further constraints and became equivalent and independent objectives of the design.

3.3.3 Multiobjective Models

Ships have usually more than a single purpose in their lifetime. This is the rule and not an exception. Ship design must account for all of the potential purposes that may occur in the ship's lifetime. The various roles in the life of the ship must be made explicit to the designer, usually in the building contract and in all legal rules and regulations that are pertinent.

There are many different reasons why multiple objectives may occur. It is the designer's responsibility to make sure to respond to all of them.

(1) ***Multiple tasks***

A ship may be assigned to perform varying tasks, either during a single voyage from leg to leg or during successive voyages in varying trade scenarios. Ore/Bulk/Oil carriers (OBOs) are a typical example.

(2) ***Multiple parties***

A ship design project involves several distinct stakeholder parties who have different objectives: the designer, the builder, the owner/operator, the user/customer, the general public, the disposal agent, etc. Many other parties and institutions also play a role: classification societies, coast guard, legal authorities, insurance companies, banks, port authorities, maritime equipment vendors, subcontractors, etc. These parties have conflicting interests which come to bear during the life of the ship. Design decisions usually require compromises between conflicting interests. But the conflicts must be pronounced before they can be resolved.

(3) ***Basic interests***

In ship design, at least three basic interests exist that will always be part of the design task:

Economic efficiency (in monetary units)
Safety (probability and magnitude of risk)
Environmental impact (probability and value of environmental damage)

These three objectives use different units to measure their magnitude. Thus, they cannot be integrated into a single criterion by simple conversion and addition. This is why multiobjective models are frequently a necessity.

(4) ***Measures of magnitude***

In comparisons of ship designs, in contract negotiations and in optimization studies, one needs standardized measures of magnitude that all parties understand. In international legislation, IMO has taken a leading role in defining such standards. The following are some of the most dominant criteria used:

For economic effectiveness

RFR = Required Freight Rate = Average Annual Transport Cost/Annual Transport Tonnage of Cargo ($/ton)

NPV = Net Present Value of the investment = sum of all in and out cash flows, discounted back with current and future interest rates to the investment date ($)

EEDI = Energy Efficiency Design Index = a measure of CO_2 emission per unit of transport in [gr CO_2/ton mile].

For safety

Probability of compliance with SOLAS safety rules: compliant or not.

For environmental protection

OOI = Oil Outflow Index = a MARPOL probabilistic estimate of the accidental oil outflow performance of a vessel, probability of oil spill and/or

EEDI = Energy Efficiency Design Index = a MARPOL measure of CO_2 emission of per unit of transport in [gr CO_2/(ton mile)].

(5) ***History***

Economy and safety have always played a significant role in ship design. The technical maturity in ship technology has grown in centuries and has found its documentation in international rules and regulations such as intact and damage stability rules, load line regulations, life-saving equipment rules and rules for the protection of the marine environment. The passing of new rules was slow, also due to wartime delays of two world wars. So the Titanic disaster of 1913 resulted in new international rules concerning flooding hazards not before SOLAS 1948.

The significant growth of ocean oil transport after World War II and sad accidents with tankers causing dramatic oil pollution in the ocean and on shores resulted in growing concern over the threat of oil pollution in the maritime environment. This concern was addressed under the auspices of IMO at the MARPOL 73/78 conventions, which went into force in 1983. To limit the potential oil outflow in the event of tanker damages by collision or grounding, the MARPOL regulations require from all new tankers of more than 20,000 tons deadweight the arrangement of segregated ballast tanks (clean tanks) in protective locations in order to shield the cargo tanks. This has led to new compartment configurations in "double hull" tankers with clean ballast tanks along the sides and in the double bottom. Such arrangements also result in more empty spaces, which add to the reserve buoyancy, but also to effectively not exploited ship spaces.

How this reserve can be best used has been the subject of everlasting discussions and optimization studies. The "double hull" concept as a "safety belt" against not too deep collision and grounding damages has also been adopted in RoPax ship design and was a consequence of the SOLAS 90 (introduced in the late 80s) deterministic damage stability requirements for passenger ships. However, in less than two decades later, SOLAS 90 was replaced by SOLAS 2009, which is a probabilistic damage stability regulatory framework, in which the extent of collision damages is not confined to a deterministic range (20% of ship's beam) and this led to a new shift in the design practice, with most RoPax ships today being designed and built as single-hull and double-bottom ships. Nevertheless, the survivability of passenger ships actually suggests the arrangement of a double skin as an elegant and safe solution and this maybe imperative for the survivability of ultra-large cruise liners in case of shallow-wetted shell damages.

(6) ***Solutions***

Multiobjective design problems require their own solution procedure to obtain concrete solutions despite the non-unique problem statement. In principle, two approaches are often chosen:

- The utility function approach
- The visualization of design solution spaces with identification of Pareto-optimal boundaries of the feasible design spaces

Often, these two methods are combined.

The utility function approach

In this multiobjective case, let M_1, M_2, M_3 be three distinct objectives, then a combined objective function (utility function) will be:

$$M_{\text{System}} = f_1 M_1 + f_2 M_2 + f_3 M_3 \tag{3.1}$$

where f_1, f_2, f_3 are arbitrary, humanly chosen weighting factors, which will bring the measures M_1, M_2, M_3, which are usually of different units, combined into a joint measure in consistent units. For more than three objectives, likewise.

This has the added advantage of offering the choice of looking at each of the objective measures M_1, M_2, M_3 separately, to study the trade-offs by looking at the relative weighting of the measures and in this way to be able to control the relative influences of the measures transparently. This enables open discussions among the stakeholder parties.

The measures for each influence can be modelled as desired and suitable. A frequent choice in recent studies is:

M_1 = measure of ship economic effectiveness = NPV or RFR, where:
NPV = Net Present Value of the investment P (or NPVI = NPV/P),
RFR = Required Freight Rate = Average Annual Transport Cost/Annual Transported Tonnage of Cargo,
M_2 = EEDI = Energy Efficiency Design Index (an IMO Index). EEDI = measure of CO_2 emission per unit of transport work in [gr CO_2/(ton mile)],
M_3 = OOI = Oil Outflow Index = probabilistic calculation of the accidental oil outflow performance of a vessel (an IMO Index).

The weighting factors may serve to avoid an overemphasis.

The visualisation of design solution spaces with identification of Pareto optimal boundaries of the feasible design spaces

After optimizing the initial candidate set and eliminating all infeasible designs and retaining in the end the most promising feasible designs only, one plots the ship

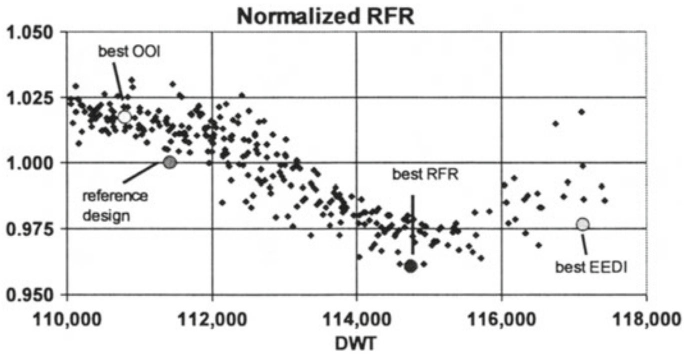

Fig. 3.4 Scatter chart for tanker design (Papanikolaou et al. 2011) showing the interdependence of RFR and DWT with references to best RFR, EEDI and OOI designs

Table 3.3 Multiobjective models

Authors	Year	Ship type	Measure of merit	Approach	References
Papanikolaou, Harries, Wilken, Zaraphonitis	2010	Aframax Tanker	RFR, EEDI, OOI, speed	Multiobjective optimization, POSEIDON and IMO rules	Papanikolaou et al. (2011)
Papanikolaou, Zaraphonitis, Skoupas, Boulougouris	2010	RoPax ferry	Geometry, stability, seaway, NPV	GA: mixed continuous and discrete design variables, TRIBON structural design	Papanikolaou et al. (2010b)

criteria values against two of the merit criteria, using a third one as a parameter. See Fig. 3.4 as an example. One can then construct an envelope curve or surface so that only the feasible designs are on one side of the envelope. See Fig. 3.5 for an example. Designs that lie exactly on the envelope are called *Pareto-optimal designs*; they are the best designs for at least one of the criteria. One can similarly find the pareto-optima for the other criteria as shown in Fig. 3.5. One may look at plots of any pair of multiple criteria and thus identify the *Pareto-optimal curves or surfaces* and on these the optimal points for each criterion. The user must now set priorities and pick any Pareto-optimum or any compromise between them. They are all feasible designs. The following examples will illustrate these techniques (Table 3.3).

Example 1 Aframax Tanker (Papanikolaou et al. 2011)

In this design case study, dating back to 2010, an Aframax Tanker was to be designed in compliance with current IMO-MARPOL rules for a trade route in the

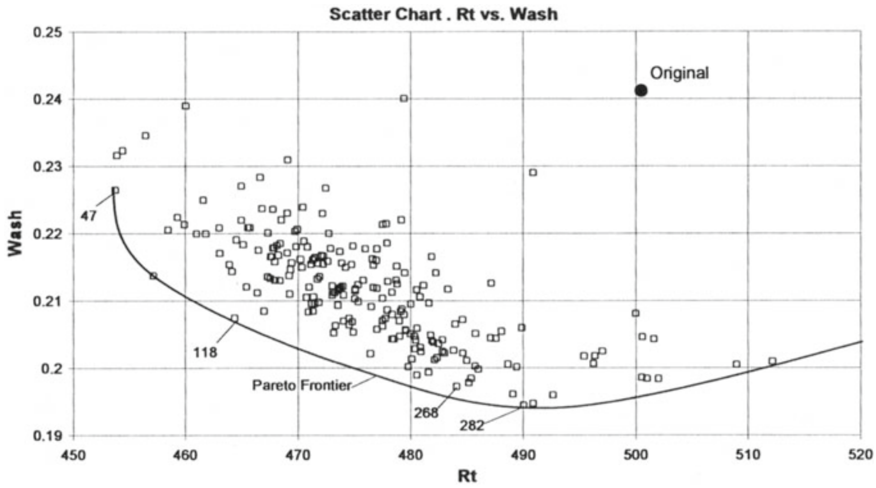

Fig. 3.5 Scatter chart, feasible designs, monohull, two objectives: total resistance R_T and wash W, plotted with ships of final sample, showing the pareto-optimal frontier as the lower envelope of all feasible design candidates (Papanikolaou 2010a, 2011a)

Caribbean from the Maracaibo area to St. Eustacius in the US Gulf Coast in the US Emission Control Area, a route of some 1600 miles one way. The design was subject to all pertinent national and international rules and regulations, especially those of Resolution MEPC.177 (52) and the requirements for Segregated Ballast Tank (SBT) capacity.

The designs were to be ranked by the *key objectives* of RFR, EEDI and OOI, hence by economy and environmental protection, while safety was implied by the MARPOL rules as constraints.

The software was subdivided in modular form into a ship design platform and into an optimization module. In a majority of case studies in connection with EU-supported projects, a random search optimization software was used for optimization in order not to miss any parts of the feasible space, viz. the application-independent Multiobjective Genetic Algorithm (MOGA) software under modeFRONTIER.

The ship design platform was tailored to each application. For the Aframax study, the following Naval Architecture software systems were combined under Friendship Framework: NAPA, POSEIDON and SHIPFLOW. For the purposes of optimization, these systems had to be reconfigured and linked so that they could be addressed by parametric free design variables. In addition to the objective functions and constraints, this set of design calculation modules also computed the following key measures:

- Cargo tank capacity in full-load and design-load conditions
- Steel weight of the cargo tank area
- Maximum ship speed at design, ballast and scantling drafts
- Probability of oil spill, OOI, in case of accidents

Some 50 form parameters were needed for the hull form definition in total, but only 12 free variables during the form optimization in this study. The tank arrangement here was fixed in the usual 6×2 configuration. The distance of the inner bulkhead from the shell was a free variable (≥ 2 m). The parametric model for the steel structure in the cargo domain is generated by POSEIDON in accordance with the prescriptive part of the Common Structural Rules (CSR), hence for a preliminary dimensioning. This serves to estimate the steel structure weight.

The hydrodynamics of this tanker are calculated by CFD solvers (SHIPFLOW, XPAN, XBOUND, CHAPMAN). Response surfaces were fitted through these raw data points to save much computing time during the optimization run for these most time-consuming computations.

The search for the optimum was started by a reference ship, an existing modern Aframax tanker. The results of this study for the tanker are visualized in Fig. 3.4. Deadweight DWT, RFR (normalized by the reference design), EEDI (MARPOL's Energy Economic Design Index) and OOI (MARPOL's Oil Outflow Index) are the criteria of main interest in this study. The designer has the choice of which one to favour since all are close to Pareto-optimal. Figure 3.4 shows that the best RFR design is achieved for a value of about 3000 tons DWT above the reference ship, whereas the best EEDI design is bigger yet and the best OOI ship is a bit smaller than the reference ship. But since the losses in RFR and EEDI for this ship were small, the study team favoured the best OOI vessel. The possible trade-offs between the different criteria are evident.

Example 2 RoPax Ferries (Papanikolaou et al. 2010b)

In this investigation by NTUA, promoted by the Elefsis shipyard, a set of three monohull RoPax ferries was developed for exploration and demonstration. Ship sizes of these target vessels were given as:

Ship 1: 500 passengers, 9 trucks, $V_S = 18$ knots
Ship 2: 590 passengers, 12 trucks, $V_S = 19.5$ knots
Ship 3: 1300 passengers, 35 trucks, $V_S = 23.5$ knots

The route was intended for a distance of 21 nautical miles between Kylini, Western Peloponnese and Zakynthos in the Ionian Sea. NPV was chosen as the only objective function. All other requirements were handled as constraints (owner's preference). This included many other design calculations such as: initialization of hull forms in the feasible domain from parametric hull form definitions, a parametric tank arrangement, a parametric structural design software using GL's POSEIDON, structural analysis by FEA analysis software, hydrodynamic assessment by SHIPFLOW, stability assessment for intact and damaged condition, MARPOL rules analysis for OOI and EEDI. These data provide a rich supply of information for systematic comparisons of the designs.

The optimization is performed by the probabilistic, multiobjective optimization software MOGA, a module available under modeFRONTIER. It goes through several steps:

Step 1: Initially the magnitude of the computational task must be limited. Beginning with exploratory, stagewise optimization runs according to the stage structure shown in Fig. 3.2, the free variables for each stage are picked in reasonable practicality, but liberally, and each stage is randomly sampled by the optimization software MOGA within modeFRONTIER in order to find promising candidate designs for each objective and by eliminating infeasible designs. The random sampling by MOGA avoids the omission of candidates in remote corners of the decision space. The first generation of MOGA furnishes only eight initial feasible candidates.

Step 2: For each new generation of MOGA, from now on, the search around temporary candidates is intensified, moving from rather uniform to very selective sampling. The probability of success in finding new candidates with feasible objective values increases in each generation. Here some 100 further generations were sampled with increasingly modest improvements.

Step 3: The final best designs are then fully elaborated to contract and specification level using the best software design tools for all stages.

The shipbuilding software platform here supports the parametric design of RoPax ferries by integration and parametric adaptation of Naval Architecture (NA) software, such as NAPA for geometry and layout, semi-empirical hydrodynamic modules, an internal layout template, a preliminary structural design module based on DNV class rules, steel weights by direct calculation, empirical formulas for other weights, intact and damage stability (NAPA) based on SOLAS 90, itemized economic performance assessment.

The user has a choice of several objective functions: minimization of lifecycle cost, maximization of annual revenues or a full economic analysis based on NPV or RFR can be chosen. Other performance criteria like stability margins, seaway motions and comfort can be included as objectives or constraints. This is the advantage of a multiobjective formulation and a modular, parametric software structure.

The optimal designs were further elaborated by the Elefsis shipyard using the TRIBON Hull software. Thus, contractual design-level documentation and detailed shipbuilding specifications were obtained.

3.3.4 Holistic Design Models

The purpose of holistic design models (Table 3.4) is to look at *all* economic and non-economic measures simultaneously, though by separate indicators. In particular the safety-related and the environmental impact-related criteria are initially expressed in non-economic terms. These models are thus multiobjective and multiconstrained models for the whole life cycle of the ship.

The attributes used to perform a holistic, i.e., comprehensive whole lifecycle evaluation are in three categories, viz. economic, safety and environmental impact indices. The economic performance of the ship can be measured by the Energy Efficiency Design Index (EEDI), defined by IMO in its MARPOL regulations as an interim measure of ship size and fuel consumption, hence indirectly of CO_2 air pollution. This does not yet take into account the engine efficiency and the propulsive

Table 3.4 Holistic design models

Authors	Year	Ship type	Measures of merit	Approach	References
Papanikolaou	2011	High-speed passenger ship monohull, Twin-hull RoPax ferry	Total resistance R_T, wave wash and safety	Genetic algorithm (GA), Pareto scatter diagram	Papanikolaou (2011a)
Boulougouris, Papanikolaou, Pavlou	2011	Container Ship	EEDI, ISP, displacement, speed	NAPA, modeFrontier, parametric design tool	Boulougouris et al. (2011)
Papanikolaou	2012	Merchant and naval ships	RFR, safety, environmental impact	GA: direct search, PDT, NAPA, POSEIDON, SHIPFLOW	Papanikolaou (2011b)
Köpke, Papanikolaou, Harries, Nikolopoulos, Sames	2014	Container feeder vessel	RFR, EEDI, capacities, low emissions, low weight	GA for multiobjective design using FFW	Köpke et al. (2014)

efficiency. They might be added to the list of objectives, but more traditional RFR or NPV can be used instead or in addition.

Safety and environmental protection cannot be measured directly in currency units. These criteria must be assigned indices to collect all contributions in each category over the lifetime and must use these sums as separate objectives together with the economic indicator in the same manner as explained in multiobjective optimization, viz. with assigned utility functions or by displaying Pareto space maps or other visualization aids (scatter diagrams). Thereby the results of holistic optimization can be judged by three (or more) independent indices as well as by some weighted combination of all individual measures taken according to the preferences of the parties involved in the design. Table 3.4 gives an overview of several holistic design studies.

The term “holistic” design, if taken literally, requires that in fact *all* influences are taken into account in the design study. In practice, I would recommend a softer definition: “A holistic study takes into account *all* influences that are relevant to the issue under investigation”. It should be understood that in a modern ship design context, every design issue has an effect on the overall economic, safety and/or environmental performance of the ship. Thus, the explicit or sometimes hidden presence of these three elements should be a minimum requirement to classify a design study as “holistic”. This section of the text should help to clarify this terminology by concrete examples.

Example 3 High-Speed Passenger Monohull (Papanikolaou 2010a, 2011a)

In this example, studies were performed by the same partners as in Example 2, though for a different scenario and ship type, for various RoPax ferry service routes between the Aegean islands and the Greek mainland. The routes varied between 20 and 80 nautical miles. High-speed transport was desired with targets of 30 knots and above. Similar assumptions as in Example 2, but a different design modelling methodology, were used. A single key objective, the NPV, as a measure of merit, reflecting the viewpoint of the ship owner, was adopted, whereas all other requirements of the scenario were modelled as constraints. This worked equally well methodically demonstrating the legitimacy of this approach.

The exploratory case study deals primarily with the design of a high-speed monohull. It is destined for a ferry service between the Greek mainland (port of Lavrion) and islands in Aegean Sea, e.g. the island of Mykonos, a route of 75 nautical miles one way. High-speed transport was desired with targets of 30 knots and above.

However, the level of elaboration in the design software tool was much extended for the modelling of the design stages, again using a similar breakdown for the stage-wise initialization procedure. The tools available here included NAPA, SHIPFLOW and the ITTC 1957 formula for the frictional resistance or optionally systematic series results like a regression formula by NTUA, an interior layout topology module, DNV class rules for structures, intact and damage stability software by NAPA and a detailed cost assessment module. These modules were combined into an integrated system of design evaluation by linking these software components. In this way, an integrated system of design assessment for each single design was created, which combined the modules of design variation, design assessment and design optimization. The optimization software modeFRONTIER with MOGA worked for this form of Integrated Model as well as it did in the case of multiple objectives. The constraints were ascertained in the calculation process for each ship. The high-speed monohull was a demonstration example.

The hull form of a reference ship was parameterized for variation by form parameters (points and angles). This defines a grid from which surface representations can be interpolated and faired. The hull form can now be modelled parametrically using NAPA macrolanguage. Compliance within the series with geometric constraints is checked and ensured. The resulting hull representations are then processed for hydrodynamic performance by SHIPFLOW, augmented with semi-empirical viscous flow data.

A starting set with promising favourable hydrodynamic properties is identified and becomes the input to the optimization.

While the ship owner was interested mainly in NPV, the optimization approach was multiobjective in this article. Two objectives were pursued here, they consisted of the total resistance R_T as a measure of hydrodynamic effectiveness and the wave wash, taken as the average wave height along a longitudinal wave cut at a certain distance (0.25 L or 0.5 L) off the centreplane. This second objective is regarded as a measure of the potential damage done to the ship's environment in narrow waters.

Table 3.5 Comparison of original ship with the Pareto-optimal designs

	R_T (kN)	W(m)	H_{Max}(m)
Original vessel	500.5	0.205	1.0515
Hull no. 47	449.3	0.173	0.8840
Hull no. 118	464.3	0.160	0.7890
Hull no. 282	494.4	0.155	0.7473

Although this case is a very crude model of a two-objective optimization, it does illustrate the decision process.

The modular optimization software used is again the stepwise method by the random search system MOGA under modeFRONTIER described in Example 2.

Figure 3.5 illustrates the result of the search and design decision process. A scatter chart plots the resulting cloud of feasible designs of the final candidate set against the two objectives R_T and Wash W. A solid line is fitted so that all feasible sample points lie above or on that line, none below because those are infeasible. This boundary of the feasible domain is the *Pareto frontier.* Designs lying exactly on this frontier are the *Pareto-optimal designs*. They are characterized by meeting at least one objective exactly. Here designs 47, 118 and 282 are *Pareto-optimal.* The user can now choose among these from secondary considerations. The trade-offs are in the direction of a least wash for a medium resistance, hence design 282. The best design shows significant improvements over the original reference design, a built ship, in the order of up to 28% for the wash or up to 10% for R_T, though not for the same vessel, but for one or the other. But all Pareto-optimal results are improvements relative to the original design, the original reference ship.

A multistage, multiobjective optimization was performed following the stepwise pattern described in Example 2. The following results were obtained (Papanikolaou 2010a, 2011a), where R_T is the total resistance, W is the wash and H_{Max} (m) is the maximum wave amplitude in a longitudinal wave cut $L_{PP}/2$ off the centreplane (Table 3.5; Fig. 3.6).

For more than two objectives, the logic of the decision process must be generalized to multidimensional optimization with scatter diagrams for each pair of objectives and with multidimensional *Pareto frontier surfaces* and Pareto-optimal results thereon. Software utility tools within *modeFrontier* help to locate these. A random search following MOGA after several generations with more and more local search density, each with several iterations, follows and yields a final result close to a Pareto-optimal set. The results are now prepared for a final choice of candidates for optimization by multiple criteria as described in Fig. 3.4.

It was shown in this example study that multiobjective optimization approaches are valuable ship design tools and in deviating from the former rule-based MARPOL regulations are able to improve the economic and technical performance of new designs relative to existing ships while complying with increasing safety and environmental protection requirements.

Example 4 Twin-Hull RoPax Ship (Papanikolaou 2011a)

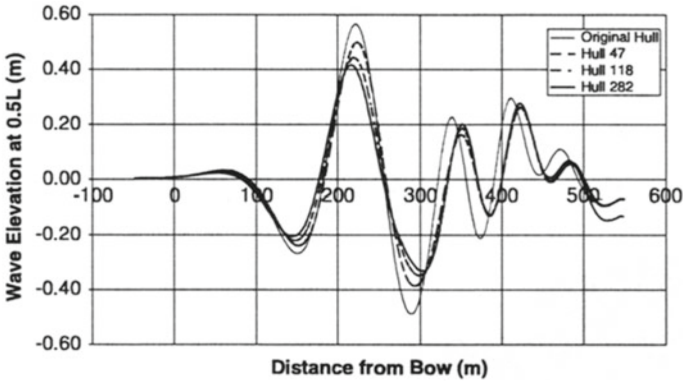

Fig. 3.6 Longitudinal wave cuts of original and Pareto-optimal monohulls, LPP/2 off centreplane (Papanikolaou 2010a)

The second example treated in (Papanikolaou 2011a) deals with the design of a high-speed twin-hull RoPax ship of catamaran type. It is destined for the same sort of ferry service between the Greek mainland (port of Lavrion) and islands in Aegean Sea, as in Example 3. The desired service speed was held at 30 knots. The configuration was that of a twin-hull semi-SWATH.

Comprehensive *design calculations* were performed, which included:

- Hull form development (with 23 form parameters, but only five of these as independent variables)
- Resistance and propulsion estimates (SHIPFLOW and semi-empirical formulae)
- Development of the internal layout (using NAPA, controlled by form parameters)
- Preliminary structural design (DNV rules, for aluminium and/or steel, 12 free variables)
- Weights' estimate (many weight categories)
- Intact and damaged stability (actual GM vs. required GM for relevant loading conditions)
- Seakeeping performance, if desired (crew comfort and cargo safety)
- Assessment of economic performance (mainly NPV, but also RFR, EEDI, OOI)

The *optimization* was again performed by random variation of the free variables in all stages of the design as in earlier examples accounting for continuous and some discrete variables. The optimization software modules of MOGA under modeFRONTIER were used again.

The results obtained in Examples 3 and 4 are only approximate by several assumptions, but have produced encouraging success for the holistic approach. The results are still reliable since the approximations do not distort the ranking of the designs.

Example 5 Tanker and Container Ship (Boulougouris et al. 2011)

The studies presented in this paper, developed in the frame of the EU project LOGBASED, address the issue of a changing market environment during the lifetime of the ship. The reduction of greenhouse gas emission (Water vapour, CO_2, NOX, SOX) will be of growing significance in the next few decades for worldwide increases in average temperatures, i.e. for the ships being designed now. Ships need to be designed to be flexible enough to be adjusted to operate in changing scenarios, standards and rules. How can these requirements be accommodated in today's design methodology? The answer lies in holistic design for a time variable set of requirements. The methods can be applied to the design of a single new ship as well as to the design and management of a whole fleet of current and future ships.

The EU project LOGBASED has built up an empirical database with all applicable data of all relevant ship types, here for tankers and container ships. EEDI is recorded as a criterion in multiobjective design. Many other properties are also collected in the database. This database serves to initialize optimization runs for new ships. These runs are performed by a random search software in MOGA and modeFRONTIER. The model uses the appropriate constraints for each ship type, e.g. the MARPOL regulation standards for the Aframax tankers for the given deadweight. The objective functions in this study are EEDI and ISP = Ideal Ship Price. Similarly, the same objectives were used for a containership of reduced speed. In the multigeneration runs, about 4000 ships are sampled. The most promising subsets are sorted out for final optimization and elaboration.

The study thus presents recommendations for ship design in a gradually or abruptly changing economic and technical environment.

Example 6 Merchant and Naval Ships (Papanikolaou 2011b; Boulougouris and Papanikolaou 2013)

In these articles, the basic similarity of holistic optimization of ship design for the life cycle for merchant and naval ships is emphasized. Both design tasks can be handled in the category of holistic design, although with quite different technical evaluations. The owner's requirements for the merchant ship are replaced by the navy's mission requirements. The internal subdivision into compartments plays a major role for both ship types. Both ship types are equipped with double hulls for safety purposes. The placement of the side tanks and the height of the double bottom are design variables in order to explore the reserve capacity in buoyancy when the outer hull is damaged in side or bottom by collision or grounding. As it turns out, the damaged ship may still be safe if the GM in this position is sufficient. The longitudinal bulkhead and the double bottom must be placed far enough inboard to protect them from penetration. The lost cargo volume can be made up for by raising the freeboard and thus enlarging the effective tank volume. For naval ships, the same measure increases the survivability.

For the reference merchant ship, the side tank width and the double-bottom height is placed 2.5 m away from the outer skin, while the MARPOL rules require only 2.0 m. This necessitates a correspondingly increased freeboard. The object functions are cargo capacity and Oil Outflow Index. The tank configurations range from

6×2 to 6×3 and 7×2 designs. The 6×3 configuration dominates the others in terms of its oil outflow performance. The 6×2 solution has the advantage of lower steel weight.

For the naval ship, many requirements were included in the list of the naval ship code NSC 2000. An integrated toolset on top of the software of TRIBON, PARAMARINE, CATIA, NAPA, etc., provided a platform for a preliminary global optimization by means of Parametric Design Tool (PDT). The objectives included in this tool are: ship's economy, cargo carrying capacity, safety, survivability, comfort, required powering, environmental protection, combat strength, as applicable.

The project has demonstrated the applicability of holistic, multiobjective, early design studies for a variety of ship types and operating scenarios. More software will be needed for evaluating later design and operational stages.

Example 7 Container Feeder Vessel (Köpke et al. 2014)

This study explores the influence of draft constraints in intra-Asian ports on the dimensions of feeder container ships for local distribution. These ships tend to have wide beams and shallow drafts because of the shallow water depth in the access waterways. The design speed is derived from analysing different intra-Asian routes. Transit times depend on delays in port. Port efficiency for faster voyages is one of the objectives in this study to minimize cargo-handling delays, hence also a trend to shorter hulls.

In the initial design of experiment stage, existing ships for this service are analysed and collected in an empirical database. The number of containers in a row across the beam, in practice 6 or 7 here, is an integer design variable resulting in gaps in the data. The solution can again be based on holistic design with changing objective functions with time. The methods can be applied to the design of a single new ship, but also to the management of a whole fleet during the lifetime of current and future ships.

The presented method has been integrated into the FFW design software platform and allows the fully automated generation of valuable containership designs with superior design characteristics. The obtained results indicate significant improvements regarding the IMO EEDI, major reductions of the RFR and an improvement of the herein defined port efficiency. Another step forward is the reduction of the required ballast water by almost 40% and the increase of carried containers (nominal capacity and containers on deck) that can be loaded without the need for using ballast for stability purposes. The homogenous weight for this condition is close to the statistically observed homogenous weight for containers (approximately 12–15 tons). This means that in most real-life loading cases, the ship can waive ballasting with the exception of some limited loading of the aft and fore peak tanks for trim improvement purposes. The increased port efficiency that was defined within the methodology based on previous research activity allowed the designers to lower design speed with no implications in the supply chain of the intra-Asian trade studied in this paper. This reduction is beneficial in terms of both fuel costs, and emissions and efficiency without sacrificing the competitiveness of the vessel (in terms of trips per year).

3.3.5 Risk-Based Design Models

The design of complex systems operating under hazardous conditions and subject to immense damages in the event of catastrophic failures has become a specialized discipline, now commonly called risk-based design. This approach has been a necessity in the nuclear industry for many decades and has also prevailed in aerospace design and in other industries with great public and economic risks. In the maritime field, the offshore oil industry first introduced this approach by legislation based on risk analysis for offshore systems, e.g. in Norway in 1986, in the UK in 1992. For ships, IMO is currently following a strong trend towards risk-based ship design in the development of new safety standards (Sames 2009; Skjong 2009).

This entails a number of methodical elements:

> Future standards and some current pilot regulations are intended to replace, at least in part, the traditional rule-based approach of classification and regulations, which describes in technical detail how a safe design is to be realized, by Goal-Based Standards, where a safety goal is set regardless of how it will be achieved. This requires quantitative risk analysis (QRA) with quantified risk assessment. Goal-Based Ship Design (GBSD) aims at an optimal solution for the overall safety of the ship. This is to be achieved in the most cost-effective manner.

The risks will be defined for each hazardous operational scenario in probabilistic terms by the predicted probability of occurrence of the hazardous event multiplied by the economic value of the consequent damage. All damages, whether to the public, the ship owner or to individual humans, are to be included in the analysis. The total risk is evaluated by combining the risks of all scenarios. The total risk will be compared to the acceptable risk, chosen either relative to ships designed by existing IMO rules or in absolute terms based on forthcoming new IMO risk acceptance criteria (Sames 2009).

In optimizing designs simultaneously for their economic viability and their safety, safety is no longer regarded as a rule-based constraint but is treated as an objective in its own right. After all, the owner's and the public's interest lies in both economy and safety. Risk analysis quantifies safety in comparable units as the functional economic measures.

The historical EXXON Valdez accident 2009 in Prince William Sound in Alaska has led to the legal banning of single-hull tankers first in US waters (OPA 90), later internationally by IMO-MARPOL for any new tankers today. The risk of oil spillage by tanker accidents should be kept as low as possible. The EU has funded several projects on modern design issues, notably the SAFEDOR project and up to the present HOLISHIP project.

The risk-based design models are actually built like the holistic models for multi-objective modelling with constraints for the whole life cycle except that the uncertain safety hazards are quantified differently as probabilistic risks. The cumulative risk will then serve as a safety term in the measure of merit. This opens the door for goal-based justification of safety features. Thereby the overall safety of the ship can be enhanced if the equivalence of the goal-based design to a rule-based reference design is demonstrated. This approach may result in safer and/or more economic

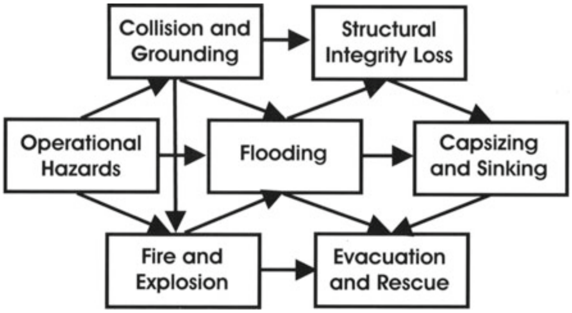

Fig. 3.7 Structure of hazardous scenarios in ship safety (Vassalos 2009)

solutions than prescriptive rule-based design. A good overview of this approach is presented in the book on Risk Based Ship Design, edited by Papanikolaou (2009a), which summarizes the main results of the EU-funded project SAFEDOR.

An example of the structure of Quantitative Risk Analysis for ships, which will comprise all hazardous events, is given in Fig. 3.7 (Vassalos 2009), which is a basis of current standardization activities at IMO SOLAS regulatory level.

Example 8 Risk-Based Aframax Tanker (Papanikolaou 2010b)

The main objective of the addressed risk-based studies (first two in Table 3.6) was to reduce the risk of accidental oil outflow by optimizing the cargo tank arrangement while at the same time minimizing the steel weight and maximizing the cargo capacity. A generic optimization framework developed earlier by NTUA-SDL was adapted to the present optimization problem by adding methods and software tools for the structural design and probabilistic assessment of the oil outflow. The design pool in the heart of the framework is based on a parametric ship design and systematic variation of design parameters. The approach allows integrating an arbitrary number of objective functions and constraints (constrained multiobjective optimization). The whole process is initiated by relevant owner's requirements from a technical database. The optimization procedure is implemented by integration of the following software tools:

NAPA (geometric modelling and Naval Architecture calculations)
POSEIDON (structural design and analysis software, developed by GL)
modeFRONTIER (a general-purpose optimization software from Esteco).

The reference design in this study makes use of higher double bottoms and wider side tanks of 2.5 m each compared to MARPOL requirements of 2.0 m each (for ship as built). This configuration with six tanks longitudinally and two transversely is compared with other arrangements of the cargo tanks in configurations of 6×3 and 7×2 sets of tanks, where each set is optimized with respect to Pareto-optimality in cargo capacity and oil outflow. Figure 3.8 shows the results for several configurations. The 6×3 "flat" arrangement, i.e. without corrugation of the tank walls, dominates all others, but has a higher steel weight and hence lower cargo capacity than "6×2 flat". The steel weight in the additional bulkhead for the 6×3 option defeats

Table 3.6 Risk-based design models

Authors	Year	Ship Type	Measures of Merit	Approach	References
Papanikolaou	2009	Tanker: Aframax Built on class rules by GL	Mean oil outflow index, steel weight in cargo area, cargo capacity	GA with random search and direct search	Papanikolaou (2010b)
Papanikolaou, Zaraphonitis, Boulougouris, Langbecker, Sames	2010	Aframax Optimized Tanker, Naval Ships	Cargo capacity, deadweight, outflow index	GA, direct search: NAPA, POSEIDON, modeFrontier	Papanikolaou et al. (2010a)
Vassalos	2009	Passenger cruise ship	Economics, risks of fire, collision, grounding, damage stability	GA: Economy and safety	Vassalos (2009), Project GENESIS, Vassalos and Papanikolaou, (2015)
Plessas and Papanikolaou	2015	Bulk carrier	RFR	Stochastic lifecycle design, six design variables	Plessas and Papanikolaou (2015)

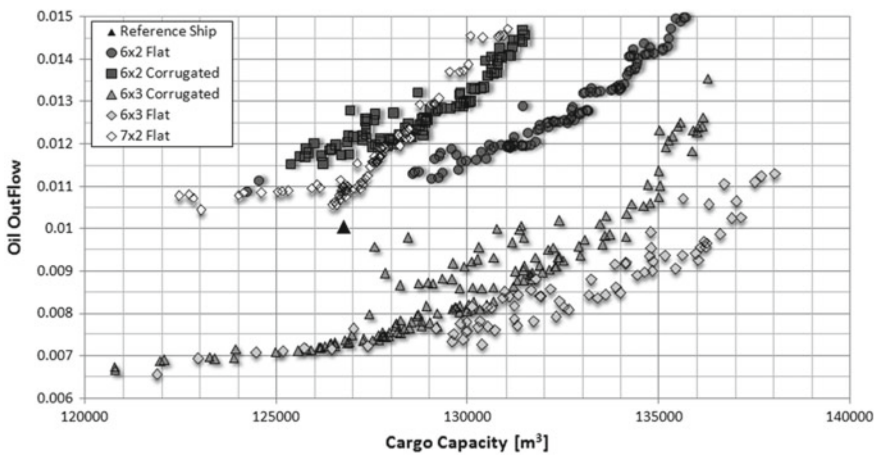

Fig. 3.8 Oil outflow versus cargo capacity for Aframax Tanker, optimized, for several tank configurations, flat and corrugated tank walls (Papanikolaou et al. 2010b)

the benefits of this option. Thus, “6 × 2 flat” seems to be the most practical option, since it allows more cargo capacity. Figure 3.8 adds some information as to the possible gains in cargo capacity versus the loss of oil outflow.

Table 3.7 Project GENESIS main particulars (Vassalos 2009)

Length	361 m
Beam, WL	47 m
Draft	9.15 m
Depth	22.55 m
Height, above WL	72 m
Gross tonnage	225,000 RT
Number of passengers	5400
Number of crew	2166
LSA capacity	8460
Passenger decks	16
Speed	22.6 knots
Propulsive power	3×20 MW

Example 9 Passenger Ships (Vassalos 2009; Vassalos and Guarin 2009; Vassalos and Papanikolaou 2015)

The reference Vassalos and Papanikolaou 2015 is a state-of-the-art report of May 2015 on the "Design for Safety, Risk-Based Design, Lifecycle Risk Management" presented by Dracos Vassalos and Apostolos Papanikolaou to the 12th International Marine Design Conference held in Tokyo in May 2015. It is not the description of any particular design. But it explains the general approach taken by IMO and related institutions in assessing and managing the risks that exist during the lifetime of a ship. This combines the passive risk control measures at the design stage with the prevention/reduction of risks as a design objective and the active control at the operational stage by lifecycle risk management. Thereby safety rules are being replaced by safety objectives.

Nonetheless, the article describes ongoing developments in ship safety research for a few particular projects of Lifecycle Risk Management from two perspectives, the EU SAFEDOR project perspective and briefly the general perspective of lifecycle risk management, introduced by the Health and Safety executive of the EU. SAFEDOR was an EU Project accompanying the development of the major shipbuilding cruise ship project GENESIS. See Table 3.7 and Fig. 3.9. The prototype "Oasis of the Seas" was the largest cruise ship ever built, when delivered in 2009.

For the *design* phase, risks are evaluated comprehensively for all hazards shown in Fig. 3.7. Risk is quantified as the probability of occurrence multiplied by the value of the loss resulting from the event using statistical data and extensive simulations. The value comprises all damages, whether to the public, the ship owner or individual humans. The investigation for project GENESIS involves a case-by-case explicit dynamic flooding simulation for 342 collision scenarios alone (3rd study in Table 3.6).

For the *operational* risk, the issue is how to manage the residual risk which every design possesses over the lifetime of the ship. In addition to providing sophisticated

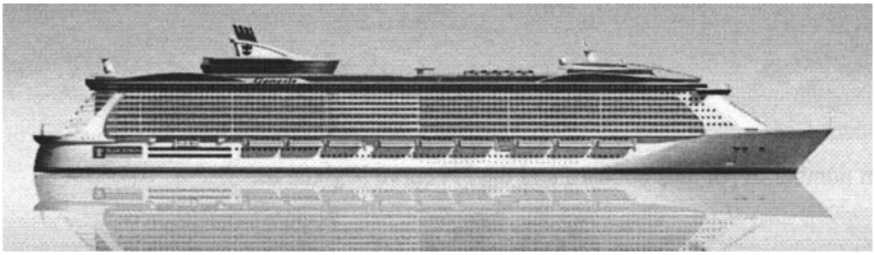

Fig. 3.9 Project GENESIS

computer-based support and surveillance of the on-board safety systems and continuous monitoring of shipboard sensors for tank levels, door states, water ingress alarms, wind and waves, etc., it is necessary to create the required risk awareness and preparedness for crisis management on the part of the crew. Structured action plans exist and are being further developed for lifecycle risk management by the crew. *Training and awareness*, promoted by systematic IMO-based inspections, are a *key element* in the continuing progress of lifecycle risk management.

Example 10 Time-varying Values—Stochastic Optimization (Plessas and Papanikolaou 2015)

Certain parameters in a design model are always uncertain, among them the fuel price in the lifetime of the vessel. This study examines the effects on a design of time-varying fuel prices. It investigates how the resulting main dimensions of a tanker are affected if one assumes a time-varying fuel price (4th study in Table 3.6).

The variation in fuel price is given by a probability distribution around a mean value, rather than a fixed rate. The reference design is a tanker operating at a constant speed in its life of 14.5 knots and a mean value of the fuel price of $500 per ton. The optimization for the fixed fuel price with the principal dimensions as design variables yields a deterministic optimum design and the stochastic modelling of the fuel price a stochastic optimum design, as shown in Table 3.8.

Thus, whoever is expecting a tendency of falling (in the mean) fuel prices should hedge by ordering a somewhat smaller and fuller vessel. *Take this with a grain of salt.*

The main point is that varying financial environments in the life cycle of a ship, if sufficiently well known in advance, can be taken into account in planning and properly designing the ship for its lifetime.

3.4 Conclusions

Maritime transport in its continuous development, especially after two world wars, has become an indispensable factor in the world economy and helps to secure our

Table 3.8 Deterministic and stochastic optimization of tanker design for varying fuel price

Optimum dimensions for the same engine rating	Deterministic optimum	Stochastic optimum
Mean value of fuel price ($ per ton)	500	264
Service speed (knots)	14.5[a]	10.9 for fuel price $500/ton
Length (m)	232.8	223.6
Beam (m)	38.8	37.3
Draft	16.0	16.0
Depth	21.8	21.8
CB	0.79	0.85
RFR ($/ton)	22.68[b]	20.65

[a]the speed of the deterministic design can be optimized based on the assumed fuel price for minimum RFR: $V_{opt} = 11.25$ kn

[b]can be reduced to 21.04$/ton, if the speed of the deterministic design is optimized (e.g. $V_{opt} =$ 11.25 kn)

welfare and prosperity in a more and more globally coherent world. The world fleet as a means of transport is bigger than ever before.

At the same time, the risks of maritime transport have also steadily grown with the size of the fleet and the complexity of maritime technology. The public is increasingly aware of the risks of potential damages to the ships and shores, to the world's natural maritime environment and to human lives aboard on land and sea. Major disasters with catastrophic ship losses like the *Exxon Valdez* drama and the *Estonia's* sinking have acutely raised the awareness of the public of necessary action for the safety on sea.

In the last several decades, national and international authorities and institutions have worked intensively on increasing maritime safety. Under the leadership of IMO, the international maritime community has responded to the challenge and has issued modern new safety rules and standards, which are gradually going into effect. This chapter has attempted to give a synopsis of the most important developments.

It is also important that safety awareness must still grow in ship operations. Crew training with regular practice and inspection is a key element in maritime safety over the life cycle.

The developments and research studies performed in recent years by the ship design and research community on the basis of the objectives of risk-based ship design have been broad and successful. They ought to be continued in many details. For now they are providing a reliable methodical approach to designing safer, cleaner and economically more effective ships.

References

Bouguer P (1746) Traité du Navire, de sa Construction et de ses Mouvemens, Jombert, Paris
Boulougouris V, Papanikolaou A, Zaraphonitis G (2004) Optimization of arrangements of Ro-Ro passenger ships with genetic algorithms. J Ship Technol Res 51(3):99
Boulougouris E, Papanikolaou A, Pavlou A (2011) Energy efficiency parametric design tool in the framework of holistic ship design optimization. In: Proceedings of IMechE, vol 225, Part M: Journal of Engineering for the Maritime Environment
Boulougouris E, Papanikolaou A (2013) Risk-based design of naval combatants. J Ocean Eng 65:9–61
Chapman FH (1775) Traktat om Skeppsbyggeriet ("Treatise on Shipbuilding"), Stockholm
Chernoff H, Moses LE (1986) Elementary decision theory. Dover Publications, New York
Duckworth AD (ed) (1955) The papers of William Froude, 1810–1879. RINA, London
Euler L (1749) Scientia Navalis seu Tractatus de Construendis ac Dirigendis Navibus, 2 vols., St. Petersburg, 1749. Reprinted in Euler's Opera Omnia, Series II, Vols. 18 and 19, Zurich and Basel, 1967 and 1972
Fiacco AV, McCormick GP (1968) Nonlinear programming: sequential unconstrained minimization techniques for nonlinear programming. Wiley, New York
HOLISHIP (2016–2020) Holistic optimisation of ship design and operation for life cycle, Project funded by the European Commission, H2020- DG Research, Grant Agreement 689074, http://www.holiship.eu
International Maritime Organization (2004) Resolution MEPC.117(52), Revised Annex I of MARPOL 73/78
International Maritime Organization (2007) Resolution MEPC. 141(54), Amendments to Regulation 1, addition to regulation 12A, consequential amendments to the IOPP Certificate and amendments to regulation 21 of the Revised Annex I of MARPOL 73/78
Köpke M, Papanikolaou A, Harries S., Nikolopoulos L, Sames P (2014) CONTIOPT—holistic optimization of a high efficiency and low emission containership. In: Proc. Transport Research Arena, Paris
Kuniyasu T (1968) Application of computer to optimization of principal dimensions of ships by parametric study. Jpn Shipbuild Mar Eng
LOGBASED (2004) Logistics based design, EU FP6 project, Contract number TST3-CT-2003-001708, 2004–2007
Mandel P, Leopold R (1966) Optimization methods applied to ship design, Trans. SNAME, Vol. 74
Michell JH (1898) The wave resistance of a ship. Phil Mag 45:106–123
Murphy RD, Sabat DJ, Taylor RJ (1965) Least cost ship characteristics by computer techniques. Mar Technol 2
Newton I (1726) Philosophiae naturalis principia mathematica, 1st ed., Cambridge, 1687, 2nd ed., Cambridge, 1713, 3rd ed., London (1727)
Nowacki H (2009) Developments in marine design methodology: roots, results and future trends. In: Proceedings of 10th international marine design conference, Trondheim, May 26–29 2009, Stein Ove Erikstad (Ed.), IMDC09 & Tapir Academic Press, ISBN 978-82-519-2438-2
Nowacki H, Lessenich J (1976) Synthesis models for preliminary ship design, in German, Jahrbuch Schiffbautechnische Gesellschaft (STG), vol 70
Nowacki H, Brusis F, Swift PM (1970) Tanker preliminary design—an optimization problem with constraints. Trans. SNAME, vol 78
Nowacki H, Papanikolaou A, Holbach G, Zaraphonitis G (1990) Concept and hydrodynamic design of a fast SWATH Ferry for the Mediterranean Sea, in German, Jahrbuch Schiffbautechnische Gesellschaft (STG), vol 84
Papanikolaou A (ed) (2009a) Risk-based ship design: methods, tools and applications. Springer, Berlin. ISBN 978-3-540-89041-6

Papanikolaou A (2009b) RBD application-AFRAMAX tanker design), Chap. 6. In: Papanikolaou A (ed) Risk-based ship design—methods, tools and applications. Springer, Berlin, ISBN 978-3-540-89041-6

Papanikolaou A (2010a) Holistic ship design optimization, computer aided design. Elsevier Ltd., Dordrecht

Papanikolaou A (2010b) Risk-based tanker design. Japan Society of Naval Architects and Ocean Engineers, Tokyo

Papanikolaou A, Zaraphonitis G, Boulougouris E, Langbecker U, Matho S, Sames P (2010a) Multi-objective optimization of oil-tanker design. J Marine Sci Technol. https://doi.org/10.1007/s00773-010-0097-7

Papanikolaou A, Zaraphonitis G, Skoupas S, Boulougouris E (2010b) An integrated methodology for the design of Ro-Ro passenger ships. Ship Technol Res Schiffstechnik 57(1)

Papanikolaou A (2011a) Holistic design and optimization of high-speed marine vehicles. In: High speed marine vehicles (HSMV 2011) Proceedings, Naples, Italy

Papanikolaou A (2011b) Holistic ship design optimization: merchant and naval ships. Ship Sci Technol J 5(9):9–26. https://doi.org/10.25043/19098642.48

Papanikolaou A, Harries S, Wilken M, Zaraphonitis G (2011) Integrated design and multiobjective optimization approach to ship design. In: Proceedings of ICCAS, Trieste

Plessas T, Papanikolaou A (2015) Stochastic life cycle ship design optimization, MARINE 2015. In: Salvatore F, Broglia R, Muscari R (eds) Proceedings of 6th international conference on computational methods in marine engineering, Rome

SAFEDOR (2005–2009) Design, operation and regulation for safety. EU project. Contract number 516278. http://www.SAFEDOR.org

Sames P (2009) Introduction to risk-based approaches in the maritime industry. In: Papanikolaou A (ed) Risk-based ship design: methods, tools and applications (Chap. 1). Springer, Berlin, ISBN 978-3-540-89041-6

Skjong R (February 2009) Regulatory framework. In: Papanikolaou A (ed) Risk-based ship design: methods, tools and applications (Chap. 3). Springer, Berlin, ISBN 978-3-540-89041-6

Söding H, Poulsen I (1974) Methods of programming for tasks of ship design, in German, Jahrbuch Schiffbautechnische Gesellschaft (STG), vol 68

Software CATIA: computer-aided three-dimensional interactive application, multi-platform software suite for computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided engineering (CAE), PLM and 3D, developed by the French company Dassault Systèmes. https://www.3ds.com/products-services/catia/products/

Software friendship systems. https://www.friendship-systems.com/

Software mode.FRONTIER, a general purpose optimization software by ESTECO. www.esteco.com/modefrontier

Software NAPA solutions for design and operation of ships. https://www.napa.fi/

Software PARAMARINE, integrated naval architecture software. http://www.qinetiq-emea.com/home_grc.html

Software POSEIDON, DNVGL integrated software for the strength assessment of ship hull structures. https://www.dnvgl.com/services/strength-assessment-of-hull-structures-poseidon-18518

Software SHIPFLOW, FLOWTECH International. https://www.flowtech.se/

Software TRIBON Hull, now substituted by AVEVA, Integrated Suite Naval Software. http://www.aveva.com/en/solutions/product_finder/aveva_marine/

Taylor DW (1943) The speed and power of ships, 3rd ed, U.S. Maritime Commission. U.S. Govt. Printing Office, Washington, D.C.

Vassalos D (February 2009) Risk-based ship design. In: Papanikolaou A (ed) Risk-based ship design: methods, tools and applications (Chap. 2). Springer, Berlin, ISBN 978-3-540-89041-6

Vassalos D, Guarin L (2009) Designing for damage stability and survivability–contemporary developments and Implementation. Ship Sci Technol Glasgow

Vassalos D, Papanikolaou A (2015) State of the art report on design for safety, risk-based design, life-cycle risk management. In: 12th international marine design conference, Tokyo, 11–14 May

Weinblum G (1932) Hull form and wave resistance, in German, Jahrbuch Schiffbautechnische Gesellschaft (STG), vol 33

Wigley C (1935) Ship wave resistance, progress since 1930, Trans. Royal Institute of Naval Architects (RINA), vol 77

Woodward III JB, Nowacki H, Benford H (1968) Systems analysis in marine transport, The Society of Naval Architects and Marine Engineers, 1968 Diamond Jubilee Meeting, Philadelphia

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