#### 1.3.6.2 Ship Types

Before presenting an outline of our generalized approach to ship design, it is rational to proceed to a categorization of the various ship types into some main ship categories that may be characterized by common design procedures. These categories, referring to common design features of various ship types, are as follows:

a. *Deadweight carriers,* with their deadweight capacity as a decisive design characteristic. These are ships that carry relatively heavy cargos with a *Stowage Factor (SF)*[14] that is less than about 1.3 $m^3/t$ (e.g. ores, cement, coal, grain, oil etc.). Typical representatives of this ship category are bulk carriers (bulk/ore carriers) and tankers (crude oil carriers); also included herein are general cargo ships on charter trade (tramp ships), transporting dry cargo with relatively low stowage factor in bulk or as break cargo. The common design characteristic of this type of ship is that there may be available space in the cargo holds to accept even more cargo; however, the *maximum allowable draft (or minimum required freeboard)* of the ship, according to the provisions of the Load Line Convention, restricts further loading. The ship's *Capacity Factor (CF)*[15] is relatively low and generally less than about 1.5 $m^3/t$ DWT.
b. *Volume carriers,* with the most significant design characteristic being their hold volume capacity. These are ships that carry relatively light weight cargos with a stowage factor of more than about 2.0 $m^3/t$ (e.g. cotton, tobacco, fruits, high-value industrial goods, electronic and electric equipment, cars etc.). Typical representatives of this ship category are the RO-RO cargo ships, car carriers in general (PCC: pure car carrier, PCTC: pure car and truck carrier), RO-RO passenger ships (ROPAX, ferries), containerships, 'reefer' ships, general cargo ships in liner services (liners), and passenger/cruise ships; they dispose in general at least one continuous deck above the freeboard deck (bulkhead deck); they do not fully exploit, in general, the maximum allowable draft, as it results from the provisions of the Load Line Convention; they dispose in general excessive freeboard, because there is lack of available hold volume to accept more cargo; they dispose a relatively high capacity factor of more than about 2.5 $m^3/t$ DWT. Ships carrying intermediately heavy cargos (stowage factor between about 1.3 and 2.0 $m^3/t$) or alternative cargos of strongly varying stowage factor may be designed as deadweight or volume carriers.
c. *Linear dimension ships* with one linear dimension (length, beam, draft or side depth) restricted by physical external boundaries or constraints set by the carried cargo. These are ships with restrictions because of passing major canals, such as the canals of the St. Lawrence Seaway (Lake Ontario, Great Lakes bulk carriers) with a maximum allowable beam of 22.85 m; the Panama canal, with a maximum overall length of 294.13 m (965 ft), beam of 32.31 m (106 ft) and

[14] *SF,* cargo property, expresses the required volume for the stowage of 1 ton of cargo.

[15] *CF,* ship property, is the ratio of ship's cargo hold volume to ship's deadweight (German: Räumte).

draft of 12.04 m (39 ft 6 in), the so-called PANAMAX[16] ships, or operating near the mouth of important rivers, for example, La Plata River (South America), of importance to 'reefer' banana ships, with a maximum draft of 8.2 m. Also, ships carrying standardized cargo units, such as containerships (i.e. cellular-type containerships), have a well-defined beam (and side depth height) that is determined by the number of stowed containers in the transverse (and in the vertical) direction, considering that the beam (and height) of the containers is standardized (cross section: $8 \times 8$ ft, 8 ft = 2.438 m; some containers may be 8.5 ft high). The same applies to other box-type cargo ships, such as ships carrying floating barges of standardized dimensions, LASH (lighter aboard ship) and SEABEE, ships carrying vehicles of standard size (RO-RO cargo and RO-RO passenger ships, rail-ferry ships etc.). Common characteristic of all these ship types is the stepwise (discontinuous) change of their beam and the relatively increased length, especially if the beam happens to be restricted (e.g. PANAMAX ships); thus in general these are ships for which the relationship between main dimensions and displacement is distorted and less optimal.

d. *Special-purpose* ships. These are ships that cannot be categorized in the preceding main categories owing to specific conditions of their design and operational profiles, e.g. tugboats, icebreakers, fishing vessels, and offshore support vessels. Likewise, all *unconventional* ships are inherently special-purpose ships, and their design greatly depends on specific type, size and speed (high-speed craft in general, advanced marine vehicles, mono-, twin- and multihull vessels: catamarans, trimarans, pentamarans, air-cushion vehicles, submarines etc.).
e. Other methods or criteria of categorization of ship types are according to:

- Mission profile
  - Merchant ships
  - Naval and coast guard ships
  - Research/hydrographic vessels
  - Sport boats
  - Tug boats
  - Ice breakers
  - Dredgers
  - Support vessels of offshore activities: supply vessels, drilling ships, exploration and production floating platforms, floating production storage and offloading terminals (FPSO), crane ships etc.
  - Pilot boats
  - Cable ships
- Operation area
  - Open/deep water ships
  - Inland ships—river and lake boats

[16] An expansion of the Panama Canal is under way (expected completion in year 2014), in the way to allow the passing of ships (New Panamax) with maximum lengths of up to 366 m (1,200 ft), beam up to 49 m (160.7 ft), and draft up to 15.20 m (49.9 ft). These dimensions correspond to the size of the recent generation of MEGA(JUMBO)-containerships, with a carrying capacity of up to about 12,000 TEU.

- Floatability
  - Surface ships
  - Underwater vehicles
    - With forward speed (submarines)
    - Without or with very small forward speed (bathyscaphs)
- Type of power
  - Mechanical engine-driven
  - Wind sails
  - Oars/by rowing
- Propulsion type
  - Paddle wheel
    - Side-wheeler
    - Sern-wheeler
  - Propeller
    - Stern-vertical
    - Horizontal Voith—Schneider patent
  - Water jets
- Main machinery/engine type
  - Steam engines
  - Turbines
    - Steam-powered
    - Gas-powered
  - Diesel engines
    - Low-speed
    - Medium-speed
    - High-speed
  - Otto gas engines
  - Diesel/electric generator set
  - Combined diesel and gas turbines (CODAG)
  - Nuclear steam-powered turbines
  - ‘Green’ environmentally friendly prime or auxiliary energy sources
    - Wind and solar energy
      - Sail foils and solar cells
    - Fuel cells
      - LNG fuel cells
        NYK Super Eco Ship 2030
- Construction material
  - Steel
  - Aluminium alloys
  - Wood
  - Synthetic materials
  - Marine concrete

- Type of transported cargo
  - General cargo ships
  - Bulk carriers
  - Tankers
  - Gas carriers
    - LPG tankers: transportation of petrochemical gas products in liquid form at low temperature and/or high pressure
    - LNG carriers: transport of natural gas in liquid form at very low temperatures, $-163\,^{\circ}\mathrm{C}$
  - Break bulk carriers
    - Break bulk cargo ships
    - Container ships
    - Floating barge carriers
      - Barge carriers
        LASH
        SEABEE
        BACO (barge–container carrier)
    - Vehicle carriers
      - PCC and PCTC
      - RO-RO cargo ships
      - Passenger/RO-RO-RoPAX
        Rail and combined RO-RO rail ships
    - Heavy lift transport ships
  - Multipurpose cargo ships
  - Passenger ships
    - Cruise ships
      - Day cruise ships
      - Overnight cruise ships
  - Short sea passenger transport ships
    - Day ships
    - Overnight ships
  - Excursion boats

Descriptions of the main types and their development are included in Volume II of Papanikolaou (2009a).

Table 1.5 presents a breakdown of the world fleet by basic ship types for the year of 2011 (existing, newly building and on order; IHS Fairplay WSE 2011).

Table 1.6 presents a breakdown of the Greek-owned fleet by basic ship types for the year of 2011 (existing, newly building and on order; IHS Fairplay WSE 2011).

Typical representatives of the different types of ship designs can be seen in Figs. 1.20, 1.21, 1.22, 1.23, 1.24, 1.25, 1.26, 1.27, 1.28, 1.29, 1.30, 1.31, 1.32, Fig. 1.44 to Fig. 1.51.

#### 1.3.6.3 Methods for Determining Main Dimensions

There are two basic methods in ship design for the preliminary estimation of the main dimensions and the basic form characteristics, namely the *relational* or

**Table 1.5** World cargo ship fleet for year 2011 according to ship types. (IHS Fairplay WSE 2011)

| Ship type/category | No. of ships | DWT (millions) | GT(millions) |
|---|---|---|---|
| *Reference year 2011 (Ships built since 2000, including ships on order)* | | | |
| Oil | 3,665 | 382.4 | 206.1 |
| Bulk dry | 7,182 | 571.0 | 310.0 |
| General cargo | 4,689 | 41.8 | 29.1 |
| Container | 3,715 | 195.8 | 173.6 |
| Chemical | 3,344 | 75.6 | 47.3 |
| Liquefied gas | 929 | 37.8 | 43.3 |
| Ro-Ro cargo | 219 | 2.4 | 4.5 |
| Other bulk dry | 242 | 6.0 | 4.8 |
| Refrigerated cargo | 81 | 0.6 | 0.5 |
| Passenger/Ro-Ro cargo | 725 | 1.5 | 7.2 |
| Other dry cargo | 91 | 1.6 | 1.5 |
| Passenger | 697 | 0.07 | 0.4 |
| Passenger/general cargo | 43 | 0.04 | 0.08 |

**Table 1.6** Greek-owned cargo ship fleet for year 2011 according to ship types (IHS Fairplay WSE 2011)

| Ship type/category | No. of ships | DWT (millions) | GT (millions) |
|---|---|---|---|
| *Reference year 2011 (Ships built since 2000, including ships on order)* | | | |
| Oil | 489 | 66.7 | 35.3 |
| Bulk dry | 915 | 78.9 | 42.5 |
| Container | 151 | 11.9 | 9.2 |
| Chemical | 286 | 9.9 | 6.0 |
| Liquefied gas | 76 | 3.2 | 3.6 |
| RO-RO cargo | 70 | 1.1 | 3.2 |
| Passenger/RO-RO cargo | 93 | Not available | 1.0 |
| Passenger | 20 | Not available | 0.06 |

**Fig. 1.20** Bulk carrier

*empirical method* and the *parametric method* (Fig. 1.33) or method of independent parameters:

**a. Relational or Empirical Method** The estimation of main dimensions is based on comparative data from a similar built ship, with the data stemming from open source/public information (web search), commercial and internal databases and

Fig. 1.21 Ultra large crude carrier (ULCC)


Fig. 1.22 LNG carrier

Fig. 1.23 Containership

**Fig. 1.24** LASH (Ligther Aboard Ship)


**Fig. 1.25** SEABEE


**Fig. 1.26** BACO (Barge container)


**Fig. 1.27** RO-RO (Roll-On Roll-Off cargo ship)

**Fig. 1.28** Pure car carrier (PCC)

**Fig. 1.29** Heavy lift carrier


**Fig. 1.30** RO-RO/passenger (RoPax)


**Fig. 1.31** High-speed catamaran of type SWATH ROPAX

**Fig. 1.32** Mega cruise ship

available data files. A variation of this method is the use of empirical design formulas deduced through regression fitting of relevant statistical diagrams, or of properly defined design coefficients, with the help of which the sought data, e.g. ship's

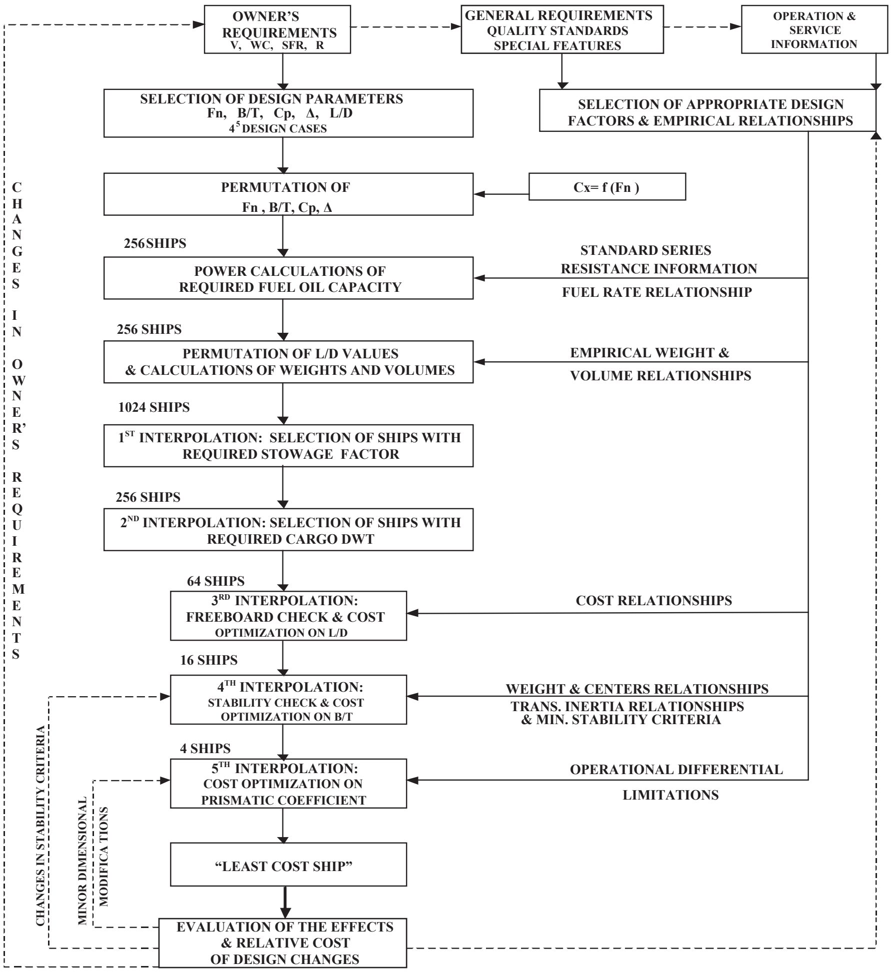



**Fig. 1.33** Parametric optimization by permutation of main design parameters for the 'least-cost' cargo ship, according to R.D. Murphy et al. (Taggart 1980). Owner's requirements: $V$ (velocity), $WC$ (weight of cargo), $SFR$ (stowage factor required), $R$ (range), $F_n = V/\sqrt{gL}$: Froude number

main dimensions, weight components and powering are brought into dependence on the initially given or earlier deduced data, e.g. relationship of length on ship's deadweight or indirectly ship's displacement. For successful application of the empirical method, it is assumed that the available comparative data or empirical relationships are sufficient and reliable for the type and size of the ship under investigation. Of course, it is additionally assumed that the comparative built ships represent economically competitive and reliable design solutions and that the relationship between the main design parameters and the assessment criteria is quite flat (of small gradient) in the region of interest for the actual design parameters, i.e. a small change in a design parameter does not lead to a significant change of the assessment criterion (a small change of ship's length does not lead to a drastic change of ship's resistance and powering demand, for constant displacement).

**b. Parametric Method** When comparative data from similar ships are lacking, e.g. in case of innovative ship types, or when the absolute ship size exceeds common limits, it is necessary to conduct a study from scratch, namely to seek the best combination of main dimensions and main design characteristics for optimizing some selected design criteria. Based on the mathematical optimization model (algorithm and corresponding computer software) of an economic criterion, such as building cost, the required freight rate for 1 ton of transported cargo (RFR: required freight rate[17]), or return on investment, the absolutely optimal set of design parameters is identified, minimizing or maximizing a set criterion. It should be noted that modern ship design optimization methods may consider multiobjective optimization procedures, optimizing simultaneously a series of partly contradicting criteria and constraints, thus identifying the so-called Pareto front of best design solution (see Papanikolaou 2010).

The setup of a satisfactory mathematical model, in which the ship's main design parameters are rationally related to the ship's performance (physical and economic characteristics), is a very demanding task and obviously strongly related to the specific conditions of the ship type. The model may be (and often is) supported by systematic experimental data of model series. The identification of the optimal ship design solution is one fundamental task of computer-aided ship design (CASD) and, mathematically, a typical nonlinear multiparametric and multiobjective optimization problem with multiple constraints.

A classical and historic example of systematic parametric optimization for identifying the 'least-cost ship' is given in Fig. 1.33. It refers to the optimization procedure of a cargo ship on the basis of the main requirements of a hypothetical ship owner for speed ($V$: velocity), payload ($W_C$: weight of cargo), stowage factor ($SF_R$: stowage factor required), and range ($R$: range) according to R.D. Murphy et al. (Taggart 1980). It should be noted that this approach was developed in the early 1960s by use of very limited resources for computer hardware and software available at that time. In addition to the systematic change of various independent parameters ('brute force' approach), which essentially is possible only with the help of computers, the parametric method can be applied in a simplified form with few but essential changes in the basic parameters, provided that the design space of the optimal solutions is known to the researcher.

In practice, Murphy et al.'s methodology has already been replaced nowadays by modern optimization methods, which are supported by strong computer infrastructure; this enables the consideration of many more design parameters, objective functions and constraints. The identification of the optimal solution is achieved with a minimum number of parametric iterations compared to the 'brute force' para-

[17] Definition of RFR = (annual costs + annual depreciation value of the ship)/annual transported amount of cargo. The definition applies strictly for uniform annual cash flow. Ships with smaller RFR are more competitive than others, as they may lead to more profit, in case actual freight rates are higher than RFR or to less loss in case actual freight rates are lower than RFR.

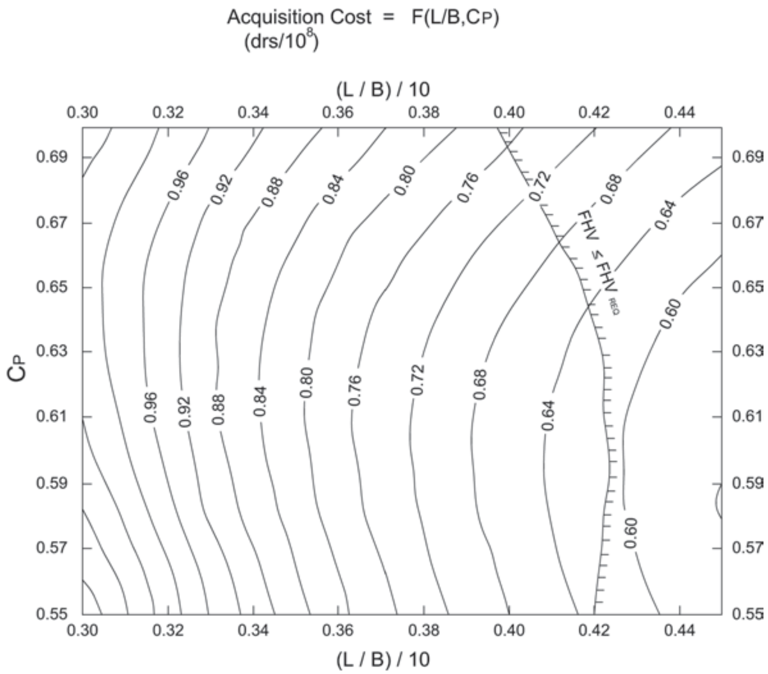



**Fig. 1.34** Optimization of medium fishery vessel (stern trawler) with respect to shipbuilding/acquisition cost (Kariambas 1996)

metric optimization used in the initial stages of CASD (mathematical optimization method and nonlinear programming problems, see Papanikolaou and Zaraphonitis 1988; modern ship design optimization with genetic algorithms, see Boulougouris 2003, Papanikolaou (2010); State of the Art review, Nowacki 2010).

One example of mathematical design optimization of a fishing vessel is given in Fig. 1.34, showing the dependence of building cost (represented herein by isolines of $10^8$ Greek Drachmas currency units in the early 90s) on the ship's prismatic form coefficient and the length-to-beam ratio; in this example the following owner's specifications are assumed: fish-hold volume = 45 m$^3$, service speed 9 knots, range/endurance 13 days; present diagram holds for length = 20 m and *B/D* ratio = 2.0.

Finally, in Figs. 1.35, 1.36, 1.37, 1.38, 1.39, 1.40 and 1.41, the process of modern ship design optimization is elaborated, along with an example of multiobjective optimization of the compartmentation and arrangements of a RoPax ship with respect to her structure weight, payload (as expressed by the length of lanes of carried vehicles) and the attained subdivision index A (representing ship's damage stability) by using genetic algorithms; examples are from recent years' research work of the Ship Design Laboratory of NTUA (Boulougouris 2003).

In Fig. 1.42, the ship design problem is formulated as a *decision process* in the frame of system theory, and its optimization is achieved by nonlinear programming methods.

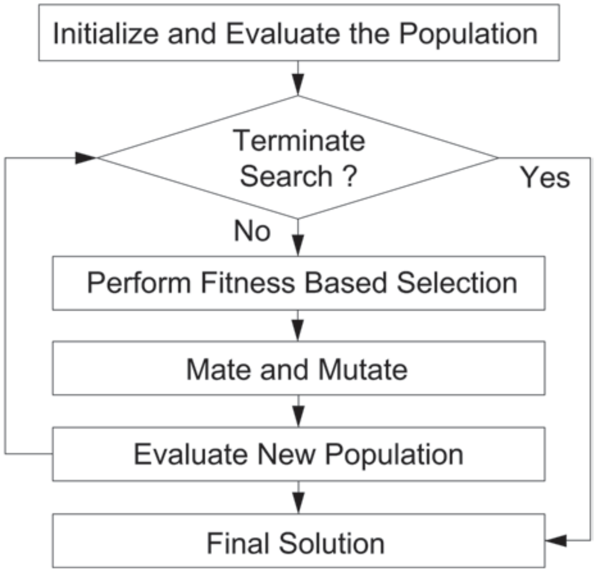



**Fig. 1.35** Basic steps of genetic algorithms (Sen and Yang 1998)

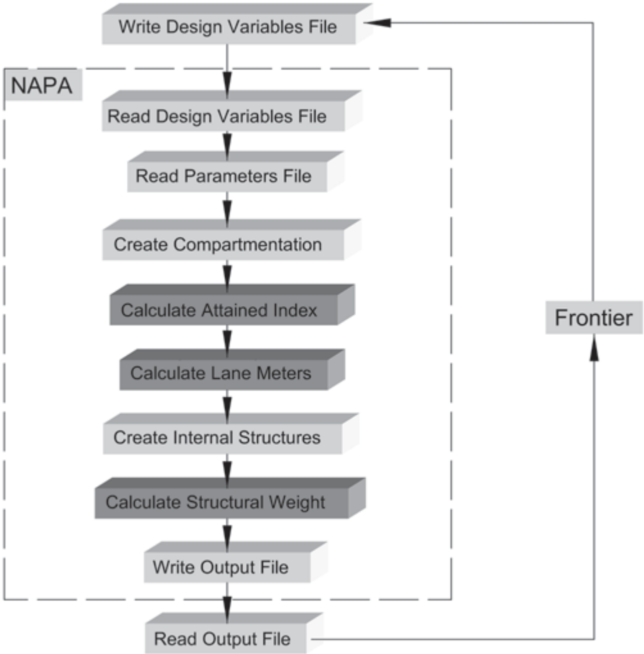



**Fig. 1.36** Flowchart of multiobjective ROPAX optimization procedure (Ship Design Laboratory—NTUA; Boulougouris 2003)

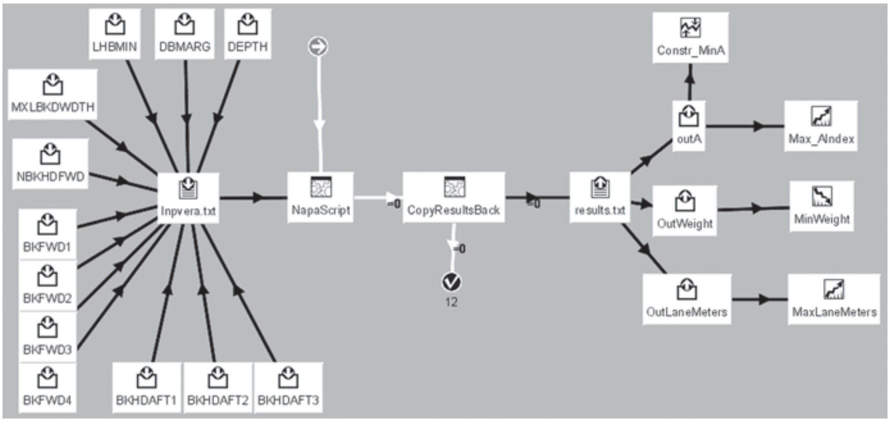



**Fig. 1.37** Logistic interface of ship design software Napa® and optimization software FRONTIER® (Ship Design Laboratory—NTUA; Boulougouris 2003)

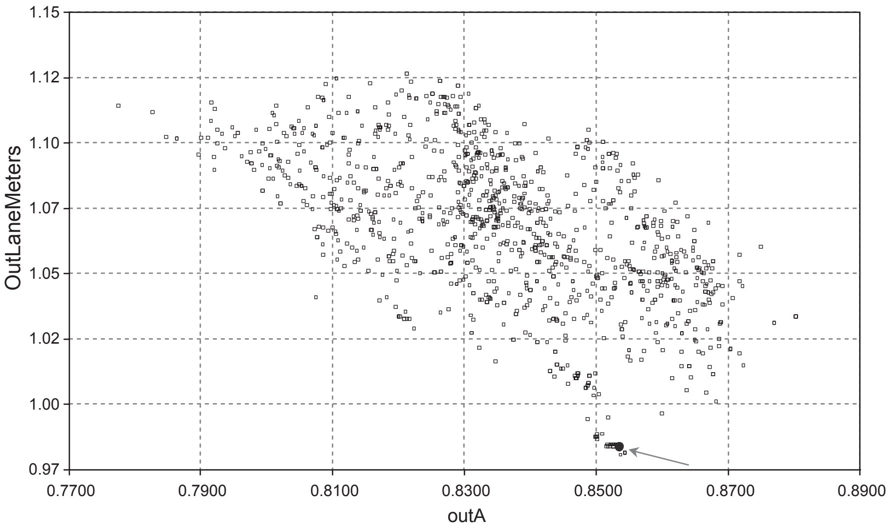



**Fig. 1.38** Population of optimal design solutions (and Pareto front) of an RO-RO passenger ship with respect to the attained subdivision index A and the achieved length of vehicle lanes (Ship Design Laboratory—NTUA; Boulougouris 2003)

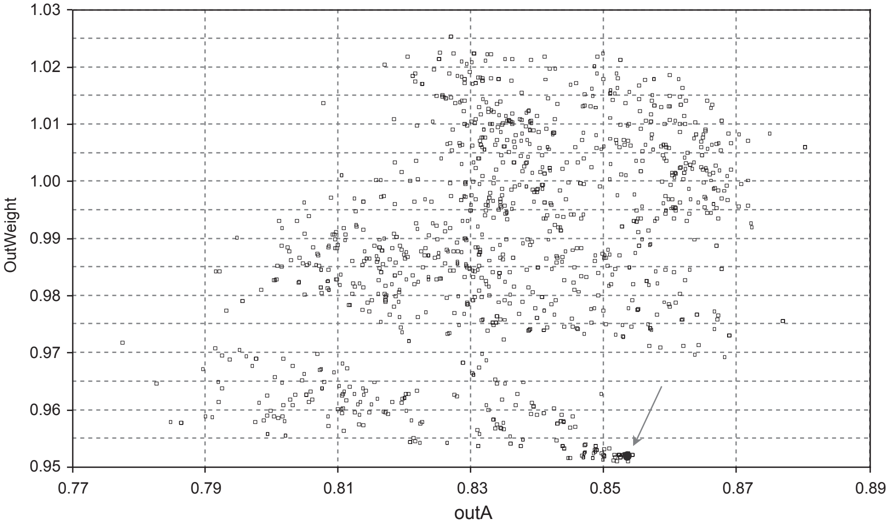



**Fig. 1.39** Population of optimal design solutions (and Pareto front) of an RO-RO passenger ship with respect to the attained subdivision index A and a ship's structural weight (Ship Design Laboratory—NTUA; Boulougouris 2003)

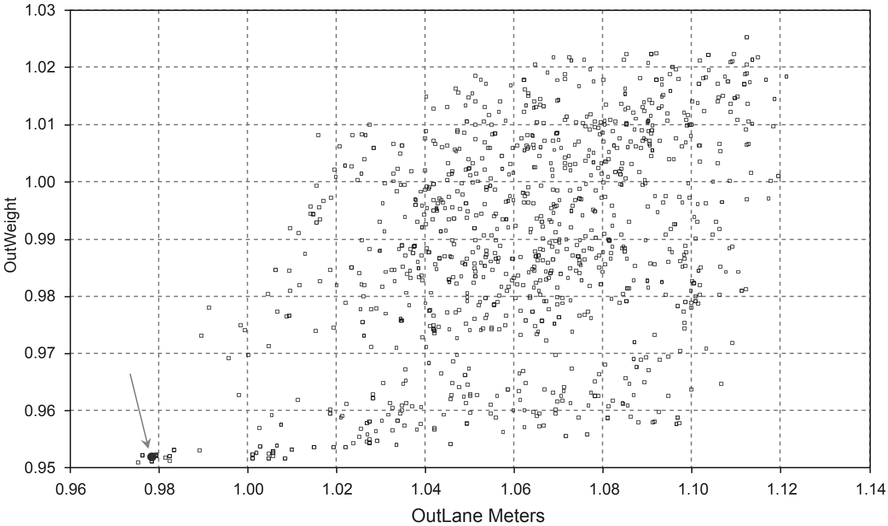



**Fig. 1.40** Population of optimal design solutions (and Pareto front) of an RO-RO passenger ship with respect to the achieved length of vehicle lanes versus a ship's structural weight (Ship Design Laboratory—NTUA; Boulougouris 2003)

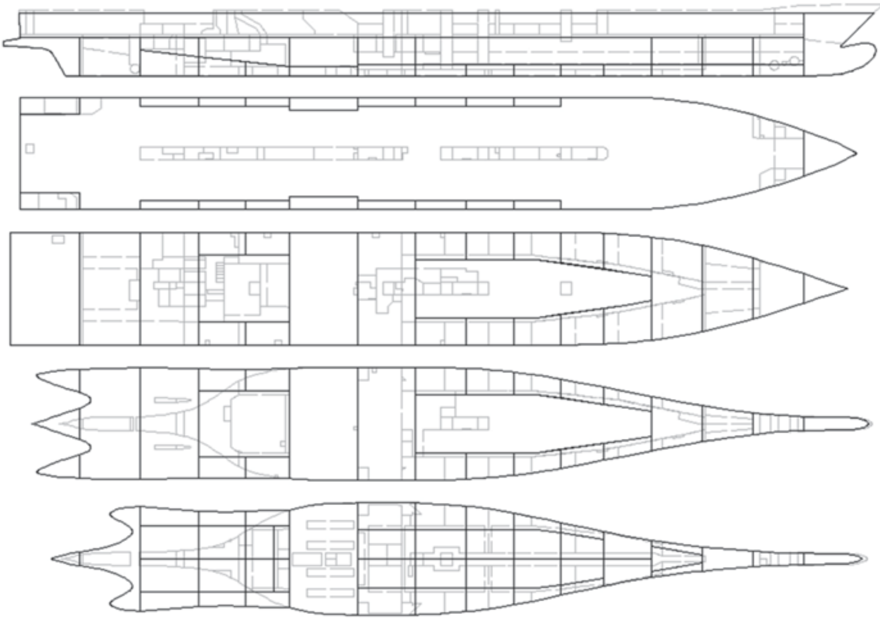
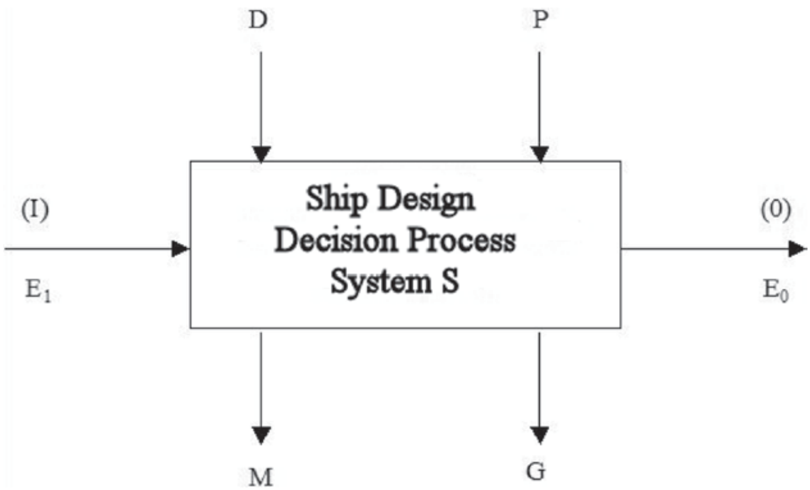


**Fig. 1.41** Comparison of compartmentalization of optimal (*dark line*) vs. initial (*grey*) RO-RO passenger ship design (Ship Design Laboratory—NTUA; Boulougouris 2003)

**Ship Design = Decision Process**




Ei: entrance, (I): input=given data
= main owner's requirements (DWT, speed, range, operational conditions) and other conditions.
Eo: exit, (O): output
= data to be calculated – data under study based on technoeconomical ship characteristics
= technoeconomic optimized solution based on a certain decision criterion
D: decision – design variables
= all the variables that can be altered freely by the designer (independent or/and dependent variables, i.e. ship principal dimensions: length, breadth, draft, dimensions ratios)
P: Restriction – parameters, constraints
= all values that cannot be influenced (controlled) by the designer (decision maker), e.g., physical constraints, limiting dimensions of canals and ports, state of shipping market, weather conditions,etc.
M: Evaluation criteria – merit function = M(D,P)
= formulation of one or more assessment criteria in terms of an objective function (or multiple functions), which will be relating to the design and restriction parameters.
G: Constraint functions – constraints = G(D,P)
= formulation of constraint functions relating to the design and restriction parameters by linear or nonlinear algebraic equalities and non-equalities, for example, implementation of stability regulations (required minimum GM value), structural rules (requirement for minimum structural moment of inertia amidships), loadline convention (required minimum freeboard), etc.
S: Design of system S (ship) = decision process
= mathematic model relating the input variables and parameters $E_I$, D, P with the output data $E_o$, M(D, P) and G(D, P).

**Fig. 1.42** System approach to ship design as a decision process

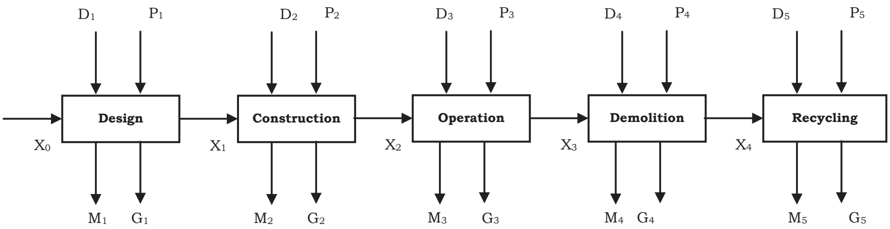



**Fig. 1.43** Life-cycle approach to ship design

Actually, in a life-cycle approach to ship design (Fig. 1.43), the entire life of a ship from concept design to construction, operation and up to demolition and recycling needs to be considered and optimized.

#### 1.3.6.4 Comments on Implementation of Design Methods

Regarding the practical application of the preceding basic design methods in practice, we may note the following:

**A) Fundamental Principles**

**a$_1$.** *Theory and practice (theoretical and empirical methods).* Only when considering both approaches we may arrive at good and possibly truly optimal design solutions.

**a$_2$.** *Exploitation of data of prototypes.* The use of empirical data from similar built ships greatly reduces the design work effort and serves also as validation of computer generated design data.

**B) Selection of Similar Ships (Prototypes, Parents) and Use of Comparative Data**

**b$_1$.** Typical comparative data for main ship types:

*General cargo ships:* deadweight, speed, trade type (tramp or liner), main machinery powering (Fig. 1.44).

*Tankers and bulk carriers:* Deadweight, speed, powering, passing limits through canals and narrow straits (Fig. 1.45).

‘*Reefer*’ *ships:* Deadweight, refrigerated cargo hold volume (net and net net), speed, powering (Fig. 1.46).

*Container ships:* Deadweight, number of containers (above and below deck, dry and ‘reefer’ containers, number of TEU and FEU), speed, powering, passing limits through canals (Fig. 1.47).

*RO-RO passenger ships* (Fig. 1.48): Speed, powering, number of passengers (with and without cabins), number of vehicles (private cars and lorries, lane meters), extent and quality of accommodations, type of service (day and overnight trips).

**Fig. 1.44** General cargo ship


**Fig. 1.45** Tanker


**Fig. 1.46** Reefer ship

**Fig. 1.47** Containership


**Fig. 1.48** RO-RO passenger ship

**Fig. 1.49** MEGA Cruise ship

*Cruise ships:* Speed, powering, number of passengers, extent and quality of accommodation and public spaces, type of service (day and overnight trips), passing limits through canals (Fig. 1.49).

*Tugboats* (Fig. 1.50): Operational area (open sea or harbour services), speed and powering, towing power (bollard pull).

**Fig. 1.50** Tugboat

**Fig. 1.51** Fishing vessel

*Fishing vessels* (Fig. 1.51): Free-running and fishing (net-towing) speeds, powering of main machinery, towing power, fish-hold volume, extent of accommodations, range, type of fishing vessel and fisheries (trawler, purse seiner, factory mother ship, coastal, oceanic etc.).

When even one of the above characteristics differs substantially from the comparative ship, then the direct use of the empirical data in hand is problematic and requires great caution. There are, however, methods for general cargo ships such as the relational method of Normand (see Appendix C), according to which by using some transfer functions the available comparative data may be still used (if better data are not available), assuming that the differences in main parameters are small (up to a maximum of 10 %, exceptionally up to 20 %).

**b$_2$.** *Use of comparative design data:* Assessment and exploitation of as much as possible comparative data form similar (parent) ships. The *interpolation* between comparative data in hand is in general seamless; however, *extrapolation* on the basis of comparative data may often prove problematic, unless for small exceedance of boundary limits.

**b$_3$.** *Use of empirical diagrams:* The ship design bibliography offers a plethora of design diagrams in which typical design data for various types of ships are presented and main ship features (length, beam, draft, side depth, deadweight etc.) are depicted as a function of a typical shipowner's requirements; for example, for cargo ships, main dimensions versus deadweight; for containerships, versus the number of TEU; for fishing vessels, versus the fish-hold volume. These diagrams should be used only in the initial conceptual design stage and should be avoided in later design stages, except as a way of checking/validating the design data obtained (see Appendix A).

C) Use of Design Constants and Coefficients

A basic tool of traditional ship design is the use of various empirical and semiempirical design constants and coefficients that are properly defined constant values, which may vary with vessel size; they account for the impact of the variation of design parameters on certain design properties, such as weight components and engine power. Well-defined design constants and coefficients do characteristically not change significantly, when the underlying design parameters vary. Design constants and coefficients may be dimensional or dimensionless, and care should be taken to consider their exact definition and the method of nondimensionalization, when using them. Especially in case of *dimensional* coefficients, the dimensional units used need to be observed; design coefficients may be used in the initial design stage for early and quick estimations of design characteristics.

Examples

*Admiralty constant*:

$$C_{\mathrm{N}} = \frac{\Delta^{2/3} V^3}{P} \tag{1.10}$$

where $\Delta$ is displacement weight (tons), $V$ is speed (knots, rarely in m/s), and $P$ is engine-horsepower (typically installed horsepower, given in HP or kW); it is a *dimensional* design coefficient allowing the quick estimation of the powering of a ship; that is, the required horsepower may be estimated on the basis of the initially estimated displacement and the specified speed.

Assuming that $C_{\mathrm{N}}$ is known from data of similar ships, it can be used for estimating the required horsepower (for given $\Delta$ and $V$) or the expected speed for the same ship, when changing her loading condition (change of displacement); for example, in the assessment of the speed at design draft, the measurements of speed and corresponding power in trial conditions (at reduced draught) can be used to calculate the constant $C_{\mathrm{N}}$, and to approximately estimate next the anticipated speed at the design displacement $\Delta$ and draft for the available/installed power $P$.

The constant is due to the British Admiralty and has a long history as a very effective way to quickly estimate speed/powering values for given ship displacement; care should be taken when determining the value of the constant, besides taking care of proper units, to consider data for ships of similar *absolute length* because of the effect of underlying physics and *similitude law* of frictional resistance components (effect of Reynolds number).

*Structural weight coefficient:*

$$P_{\mathrm{ST}} = \frac{W_{\mathrm{ST}}}{L \cdot B \cdot D} \tag{1.11}$$

where $W_{\mathrm{ST}}$ is ship's structural weight (ton, kp or kN), $L$ is length, $B$ is beam, and $D$ is side depth (all in metre). This is a dimensional coefficient (weight unit/volume unit) that also may be defined as well for other ship components, such as light ship weight and weight of outfitting.

D) Ship Design Equation

The so-called *ship design equation* is deduced from the Archimedean principle, namely, *the weight of the ship is equal to the weight of displaced water*. Methods related to the ship design equation for the initial estimation of ship's main dimensions are based on the analysis of both sides of the equation by expressing them through empirical coefficients and dimensional ratios; through this, an algebraic equation for a main dimension, such as the ship's beam or length is deduced. However, the modelling of the displacement equation for the general case of a ship's design is so complex that the methodology remains essentially impractical in practice, except in the initial design stage (feasibility study see, Sect. 2.13).

E) Computer-Aided Ship Design (CASD)

Beyond the parametric and mathematical ship design optimization, outlined in the preceding Sect. 1.3.6.3, Parametric Method, a number of ship design-specific software tools (or software platforms) are nowadays employed in the various stages of ship design. Typical examples of application of specialized computer software for the computing needs of ship design are listed below:

- Hydrostatic calculations (hydrostatic data sheets and diagrams, parametric stability/Bonjean data/curves, floodable length data/curves, stability booklets, probabilistic damage stability calculations; control of stability criteria in intact and damage conditions etc.)
- Resistance and propulsion calculations (for selection of main machinery and propulsion system)
- Calculations of load line convention (determination of freeboard height, allowable draft)
- Weight component calculation (structural weight, weight of machinery and outfitting)
- Structural strength calculation (analysis of static and dynamic ship strength, control of classification society rules, strength assessment by first principles methods—finite element methods)
- Assessment of seakeeping (calculation of motions and loads in waves)
- Assessment of manoeuvrability
- Assessment of vibrations of ship's structure, machinery and propeller

Other typical software applications in ship design, beyond the pure calculation tasks, include:

- Ship design optimization with respect to various criteria, for example, minimization of ship's resistance or of required freight rate (RFR), minimization of

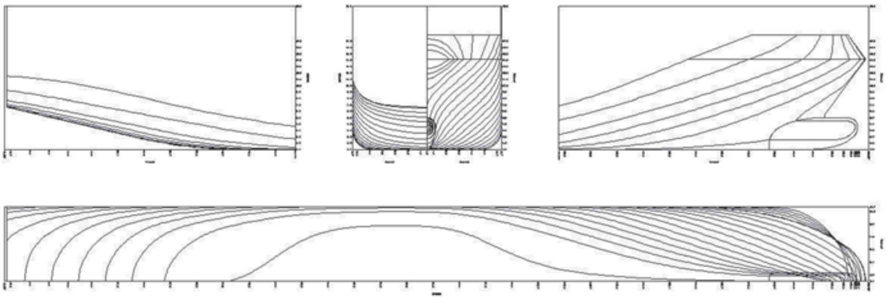


**Fig. 1.52** Development of ship hull lines for a RO-RO passenger ship by use of software package NAPA (Ship Design Laboratory, NTUA)

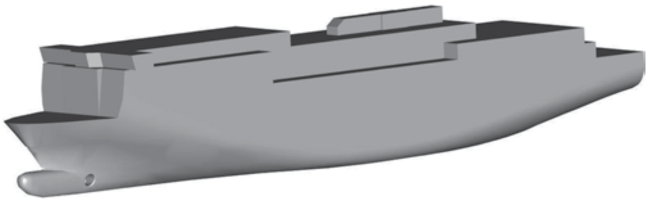


**Fig. 1.53** Development of faired 3-D hull surface (skinning) for a RO-RO ship by use of software package NAPA (Ship Design Laboratory, NTUA)

structural weight, maximization of survivability in the case of hull damage as single- or multiple-criteria optimization

- Development of ship hull lines from existing hull form lines by distortion or from systematic model series
- Fairing of ship lines and development of hull surfaces (skinning)
- Development of general arrangement of hull spaces and outfitting (conventional 2-D and 3-D graphic presentation)
- Simulation of a ship's behaviour in waves and of dynamic intact and damage stability by use of software tools (e.g. CAPSIM of NTUA-SDL)
- Simulation of ship evacuation
  - EVI,
    www.safety-at-sea.co.uk/evi
  - EXODUS,
    www.fseg.gre.ac.uk/exodus
  - AENEAS,
    www.gl-group.com/maritime

Contemporary integrated naval architectural software packages (and platforms), which are able to support the designer partly or completely, in various stages of the design of a ship, are listed below (Figs. 1.52, 1.53, 1.54, 1.55 and 1.56):

- NAPA®, http://www.napa.fi

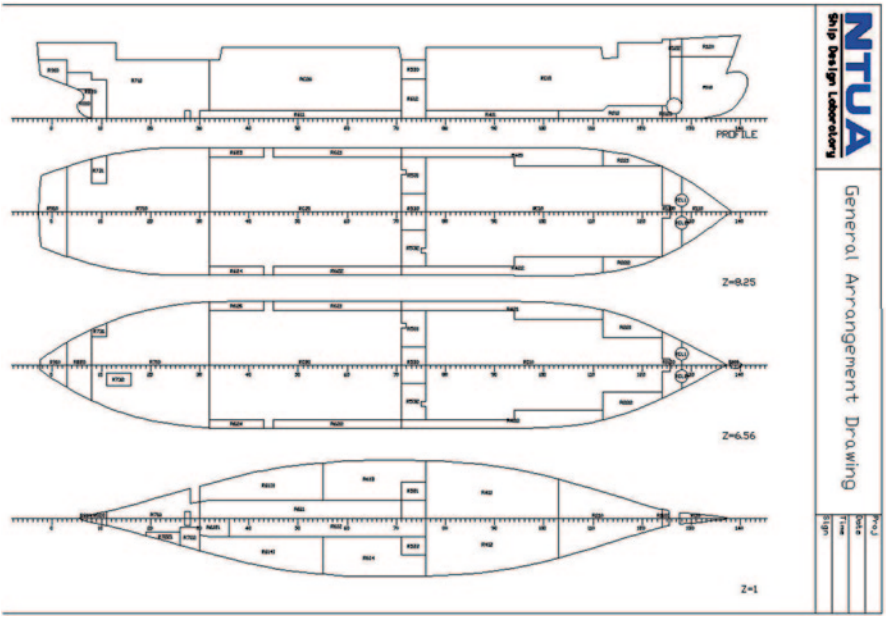



**Fig. 1.54** Development of general arrangement of spaces and outfitting (conventional 2-D and 3-D graphic presentation)

- TRIBON/AVEVA®, http://www.aveva.com
- FORAN®, http://www.foransystem.com
- GHS®, http://www.ghsport.com
- AUTOSHIP®, http://www.autoship.com
- RHINOS 3D®, http://www.rhino3D.com
- MAXSURF®, http://www.formsys.com/academic/maxsurf
- DELFTship®, http://www.delftship.net
- FRIENDSHIP SYSTEM®, http://www.friendship-systems.com

## *1.3.7 Basic Design Procedures for Main Ship Categories*

Following the preparatory steps outlined in the preceding Sect. 1.3.6.1, the designer may proceed to the gradual estimation of the ship's main characteristics in a well-defined sequential order (according to relevant main ship category) as following:

### 1.3.7.1 Deadweight Carriers

1. Estimation of displacement $\Delta$ on the basis of specified (given) deadweight DWT (see Sect. 2.1 and Table 2.1; or use of regression data from Appendix A)

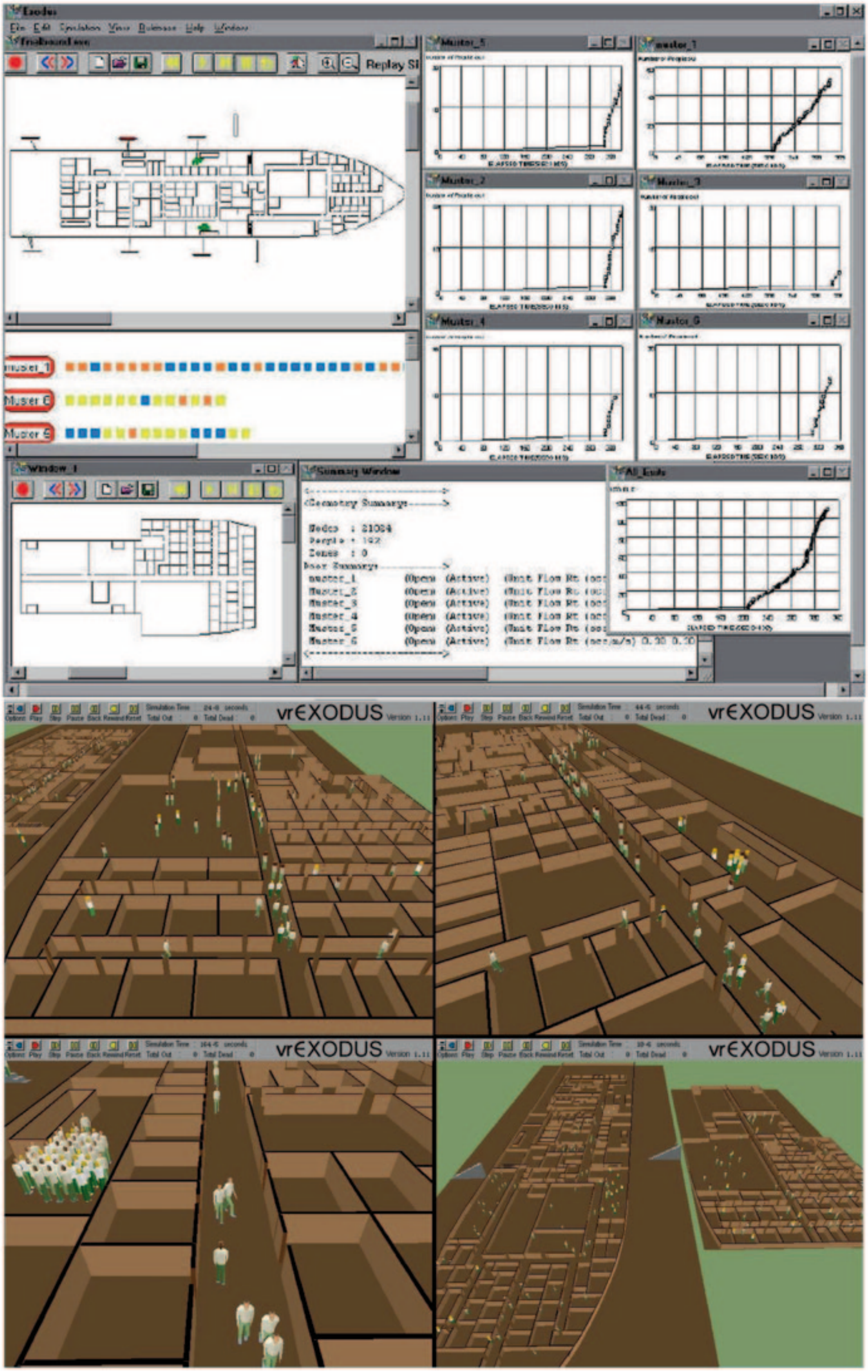



Fig. 1.55 Simulation of ship evacuation by software EVI & EXODUS

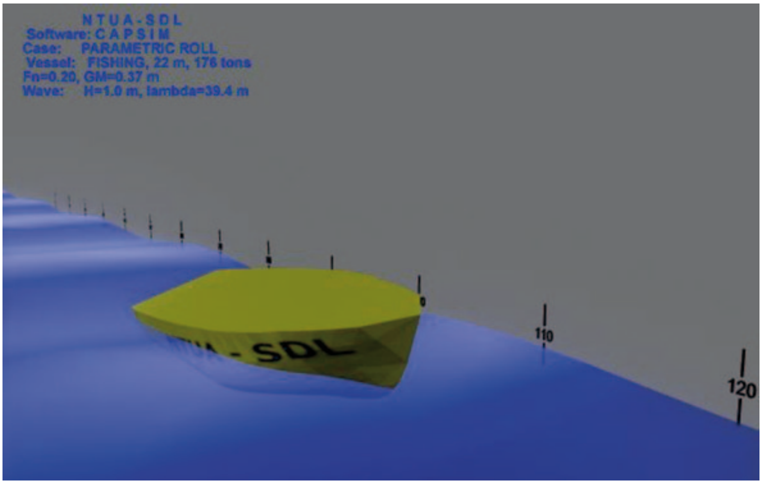



**Fig. 1.56** Simulation of dynamic intact and damage stability of ships by use of software CAPSIM (Ship Design Laboratory, NTUA)

**Table 1.7** Order of estimation of main dimensions and form coefficients for deadweight carriers

| Sizes and quantities | Basis for calculation |
|---|---|
| 1. Length $L$ | Slenderness coefficient: $L/\nabla^{1/3}$, $\nabla$: displaced volume (see Sect. 2.3) |
| 2. Block coefficient $C_B$ | Length $L$, nondimensional Froude number $F_n = V/\sqrt{gL}$ $V$: given speed, $g$: gravitational acceleration (see Sect. 2.10) |
| 3. Beam $B$ | Ratios $L/B$, $B/T$ (see Sects. 2.5 and 2.6) |
| 4. Draft $T$ | Ratios $B/T$, $L/T$ (see Sects. 2.5 and 2.8) |
| 5. Side depth $D$ | Required hold volume, ratio $L/D$, (see Sects. 2.5 and 2.7) |
| 6. Other hull form coefficients, midship section coefficient $C_M$ | $C_B$ or through $F_n$ |
| Prismatic coefficient $C_P$ | $C_B/C_M$ or through $F_n$ |
| Waterplane area coefficient $C_{WP}$ | $C_B$ (see Sects. 2.9, 2.10, 2.11 and 2.12) |

2. Estimation of main dimensions and form coefficients in the order outlined in Table 1.7, Steps 1–6, and use of regression data from Appendix A
3. Preliminary estimation of powering (see Sect. 2.14)
4. Development of a *sketch* of ship's lines and general arrangement (see Chap. 4), preliminary estimation of displaced volume
5. Control of balance between the sum of ship's weight components and of the weight of displaced water on the basis of the sketched ship lines (balance between geometric displacement and displacement weight)
6. Estimation of cargo hold volume (see Sect. 2.17)
7. Preliminary estimation and control of minimum freeboard (see Sect. 2.19.2)
8. Control of stability and trim (see Sect. 2.18)
9. Preliminary estimation of construction cost (see Chap. 6)
10. Review and summary of results

After the completion of the last step in this procedure for the estimation of the main dimensions and form coefficients, a more detailed reassessment of the pre-estimated quantities is initiated; in particular, the more complex design studies related to Steps 3–8 are conducted in the frame of ship's preliminary design. In the second iteration, the confirmation of the initially estimated absolute values of main dimensions is necessary; they need to fulfil the technical criteria set up in the statement of work by the ship owner and correspond to the extent possible to economically optimal solutions.

In the following, the preliminary main naval architectural plans are developed, namely,

- The ship lines plan
- The general arrangement plan
- The sectional areas and lengthwise volume distribution plan

They enable, among others, the estimation of the available cargo hold volume, the verification of ship's displacement and its lengthwise distribution, ship's hydrostatic properties and arrangements of spaces and main outfitting.

The technical part of the preliminary ship design study is completed by the control of stability and trim of the *intact* ship in main loading conditions (departure, fully loaded at design draft, arrival at port, fuel tanks partly empty, ballast condition etc.), assuming the hull form description and the weight distribution known from previous design steps. This assessment is generally conducted using appropriate software for hydrostatic calculations; the results include, among others, complete details of the ship's geometry (ship lines offsets), the entire hydrostatic data/diagrams and parametric stability (*Bonjean*) curves of the ship, which allow the assessment of the ship's adequacy with respect to floatability, transverse stability and trim, for a given ship's geometry and weight distribution. In addition, ship's *damage* stability needs to be assessed, thus the adequacy of the ship's watertight subdivision with respect to possible flooding due to collision and grounding. This assessment is nowadays accomplished by specialized software tools and is based on the probabilistic damage stability framework of SOLAS 2009,[18] introduced for all-new dry cargo and passenger ships built after January 1, 2009 (see Papanikolaou 2007).

It should be noted that, in older times and until the early 90s the control of a *cargo ship's damage* stability (thus of flooding of spaces due to loss of ship's watertight integrity) was not required for dry cargo ships (but only for passenger ships), except for the B-60 and B-100 type bulk carriers. The latter are allowed to have a reduced freeboard, compared to other cargo ships, assuming compliance with respect to requirements on buoyancy and stability after damage of 'one'- and 'two'-compartment standard ships respectively (according to the International Load Line Convention—ICLL). Non-dry cargo ships are excluded from applying the above requirements. Their stability and floatability are controlled by other regulations, such

[18] The attained subdivision index $A$ (which corresponds to the probability that the ship survives a likely side collision damage) must be greater than the required subdivision index $R$ ($A>R$). $R$ increases with ship's size and is a function of ship's length (dry cargo ships) and additionally of the number of people onboard (passenger ships).The value of R is determined by international safety regulations (SOLAS).

as MARPOL 73/78 for oil tankers and likewise for the liquefied and natural gas carriers (International Bulk Chemical Code and International Gas Carrier Code).

After the completion of the technical part of a ship's design, a preliminary calculation of the ship's construction cost is conducted, along with a critical review and concise presentation of the design outcome (Steps 9 and 10).

The preceding studies, if conducted manually without use of integrated design software tools, are traditionally repeated, in a trial-and-error iterative procedure until, after about the third iteration, the ship's main dimensions converge to their final values; the final dimensions are characterized by their harmonic interrelationship while fulfilling ship's technical and operational requirements cost efficiently.

In Papanikolaou (2009a, Vol. 2), the reader may find a description of the step by step design procedure for a series of cargo ship types in the frame of the above outlined general design procedure for deadweight carriers.

#### ~~1.3.7.2 Volume Carriers~~

Compared to the deadweight carriers, the procedure for the volume carriers commences with an estimation of the *required cargo hold volume* below the main deck (instead of displacement) on the basis of the required overall hold capacity. The step by step procedure is as follows:

1. Estimation of the required cargo hold volume below the main deck on the basis of the overall hold capacity specified by the shipowner.
2. Estimation of the main dimensions and form coefficients in the sequence order outlined in Table 1.8. The subsequent procedure is the same as that for deadweight carriers, i.e. Steps 3—10 in Sect. 1.3.7.1.

**Table 1.8** Order of estimation of main dimensions and form coefficients for volume carriers

| Sizes and quantities | Basis for calculation |
|---|---|
| 1. Length $L$ | Hold capacity BALE $V_{BALE}$[a] (cargo ship) hold capacity NET $V_{NET}$[b] TEU number $n_{TEU}$[c] (container ships) |
| 2. Block coefficient $C_B$ | $L$, $F_n$ |
| 3. Beam $B$ | Ratio $L/B$, or on the basis of the above data for estimation of $L$ |
| 4. Side depth $D$ | Ratio $B/D$, or on the basis of the above data for estimation of $L$, or coefficients (hold capacity/L·B·D) |
| 5. Light ship weight $W_L$ | Coefficient $W_L$/L·B·D; from tables or data of similar ships, as function of block coefficient $C_B$ |
| 6. Deadweight $DWT$ | Weight of cargo, fuel, supplies etc |
| 7. Displacement Δ | $W_L+DWT$ |
| 8. Draft $T$ | $\Delta$, $L$, $B$, $C_B$ |
| 9. Other hull form coefficients namely: $C_M$, $C_P$, $C_{WP}$ | $C_B$, $F_n$ |

[a] Hold capacity BALE = required volume for bale cargo
[b] Hold capacity NET = required net volume for refrigerated cargo
[c] Number of standard containers TEU (8 × 8 × 20 ft) below deck (considering, however, also the number of above-deck containers)

In the frame of the assessment of the damage stability of passenger ships and ROPAX ships, which are typical volume carriers, the determination of the position of the watertight bulkheads as well as of their freeboard, is accomplished through compliance with relevant in-force damage stability regulations, as applicable to passenger ships in the region of ship operation; these are first the SOLAS 90 (SOLAS, Ch. II-1, Reg. 8) deterministic requirements; for ships sailing in territorial waters of the EU the compliance with the requirements of the so-called Stockholm Agreement (on top of SOLAS 90, accounting for 'water on car deck' effects) is required in addition. Relevant assessments of compliance with the above requirements must be done at an *as-early-as-possible stage* (already in the feasibility study) to avoid likely insurmountable problems in the design in subsequent stages.[19]

Some special provisions need also be taken into account in the design of RO-RO passenger ships and RO-RO ships in general: The required volume for the accommodation of passengers, of crew and of public spaces, of machinery room, and cargo hold spaces (for RO-RO: space for carried vehicles), can be estimated by use of the required area

- Per passenger; in dependence on accommodation quality
- Per vehicle; commonly expressed in length in metre of vehicle lanes of private cars and/or trucks

The allocation of spaces below and above the main deck, particularly in terms of volume and extent of the superstructures of passenger ships, is determined by the fundamental requirements resulting from the criterion of sufficient stability, particularly satisfaction of *intact stability criteria,* according to Regulation A.167; they greatly depend on lateral/shaded profile of the ship, which in turn affects the magnitude of forces/moments due to side waves and winds. The ship's intact stability is significantly influenced by the *B/D* ratio and height and extent of the superstructures; an early intact stability assessment can be made on the basis of information from similar vessels, as long as the extent of the superstructures is comparable (Fig. 1.57).

### 1.3.7.3 Linear-Dimension Ships

With at least one main dimension being fixed in terms of maximum permissible values, for example, the beam *B* from the passing limits of canals or by the dimensions of box-type cargo (containers), the preliminary design procedure for linear dimension ships does not differ from the ones outlined before for deadweight and volume carriers. However, attention should be paid when using comparative data for similar ships, because of the discontinuous change of main dimensions (e.g. by adding a

[19] In addition to the requirements of SOLAS90/Stockholm Agreement, the assessment of the damage stability of all passenger and ROPAX ships (built after January 1, 2009) needs to be also conducted by use of the harmonized probabilistic procedure of SOLAS (2009) (like for the dry cargo ships, IMO 2013b).

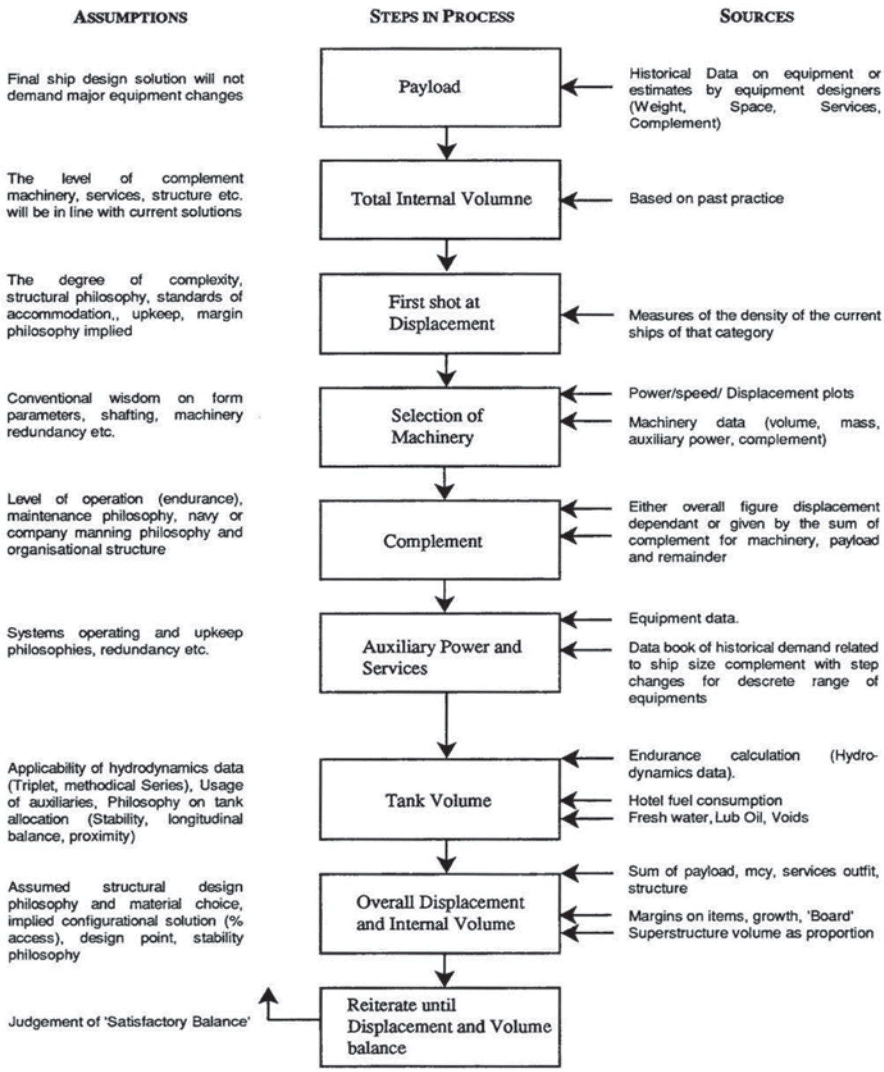



**Fig. 1.57** Iterative preliminary design procedure for volume carriers (Sen and Birmingham 1997)

row of containers or an additional lane of vehicles across for containerships respectively Ro-Ro ships) and the impact of the constraint dimension on the other ship characteristics; typical examples herein are the third-generation PANAMAX containerships (about 3,700 TEU), with their beam limited (Fig. 1.58) to 32.20 m, whereas their length reaches values of 245 m (excessive/nonoptimal length to beam ratio $L/B=7.61$).