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Design Procedure and Mathematical Models in the Concept Design of Tankers and Bulk Carriers

Original scientific paper

Paper presents design procedures and mathematical models applicable in initial design of merchant ships with high block coefficient. Special attention has been paid to two dominant ship`s groups: tankers and bulk carriers. Presented design procedure is common for both groups and it can be applied using various application techniques: from the simplest handy methods to the most sophisticated optimization methods and techniques. Presented mathematical model includes optimization of main ship characteristics as well as optimization of commertial effects of newbuildings. Mathematical models are based on designer´s long-time work experience. Large number of data has been derived from more than 150 executed designs and more than 40 ships built in *Shipyard Brodosplit*. Recommendations for execution of design are shown in number of pictures and diagrams. Presented design procedure and mathematical models have been applied in the multiattribute decision support optimization programme developed in *Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb*.

Keywords: *bulk-carrier, full hull forms, mathematical modelling, multiattribute approach, ship design, tanker*

Projektne procedure i matematički modeli u projektiranju brodova za tekuće i rasute terete

Izvorni znanstveni rad

U radu su razvijene projektne procedure i matematički modeli za osnivanje trgovačkih brodova pune forme. Posebna je pozornost posvećena dvjema dominantnim skupinama ovakvih brodova: brodovima za prijevoz rasutih tereta i brodovima za prijevoz tekućih tereta (tankerima). Izložena projektna procedura je zajednička za obje skupine i može se primijeniti u postupku osnivanja broda različitim metodama: od najjednostavnijih metoda priručnim alatima do suvremenih složenih optimizacijskih metoda i postupaka. Prezentirani matematički model osnivanja broda se zasniva na dugogodišnjem projektantovom iskustvu. Iz više od 150 izvedenih projekata i više od 40 izgrađenih novogradnji u *Brodogradilištu Brodosplit* je selektiran veliki broj podataka o brodovima. Zasnovano na tim podacima su dane preporuke i za projektiranje koje su prikazane slikama i dijagramima. Izložena projektna procedura i matemački modeli su primijenjeni u višeatributnom programu za sintezu projekta razvijenom na *Fakultetu strojarstva i brodogradnje* u Zagrebu.

Ključne riječi: *brodovi za prijevoz tekućih tereta, brodovi za prijevoz rasutih tereta, modeliranje, projektiranje broda, pune forme, višeatributni pristup*

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1 Introduction

Over years, the development of merchant ships has been directed to obtaining increasingly higher deadweights without increasing main dimensions of the ship or decreasing the ship speed. This trend, very often contradicting the designer's beliefs, is caused by commercial effects of the ship operation. To put it in simple words, full hull form of merchant ships with bigger deadweight brings higher profit to the shipping company. In view of that, there is a real competition going on in the design and building of ships with deadweights quite unimaginable until very recently. In order to achieve the targeted deadweight, the designer has at his disposal only two possibilities: to reduce the ship's light weight or to choose the full hull form with a high block coefficient.

This trend in the development of full hull form merchant ships, of bulk carriers and tankers in the first place, started in Japanese shipyards some thirty years ago. A few years later, Korean shipyards joined the Japanese ones, and then all other shipyards, which had been trying to be competitive in building these ships, joined them. The magnitude and power of the Far East shipyards have caused the development of own projects. While shipyards are building "mass-produced" newbuildings with minimal modification possibilities during the building process, a new generation of a “standard” design is being developed simultaneously. When completely developed, it will replace the one of the previous generation. These designs have reached the very frontiers of current technical knowledge; therefore they are made very difficult to compete with.

The ship design development in less powerful shipyards, including Croatian ones, is completely different from the Far East model. In order to accommodate the design to specific requirements of potential customers, it is defined on the level of conceptual and partially preliminary design before the shipbuilding contract is signed. The completion and detailed development of the design is postponed for the post-contract phase, so that they overlap with preparatory activities for the shipbuilding process, and very often with the building process itself.

In such a situation, designers have a very short time at their disposal. Basic design assumptions cannot be confirmed in the pre-contract phase; therefore, designers are forced to take some risk while developing their design. In order to minimize the risk, it is of vital importance to base the design in its conceptual and preliminary phases on quality design procedures and adequate mathematical models.

Therefore, the development of design methods and the application of modern optimization techniques in all phases of ship design have a major importance. Without a continuous development it is not possible to retain the position of one of leading countries in the modern ship design development, which is an indispensable precondition of further strengthening the position of Croatian shipyards at the world shipbuilding market growing ever so more competitive.

This goal can be achieved only by a continuous development and by sharing experience and ideas between all shipbuilding centres: shipyards, scientific and shipbuilding institutions. The purpose of this work is to give a modest contribution to the improvement of basic design and to the application of optimization procedures in the design of full hull form ships.

The basic aim of this paper is to give a systematic and comprehensive overview of the conceptual design of ships which dominate the world shipping fleet. The paper represents the design procedure of ships with a high block coefficient, primarily of modern bulk carriers and tankers. The presented design model can be applied to a wide variety of design tasks and with different working techniques.

The design procedure and mathematical models used for the design of full hull form merchant ships presented in this paper are based on a number of successful designs and nebuildings of the *Brodosplit* shipyard in the past fifteen years. The applied design procedure is built on and extends the so-far publicized design models [7, 8, 9, 10, 11, 12, 13, 14, 15].

In this paper at first are shortly described common basic features of full hull form merchant ships, i.e. of basic elements which have a dominant influence on the design procedure. It also gives a summary of reasons for choosing full hull form ships, of interrelations and cause-effect relations between particular influential factors and ship elements, as well as of solutions to basic problems.

The next section gives a classification of merchant ships with a high block coefficient, a list of particulars for two dominant groups of vessels, i.e. of bulk carriers and tankers.

The fourth section gives a detailed description and a more precise definition of specific problems encountered in the design of vessels belonging to these two groups, based upon published papers [14, 25, 26].

Bulk carriers are divided into two major groups: ore carriers and ships for the transport of light bulk cargo. Their typical cross-sections are given in the relevant figures and their main particulars are described. A short description of transported cargoes and the related problems is also given, together with basic factors determining the design of these ship types.

Tankers are divided into vessels for carriage of special liquid cargoes, vessels for carriage of liquid cargoes that need to be cooled down or heated to high temperatures, chemical carriers, crude oil carriers and oil product carriers. A short description of all groups is given. The figures represent typical cross-sections of dominant groups: crude oil tankers and product tankers for carriage of petroleum products and less hazardous chemical substances. A description of basic characteristics affecting the design of these vessels is given at the end of the section.

The fifth section deals with international legislation and requirements of classification societies, which refer to the relevant ship types [1, 2, 3, 4, 5, 6]. The SOLAS rules defining requirements regarding bulkheads and stability are given in a short overview, as well as the basic MARPOL rules referring to the tanker cargo space configuration and stability requirements, the ICLL rules used for the calculation of the minimum freeboard and the basic classification society requirements affecting the basic ship structure. In addition, rules and constraints of the three most important canals, i.e. the Suez Canal, the Panama Canal and the St. Lawrence Canal, are briefly outlined.

The next section represents in detail the mathematical models for the design of full hull form merchant ships. Basic input data and their classification are defined. In addition, criteria which can greatly affect the choice of optimum design are listed and explained. The author represents his subjective designer’s suggestions and constraints through graphical representations. He also represents his data bases for particular ship types and sizes, gathered from his own experience, to be used as an auxiliary means in the calculation of particular groups significantly affecting the total weight of the ship.

The final section gives conclusive considerations of this work. The applied procedure is commented on and compared with traditional design methods. Possible advantages of the applied procedure in daily shipbuilding practice are described and, finally, suggestions for further development and improvement of the presented methodology are given.

2 Main Characteristics of Full Hull Form Merchant Ships

Main characteristics of full hull form merchant ships feature the following: a high block coefficient (C_B), generally ranging from more than 0.80 to the highest value of 0.89; moderate speeds characterized by the Froude numbers from 0.15 to 0.20; heavy wake fields in the plane of propeller operation; a higher degree of risk due to flow separation around the propeller; a high ratio of cargo holds volume to the total volume of the ship; moderate power of main engines; short engine rooms with adverse effects on the design of propulsion system; and finally, high efficiency in service. The latter of the listed characteristics is a dominant feature which is the cause of continuous efforts focused on improving and perfecting technical solutions of all other features and related problems.

Full hull forms are characterized by a heavy wake field in the plane of propeller operation, i.e. a high wake. This problem is being alleviated by the development of new generations of hull forms which are intended to improve the wake field and to maintain the value of the full hull form block coefficient at the same time [9, 10, 11, 12].

The present hull forms have a pronounced aft bulb, i.e. U-shaped stern lines (gondola). This bulb form results in a slight deceleration of the mean wake, resulting in a more uniform wakefield, and, consequently, easier and more efficient performance of the ship's propeller. Naturally, there are some undesired side effects, such as the lack of space in the engine room, poor seakeeping in following waves, and more complex hull structures for the stern.

At present, full hull form merchant ships are predominantly bulk carriers and liquid cargo carriers (tankers). Both ship types have similar hull forms, but tankers, as freighters of a higher quality (more expensive) cargo, can reach a bit higher speeds, i.e. higher Froud numbers. Although these two ship types are completely different with respect to the type of the cargo, general ship configuration and relevant regulations, they do have some common characteristics [14, 25, 26].

Both ship types need cargo holds/tanks with high cubic capacity. Also, in most cases, the main dimensions of the ship are limited by their particular route, e.g. the St Lawrence Seaway, the Panama Canal, the Suez Canal or some ports. Despite distinct differences in their structure, the longitudinal strength and the structure of both ship types depend on the same loading conditions.

The characteristics and design problems related to the full hull form ships discussed above are just a consequence of their high commercial value in service. A comparison of previous generations of standard size ships with the present projects shows clearly a trend towards the development of increasingly fuller hull forms. A question remains where the ultimate limits are and how they can be reached.

3 Classification of Full Hull Form Merchant Ships

There are two major groups among full hull form merchant ships: bulk carriers and tankers.

High block coefficient ship forms are applied to some specific designs of merchant ships intended for other purposes (in cases when main dimensions are strictly limited, and the speed requirement is not of major importance) and to specialized vessels (e.g. draggers). As these ships have a small share in the world fleet, and have very few common characteristics, only two prevailing groups will be considered:

- bulk carriers, and
- tankers.

Bulk carriers have the following main characteristics:

- high block coefficient,
- moderate speed,
- one (main) deck,
- high cubic capacity of cargo holds (with the exception of ore carriers),
- short engine rooms and peaks,
- accommodation and engine room positioned aft,
- minimum/reduced freeboard,
- vertically corrugated transverse bulkheads (only in rare cases double-plated bulkheads),
- large hatches (the width of hatches is equal to or greater than the half beam),
- specific cross-section with double-bottom, bilge and wing tanks (requirements for double side are expected to be regulated).

The main characteristics of tankers are as follows:

- high block coefficient,
- slightly higher speed,
- one (main) deck,
- high cubic capacity of cargo tanks,
- short engine rooms and peaks,
- accommodation and engine room positioned aft,
- freeboard exceeding minimum requirements,
- plane or corrugated bulkheads in cargo holds (depending on the ship size and the "quality" of the cargo),
- deck structures below or above the deck (depending on the ship size and the "quality" of the cargo),
- cross-section with double bottom and double sides.

4 Specific Design Characteristics of Particular Ship Types

The presented classification of bulk carriers and tankers and specific design characteristics of these ship types are based on the author's design experience and relevant literature [14,25,26].

4.1 Design of bulk carriers

Modern bulk carriers can be generally divided into two main groups:

- ore carriers for the transport of ore and other heavy dry bulk cargo;
- ships for the transport of light bulk cargo (grains, light ores).

The former group of ships is characterized by high density of the intended cargo, hence by a narrow specialization. The required cargo holds capacity is relatively small in relation to the cargo mass. Therefore, satisfying the requirement of the minimum volume of buoyancy entails ballast tanks of a large volume. Generally, it is sufficient to satisfy the requirement of reduced minimum freeboard. High specific cargo mass is the cause of a low centre of gravity in loaded condition, i.e. "over stable" ship with a stiff ship behaviour on waves. Accelerations occurring in such conditions are inadequate for a long-term quality accommodation of the ship's crew and for neat operation and good maintenance of particular ship's equipment. This problem is dealt with by lifting the cargo position.

Considering the problems stated above, there are two possible solutions: increasing the height of double bottom above the required minimum (either by regulations of classification societies, by conditions for the ballast tanks minimum volume or by results of ship structure optimization) and/or adaptation of the cargo holds geometry with sloped longitudinal bulkheads. Since these vessels have a very narrow specialization, there are not many of them and they usually have high deadweight (capsize). A typical cross-section of an ore carrier is given in Figure 1. Considering the problems stated above, there are two possible solutions: increasing the height of double bottom above the required minimum (either by regulations of classification societies, by conditions for the ballast tanks minimum volume or by results of ship structure optimization) and/or adaptation of the cargo holds geometry, i.e. by sloping longitudinal bulkheads. Since these vessels are highly specialized, they represent a smaller number of bulk carriers and are of large sizes (Capsize ore carriers). A typical cross-section of an ore carrier is given in Figure 1.

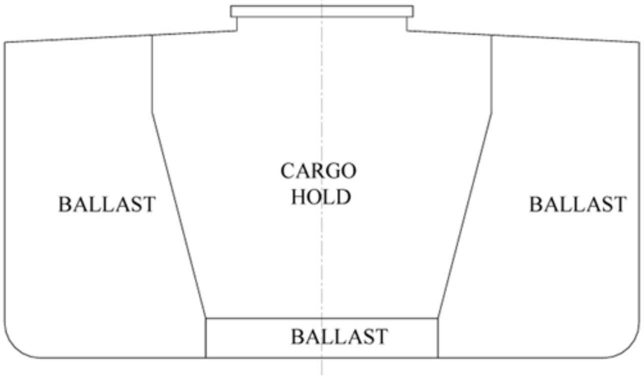


Figure 1 **Typical cross-section of an ore carrier**
Slika 1 **Tipični poprečni presjek broda za prijevoz rudače**

The ships usually called "bulkers" or bulk carriers belong to the latter group in the previously represented classification. They are greater in number than ore carriers, more universal and their exploitation for the transportation of various bulk cargoes, or even general cargo, is economically feasible.

Although the large capacity of their cargo holds enables them to transport relatively light cargoes at the scantling draught (cargo density of approximately 0.8 kg/m^3), modern "bulkers" can also transport very heavy cargoes. In such cases, the ship is alternatively loaded into particular, specially strengthened holds. Alternative loading is carried out into odd holds, i.e. holds number 1, 3 and 5 for "handy" size, 1, 3, 5 and 7 for "laker" and "panamax" size, and 1, 3, 5, 7 and 9 for "cape" size.

When loading very light cargos, especially timber, the cargo holds capacity is not sufficient for loading the ship up to its maximum draught. In that case, the cargo is also loaded onto the open deck. The cargo on the deck is secured by special deck equipment. This loading condition is specially considered in the calculation of minimum freeboard.

These ships can also transport packed cargo. Until recently, the most common requirement was the transport of containers on the open deck or in cargo holds. In those cases, ships were additionally equipped by fixed and portable equipment for cargo fastening. This loading condition does not greatly affect the ship design as it represents only a possibility of carriage of an additional cargo type. The only thing to be dealt with is to adapt the geometry of cargo hatches to the standard container dimensions, and possibly to maximize the number of containers by adapting the beam and depth of the ship, as well as by the general arrangement of the main deck.

Recently, there have been requirements for the transport of semi finished steel products (steel coils, mostly). Such cargos do not greatly affect the ship design in the initial phase, but they affect the later phase of ship steel structure dimensioning (inner bottom plating) and loading condition calculation (packed cargo with a great number of possible position variations).

Bulk carriers are characterized by minimum capacity of ballast tanks. While sailing in a light ballast condition, it is important to achieve the aft draught which enables minimum immersion of the ship propeller and its cavitation-free operation, and the fore draught to avoid slamming in most cases. Safe sailing on heavy seas and the minimum draught for passing through the Panama Canal are obtained by ballasting one or more cargo holds. To enable that, it is necessary to design and construct a cargo hold and a hatch cover for that particular loading condition, and to equip it with devices for the ballast loading/unloading.

The design of bulk carriers is commonly characterized by the following:

a) standard size:
  - lake freighters or lakers –ships that can sail the Great Lakes;
  - Handy and Handymax vessels of 35,000-40,000 dwt or over 50,000 dwt, respectively, with a limited beam to be able to pass through the Panama Canal, and, with the maximum draught of up to 40 feet (12.2 m);
  - Panamax vessels that can pass through the Panama Canal, and, in most cases, with the length over all limited to only 225 m;
  - Capesize vessels – the biggest vessels for carriage of bulk cargo, deadweight of approximately 170,000 dwt;
b) large volume of cargo holds;
c) general configuration with 5 to 9 cargo holds (depending on the size of the vessel);
d) reduced freeboard (B-60);
e) moderate speed (generally 14.5 to 15 knots in the trial sailing conditions and at the design draught);
f) the use of high tensile steel;
g) typical cross-section represented in the following figure.

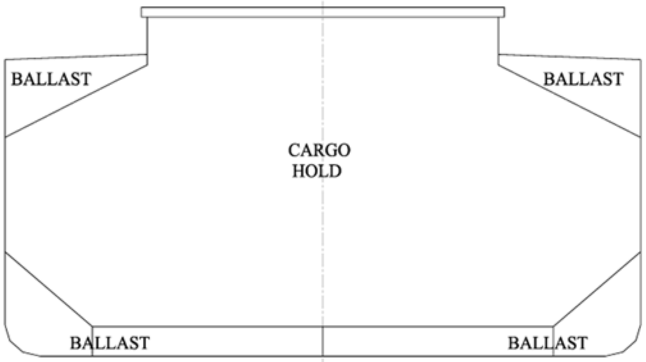


Figure 2 **Typical cross-section of a bulk carrier**
Slika 2 **Tipični poprečni presjek broda za prijevoz rasutih tereta**

The cross-section is characterized by a low double bottom – of the minimum height required by regulations of classification societies or slightly higher (in case it is required by technological causes or as a consequence of optimization of the double bottom structure). The inclination of bilge tanks is usually set at an angle of 40^o, which enables efficient cargo unloading, as well as the structural design of aft cargo hold end (stern frames in this area of the ship are rather "sloped"). In some designs, the inclination is at smaller angles, which makes the design of the stern structure easier, but increases the frame span.

The geometry of topside tanks is determined by the deck hatch width and the angle of rise of the tank bottom. This angle is set at approximately 30°, which satisfies the condition of normal loading of most cargoes (angle of repose of bulk cargoes).

In the design of modern "bulkers", the requirement for a great width of cargo hatches is very important, in the first place because of easier cargo manipulation and handling. Hatch widths range from the values slightly lower than the half beam of the ship with side rolling hatch covers to 55-60% of the ship beam with end folding hatch covers. This situation entails a more complex solution of the deck framing.

4.2 Design of Tankers

Tankers may be generally divided into the following groups:

- ships for carriage of special liquid cargoes (water carriers, tankers for carriage of natural juices and oils, ships for carriage of urea, etc.);
- ships for carriage of liquid cargoes that need to be cooled down or heated to high temperatures;
- chemical carriers;
- crude oil carriers and oil product carriers.

The first group comprises highly specialized ships with their basic particulars and designs are strictly determined by the properties of the cargo they carry. In the total number of tankers in the world fleet, they represent only a very small group. Due to their special features, they can be considered as special purpose ships; therefore this group will not be dealt with in this paper.

Tankers for carriage of liquid cargoes that need to be cooled down or heated to high temperatures have a common property that their tanks are subjected to high thermal delatations due to a big difference in the temperature of the cargo and of the environment. This group incorporates liquefied natural gas vessels (LNG tankers), liquefied petroleum gas vessels (LPG tankers) and vessels for carriage of liquid cargoes heated to very high temperatures (e.g. asphalt carriers).

Cargo tanks can be structural and non-structural. In the case of structural cargo tanks, the ship structure is separated by multi-layer insulation from the cargo. In the other case, non-structural cargo tanks are connected with the ship structure by special foundations which allow thermal dilatations of cargo tanks and insulate the ship structure from the tanks. This group is a very important group of tankers which require special design. As they are not characterized by high block coefficients and moderate speeds, they will not to be considered in this paper.

Chemical tankers are characterized by a large number of cargo holds and cargo segregations, high double bottoms and wider double sides, and in some cases, by the use of stainless steel for the construction of cargo tanks. As these tankers pose great danger to the environment due to the nature of their cargo, there are numerous rules and regulations pertaining to their design and building. They have some common characteristics with oil product carriers, so design models of such tankers can be applied to chemical tankers, provided some necessary changes are made.

The fourth and dominant group are crude oil tankers and oil product tankers having the common feature of high capacity cargo tanks. Crude oil tankers have slightly smaller capacity of their cargo tanks (the density of the cargo at the maximum draught is about 0.9 t/m^3). Product tankers are designed to have larger relative volume of cargo tanks (the usual density of the cargo at the maximum draught is approximately 0.8 t/m^3).

Crude oil tankers are vessels of larger sizes (from the „panamax" size upwards), usually with three cargo segregations and cargo pumps driven by steam turbines. Cargo tank bulkheads are usually of plane type.

Product tankers are vessels of smaller dimensions (usually up to the panamax or postpanamax dimensions), with a larger number of segregations and the cargo piping system with pumps driven by steam turbines or with deep-well pumps (driven by either hydraulic or electric motors). Corrugated bulkheads are often used in cargo tanks, and in some cases the deck framing is constructed above the deck. Thus, extreme cleanliness of cargo tanks is obtained, but also the right solution for the ship structure is made more difficult to find.

The usual configuration of tankers comprises a double bottom, double skin and a centreline longitudinal bulkhead. The largest tankers, i.e. VLCCs, have two centreline longitudinal bulkheads. The minimum double bottom height and the double skin thickness are determined by international regulations. By satisfying these regulations, sufficient capacity of ballast tanks is obtained and thus the MARPOL requirement of minimum draught is met in almost all cases. Only the largest tankers of suezmax and VLCC sizes have double bottoms and double skins with dimensions exceeding the required minimum. Typical cross-sections of an oil tanker and an oil product tanker are given in the following figures.

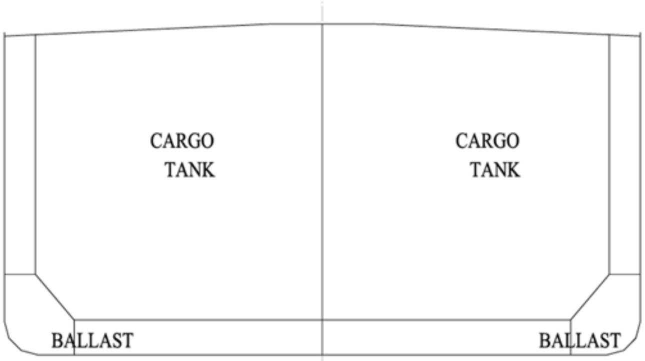
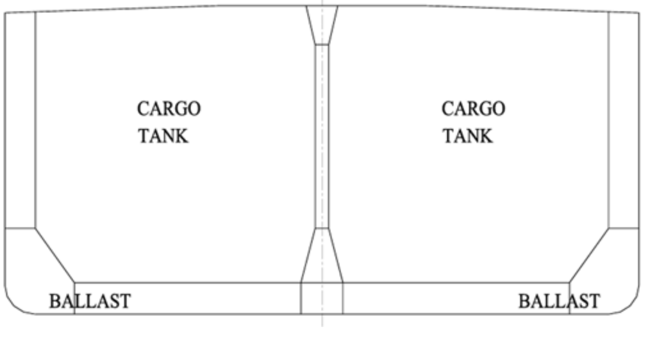


Figure 3 **Typical cross-section of a crude oil tanker**
Slika 3 **Tipični poprečni presjek tankera za prijevoz sirove nafte**

Figure 4 **Typical cross-section of a product tanker**
Slika 4 **Tipični poprečni presjek tankera za prijevoz naftnih derivata**



Basic conditions influencing the design process of tankers are as follows:

a) standard size with dominant groups:
    - Handy size group – tankers of 45,000 – 50,000 dwt, generally with the L_{oa} of up to 600 ft (182.88 m), the beam limited by the ability to pass through the Panama Canal and the maximum draught of up to 40 ft (12.2 m);
    - Panamax size group – tankers with the ability to pass through the Panama Canal, and in most cases with the L_{oa} limited to 750 ft (228.6 m);
    - Aframax size group - tankers of approximately 110,000 dwt at the maximum draught, and with the design draught, in most cases, of 40 ft (12.2 m);
    - Suezmax size group – tankers of 150,000 – 170,000 dwt, (named after the Suez Canal limitations which were in force by mid-2001);
    - VLCC size group – very large crude oil tankers (of approximately 300,000 dwt);

b) high capacity of cargo tanks;

c) general configuration with a double bottom, one or two longitudinal bulkheads, five or more pairs of cargo tanks, a pair of slop tanks and a pump room (for the cargo and ballast, or only for ballast);

d) the speed in most cases from 15.5 to16 knots in the trial sailing conditions and at the design draught;

e) the use of high tensile steel.

5 International Regulations and Requirements of Classification Societies

A great number of regulations cover the area of ship design, construction and exploitation. This section will deal with the most important rules and regulations which affect the design of tankers and bulk carriers to a great degree. These rules and regulations may be classified as follows:

- rules and regulations imposed by the International Maritime Organization (IMO): the International Convention for the Safety of Life at Sea (SOLAS), the International Convention for the Prevention of Pollution from Ships (MARPOL) and the International Convention on Load Lines (ICLL);
- rules of classification societies for the building of ships (the new harmonized IACS Common Structural Rules for tankers and bulk carriers);
- rules for sailing through canals.

5.1 Rules and Regulations Formulated by the International Maritime Organization

The SOLAS Convention [1] specifies minimum standards for the construction, equipment and operation of ships, compatible with their safety. The part of the Convention dealing with rules for subdivision and stability is the most interesting part for the initial design phase (Chapter II-1 Construction - Structure, subdivision and stability, machinery and electrical installations). It refers, in the first place, to the probabilistic calculation of the ship stability in damaged condition (Part B-1 - Subdivision and damage stability of cargo ships).

As the probabilistic calculation is very complex, it will not be dealt with in detail in this paper. Basically, it sets a great number of calculations related to the damage stability of the ship in various conditions of flooding. The effect of each condition of flooding on the overall quality of the damaged ship stability is weighted by the degree of probability that such damage should occur. The basic requirements and definitions are presented in Appendix A1.

The MARPOL Convention [2] comprises a set of rules which deal with the prevention of operational pollution. Requirements and rules dealing with the parameters to be taken into consideration in the design of a tanker are grouped in two chapters dealing with the tanker geometry and stability: Chapter II - Requirements for control of operational pollution and Chapter III - Requirements for minimizing oil pollution from oil tankers due to side and bottom damages. Because of the fact that rules are written and set in order by their time of adoptance, their usage during the design procedure can be uncomfortable. That is the reason to expound the most important rules in the Appendix A2 in order of their appeareance in the design procedure.

The ICLL Convention (1966) with its amendments [3] gives a definition of the minimum freeboard calculation for all ship types except for warships, yachts, ships of the length less than 24 m, existing ships of less than 150 GT and fishing vessels.

As the effect of all influential factors (block coefficient, depth, freeboard and trunk deck, camber, sheer, dimensions of forecastle and poop, etc.) are considered in the calculation, it is not possible to describe the calculation in detail here. Attention will be focused only on the definition of ship types with respect to their assigned freeboard (Chapter III, Regulation 27). Ships are generally divided into two ship types:

- type “A” – ships designed to carry only liquid cargoes in bulk (tankers), having cargo tanks with only small access openings closed by watertight gasketed covers;
- type “B” – all other ships.

Due to their design characteristics, the survival of tankers after flooding is of better quality than it is the case with other vessels. This is the reason why the minimum required freeboard is lower in type “A” vessels than that in type “B”. Type “B” vessels can be assigned a lower freeboard than the calculated one – the type “B” reduced freeboard (usually, there is a difference of up to 60% between type “B” and type “A” freeboards if all conditions of the ship survival in the conditions of flooding defined in the convention are met).

5.2 Rules of Classification Societies for Ship Construction

A large number of classification societies are authorized to work in maritime countries with a tradition in shipbuilding all over the world. Their primary functions are to lay down requirements for the ship construction, survey of ships during the processes of building and exploitation, as well as to improve the level of ship quality and safety by developing the engineering, technological and scientific knowledge which can be applied to shipbuilding and shipping industry.

The most prominent classification societies are members of the International Association of Classification Societies (IACS). The purpose of such an association is to share experience and data, to develop better rules for ship construction and to adjust and unify rules of all the members. IACS developed new, uniform rules for the construction of particular ship types, e.g. uniform rules for the construction of bulk carriers.

For the same purpose, the biggest classification societies in the world (*Lloyd's Register of Shipping, American Bureau of Shipping* and *Det Norske Veritas*) have coordinated their joint efforts in issuing new, common rules for the construction of tankers, and Bureau Veritas and some other classification societies have done the same for the construction of bulk carriers (*Croatian Register of Shipping* developed new set of rules and programme CREST). New rules came into force in mid-2006.

In the ship design phase, the choice of a classification society is not of vital importance for the design model. Experience can lead to a conclusion on the influence of a classification society on the own mass of a particular ship type and size, but this influence can almost be neglected. Rules of classification societies have a more considerable influence on the ship design through their requirements regarding the general configuration of the ship. Special attention should be paid to the requirements presented in Appendix A3.

5.3 Regulations for Sailing Through Canals

There are a great number of canals and sea and river passageways where only vessels of limited dimensions can sail. Only three most important canals and their restrictions regarding sailing will be briefly dealt with here: St. Lawrence Seaway, the Panama Canal and the Suez Canal.

5.3.1 St. Lawrence Seaway

Rules for sailing are published in [4]. In ship design, the following rules and restrictions have to be taken into consideration:

- maximum length overall - 222.5 m;
- extreme breadth - 23.8 m;
- maximum draught - 7.92 m;
- maximum air draught - 35.5 m.

5.3.2 Panama Canal

Rules for sailing are defined in [5]. Restrictions and requirement to be met by tankers and bulk carriers are as follows:

- maximum length overall - 289.6 m;
- extreme breadth - 32.31 m;
- maximum draught - 12.04 m, provided that the minimum bilge radius is 1.79 m (in tropical fresh water with a density of 0.9954 kg/m^3);
- maximum air draught - 57.91 m;
- minimum draughts in sea water are defined as follows:

Table 1 **Panama Canal minimum draughts requirements**
Tablica 1 **Ograničenja izmjera broda za prolaz Panamskim kanalom**

for the ship's length exceeding (m)	draught forward (m)	draught aft (m)
129.54	2.44	4.30
144.80	5.50	6.10
160.02	6.10	6.71
176.80	6.71	7.32
190.50	7.32	7.93

The minimum draught requirement for passing through the Panama Canal is important because it is stricter than the previously stated MARPOL requirement, thus making it a major parameter in determining the minimum capacity of water ballast tanks. In the case of bulk carriers, the problem is solved by loading the ballast into a cargo tank intended for that purpose.

5.3.3 Suez Canal

Rules for sailing through the Suez Canal are published in [6]. Vessels with the breadth of up to 49.98 m (164 ft) may sail through the canal at the draught of up to 18.89 m (62 ft). Vessels with the breadth exceeding 49.98 m have the maximum draught defined in the table where the ratios between the ship's breadth and draught are given. The following table is taken from the rules.

Table 2 **Ship dimensions for passing through the Suez Canal (excerpt)**
Tablica 2 **Ograničenja izmjera broda za prolaz Sueskim kanalom (izvaci)**

Breadth (m)	Draught (m)	Breadth (m)	Draught (m)	Breadth (m)	Draught (m)
49.98	18.89	56.33	16.76	64.46	14.65
50.80	18.59	57.37	16.46	65.83	14.32
51.66	18.28	58.47	16.15	67.38	14.02
52.52	17.98	59.58	15.85	68.88	13.72
53.44	17.68	60.75	15.54	70.43	13.41
54.38	17.37	61.97	15.24	75.59	12.50
54.34	17.07	63.24	14.93	77.49	12.19

The product of breadths given in the table above and the appropriate draughts gives a constant value of approximately 944.5 m^2, which shows that the limiting value for the passing through the canal is the area of the cross-section of the ship.

One can conclude from Table 2 that all ships of all sizes, except VLCCs, can freely pass through the Suez Canal. Modern VLCC tankers usually have the deadweight of 300,000 tons, the breadth of approximately 60 metres, and the maximum draught is in the range of 20-22 metres. Their permissible draught for passing through the canal is approximately 15.7-15.8 metres, which means that they can pass through the canal with slightly more than 200,000 dwt.

6 Mathematical Models of Full Hull Form of Merchant Ship Design

Mathematical definition of the previously described design procedure is dealt with in [7, 8, 13, 15]. The mathematical model follows the steps of the procedure and, in the course of the process, defines the values required for obtaining final results.

Following the logic of the general design procedure, the mathematical model can be presented in the following way:

6.1 Definition of the Design Task

6.1.1 Design Variables and Parameters

Design variables and parameters are as follows:

a) Main dimensions:
  - length between perpendiculars L_{pp} (m),
  - breadth B (m),
  - scantling draught d_s (m),
  - block coefficient C_B (-);

b) Main engine identifier I_{ME},

c) Design tasks to be fulfilled within defined margins are:
  - deadweight DW (t),
  - capacity of cargo holds (tanks) V_{car} (m^3),
  - required trial speed v_{tr} (kn) (in most cases, defined for the trial sailing conditions at the design draught).

d) Specific voluminosity of the ship $\kappa = V_{car} / (L_{pp}\, B\, D)$ - depends primarily on the ship type and size. It provides the ratio of the "net used ship's volume", i.e. of the cargo space volume and the "maximum volume" determined by the product of three main dimensions. Ships with smaller engine rooms, ballast tanks and other under deck spaces have a higher specific voluminosity (that is why bulk carriers usually have higher voluminosity than tankers). The size of the ship also affects the value of this parameter (as a rule, a larger vessel has higher specific voluminosity). In addition, the value of this parameter is affected by the value of block coefficient.

e) The factor defining the influence of the high tensile steel use on the reduction of the steel structure mass is given as a percentage of the estimated reduction with respect to the ship structure completely built of mild steel. The maximum value of mass savings (when high strength steel is used to a high degree) is up to 15%.

f) Maximum power of particular main engines MCR_i that can be selected as the main engine. While selecting the main engine, special attention must be paid not only to maximum power which can be obtained, but also to the associated nominal revolutions and to the general configuration of the engine.

g) Data required for the calculation of costs of material comprise:
  - costs of feasible main engines C_{MEi},
  - average unit costs of steel c_{st},
  - other costs, comprising costs of other materials and equipment, C_{oc}.

h) Data required for the calculation of costs of labour:
  - shipyard productivity P_{cGT},
  - unit hourly wage V_L,
  - other costs C_{oc}.

6.1.2 Design constraints

Design constraints may be defined by minimum and maximum values of basic design variables or by maximum values of ratios between basic design variables.

a) Min-max values of basic design variables (main dimensions of the ship) are as follows:
  - min-max length between perpendiculars: $L_{pp\,min}$, $L_{pp\,max}$;
  - min-max breadth: B_{min}, B_{max};
  - min-max scantling draught: $d_{s\,min}$, $d_{s\,max}$;
  - min-max block coefficient: $C_{B\,min}$, $C_{B\,max}$.

Maximum values of main dimensions are most often limited by constraints of shipyard technological capabilities of building a ship, by rules and regulations of international legislation or by shipowner's requirements.

Minimum values of main dimensions are generally given empirically as the area bounds below which an acceptable design solution cannot be expected.

Minimum and maximum values of block coefficient are also, in most cases, empirical data. The minimum value of block coefficient is given as an empirical data below which an acceptable design solution cannot be expected, and it has no major importance in defining design constraints. The main problem is to determine the maximum value of block coefficient at a level which will not deteriorate the quality of optimum design solution, and which will enable a quality design of hull form.

Defining maximum values of block coefficient is a complex task which depends on several parameters: length/breadth ratio, breadth/draught ratio, fore body shape and fore bulb size, bilge radius, aft body shape, etc. All these ratios cannot be considered at the initial design stage, and only two dominant ratios, i.e. L_{pp}/B and B/d_s, are in the focus of the designer's attention.

The length/breadth ratio affects the maximum value of block coefficient in the way that higher values of this ratio enable higher values of block coefficient. This can be easily explained by the example of increase in the length of parallel middle body on the existing hull form: both L_{pp}/B and C_B increase.

The breadth/scantling draught ratio affects the block coefficient in the opposite way, i.e. the higher B/d_s, the lower is the achievable value of block coefficient. It can also be easily explained by the fact that C_B increases with deeper immersion of the ship (due to an increase in the waterplane coefficient); due to an increase in draught, the B/d_s ratio decreases.

Recommended maximum values of block coefficient presented in Figure 5 are based on the author's experience and on the latest generation of hull forms developed in *Brodosplit* [9,10,11,12]. It is also important to note that design solutions at the very maximum value of block coefficient should be avoided unless it is an imperative.

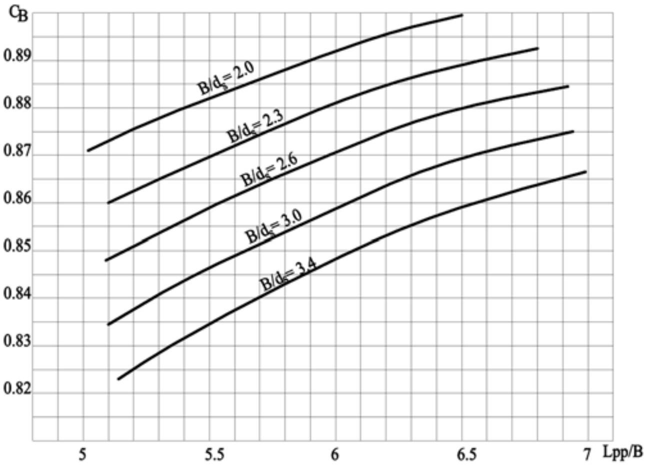


Figure 5 **Recommended maximum values of block coefficient**
Slika 5 **Preporučene maksimalne vrijednosti koeficijenta punoće**

b) Extreme values of ratios between basic design variables incorporate the following empirical or design constraints:
  - min-max length/breadth ratios: $(L_{pp}/B)_{min}$, $(L_{pp}/B)_{max}$;
  - min-max length/scantling draught ratios: $(L_{pp}/d_s)_{min}$, $(L_{pp}/d_s)_{max}$;
  - min-max breadth/scantling draught ratios: $(B/d_s)_{min}$, $(B/d_s)_{max}$;
  - min-max length/depth ratios: $(L_{pp}/D)_{min}$, $(L_{pp}/D)_{max}$.

Design constraints are based on the design experience. Recommended values of constraints vary depending on the ship size and type. They should usually be in the following ranges:

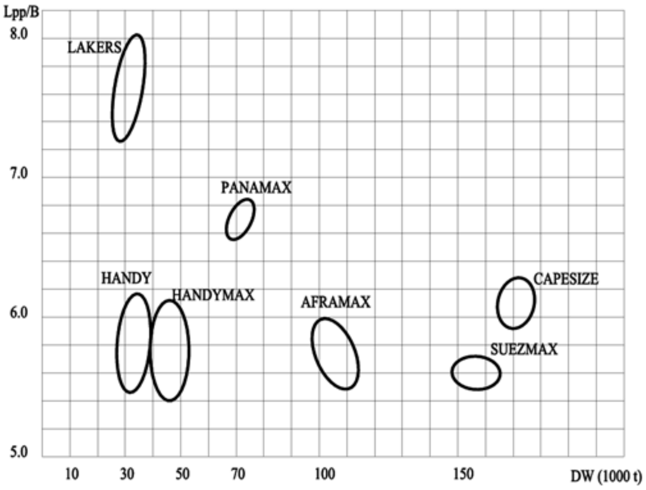


Figure 6 **Recommended constraints on the L_{pp}/B ratio**
Slika 6 **Preporučena ograničenja odnosa L_{pp}/B**

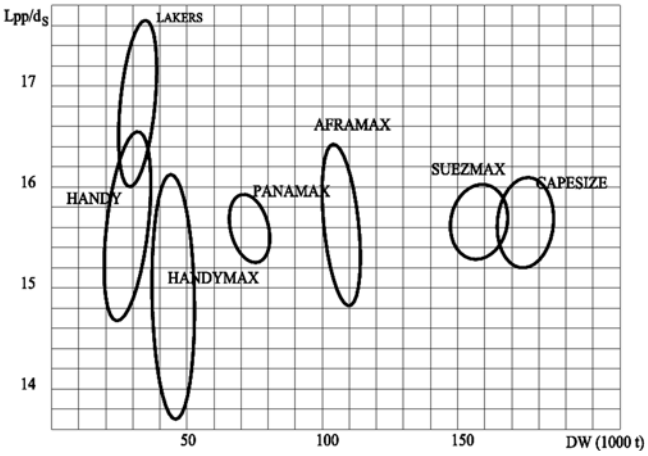
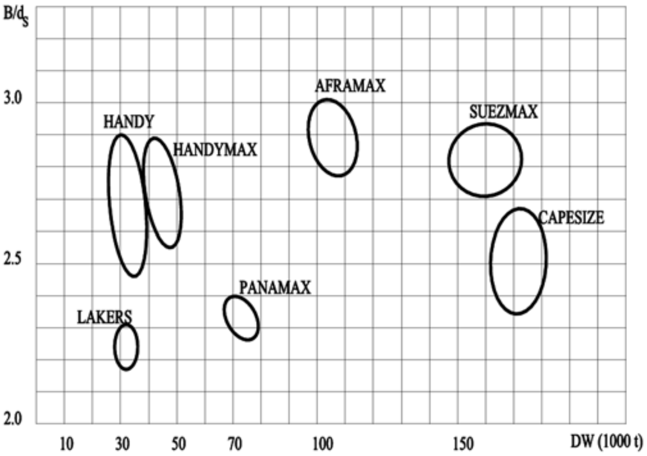


Figure 7 **Recommended constraints on the L_{pp}/d_s ratio**
Slika 7 **Preporučena ograničenja odnosa L_{pp}/d_s**

Figure 8 **Recommended constraints on the B/d_s ratio**
Slika 8 **Preporučena ograničenja odnosa B/d_s**



$$\begin{aligned} 5.0 &\le (L_{pp}/B) \le 8.0 \\ 14.0 &\le (L_{pp}/d_s) \le 18.0 \\ 2.2 &\le (B/d_s) \le 3.3 \\ 9.5 &\le (L_{pp}/D) \le 13.0 \end{aligned} \qquad (6.1)$$

Recommendations for defining design constraints are given in Figures 6, 7, 8 and 9. These recommendations are based on some sixty designs made in the several past years in *Brodosplit* and should be used only as guidelines.

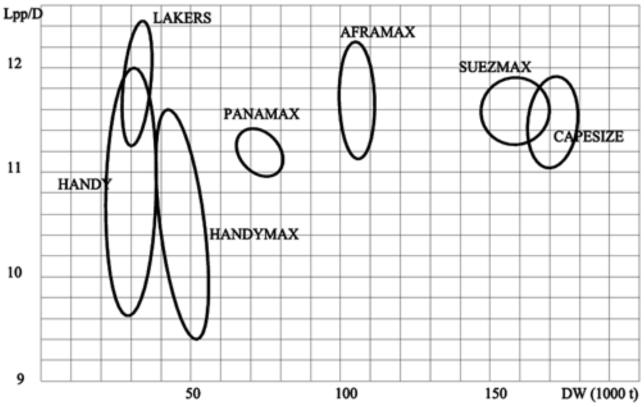


Figure 9 **Recommended constraints on the L_{pp}/D ratio**
Slika 9 **Preporučena ograničenja odnosa L_{pp}/D**

6.1.3 Dependent design properties (attributes)

Dependent design properties (attributes) described in the following sections are the properties whose values depend on input values (design variables and parameters).

a) Weight of the steel structure W_{st} (t) depends on the main dimensions, type and size of the ship. The steel structure weight is also affected by specific features of a particular design (size of the superstructure, ice class, forecastle, poop, etc.).
b) Cost of material (US \$) depend on the total costs of steel, costs of the selected main engine, and on other costs related to materials.
c) Cost of labour (process) (US \$) is calculated from the total volume of the ship, complexity of the ship, unit hourly wage and the shipyard productivity.
d) Cost of a ship (US \$) is a sum of costs of material, costs of labour and other costs.
e) Obtained deadweight DW (t) depends on the ship's main dimensions and its light weight.
f) Obtained cargo space volume V_{car} (m^3) depends on main dimensions and a given "specific voluminosity" of the ship.
g) Obtained trial speed v_{tr} (kn) depends on the ship's main dimensions and propeller revolutions.

6.1.4 Design objectives

In the design of tankers and bulk carriers, possible design objectives can be defined:

a) Minimizing the weight of steel structure

The design objective of minimum weight of steel structure is particularly interesting in the light of a tendency to minimize the weight of the steel used (the criterion of minimum weight of light ship is very similar to that since the weight of steel structure in the total weight of the ship is a dominant element). Depending on the type and size of the ship, the share of steel may reach up to 30% of the total costs.

b) Minimizing the main engine power

The main engine is the most expensive item in the ship's equipment and its share in the total costs of a ship can be up to 15%. Hence, minimizing the main engine power is of great importance. Also, attention should be paid to the fact that the maximal power (and costs) of potential main engines rises steeply with each increase in the number of cylinders; the same applies to the type of the selected main engine. Therefore, this design objective is of major importance, and the targeted main engine should be used to its maximal power.

c) Minimizing the cost of material built into a ship

When minimal costs of material required to build a ship are concerned, there are two dominant values – costs of main engine and costs of steel. The costs of other material and ship's equipment embody a large number of small items which cannot be correlated with the basic characteristics of the ship at this design stage; therefore, the amount of these costs can be considered as a constant.

d) Minimizing the cost of labour (process)

In some cases it is of importance to minimize the costs of labour (process). This refers primarily to the situations when there is a shortage of skilled workforce at the market so that a possibility of optimizing the design towards this design objective has to be considered.

e) Minimizing the cost of newbuilding

For the shipyard, this is a dominant design objective. Although it is very important to meet all design requirements, minimizing the costs of newbuilding is of major importance for the shipbuilder. This results in the most favourable commercial effects for the contracted design and the total costs of a ship.

f) Minimizing the own mass of the ship

The design objective of minimum own mass of the ship is particularly interesting in the situation when the main dimensions of the ship are strongly limited. In these cases is possible to reach requested deadweight only in the way of minimizing the own mass of the ship.

g) Maximizing the stability

This objective is very important when ship is carrying significant amount of deck cargo.

h) Maximizing the speed

In some cases maximazing the ship's speed can be of the great interest for Shipyard and/or Shipowner. Maximazing the speed can also appear in the form of minimazing the ship's resistance (when the main engine is hardly reaching needed power).

6.2 Varying the Design Variables and Checking the Design Constraints

Main dimensions (length between perpendiculars L_{pp}, breadth B, scantling draught d_s, and block coefficient C_B) are varied between their minimum and maximum values in appropriate steps:

- step of length between perpendiculars $L_{pp\ step}$,
- step of breadth B_{step},
- step of scantling draught $d_{s\ step}$,
- step of block coefficient $C_{B\ step}$.

In determining the values of respective steps, due attention should be paid to the fact that their values can be technologically feasible in the shipyard, or on the other hand, that they are not too small.

6.3 Calculation of Depth and Minimum Freeboard

Calculation of the ship's depth for every combination of design variables, i.e. L_{pp}, B and V_{car}, and a given κ parameter is performed as follows:

$$D = V_{car} / (L_{pp}\ B\ \kappa)\ (\mathrm{m}) \tag{6.2}$$

Calculation of minimum freeboard is performed by a simplified calculation of minimum freeboard based on the actual combination of design variables (L_{pp}, B, d_s, C_B) and on predetermined values of other influential factors (forecastle, camber, sheer, etc.).

In this phase it is not possible to make an absolutely accurate calculation, but it is not necessary. During the phases of design development, it is always possible to correct the calculation to a certain degree.

After having checked the ship's depth in relation to the minimum required freeboard, the calculation with the actual combination of design variables is either continued or the combination is discarded.

6.4 Calculation of the Main Engine Minimum Power

A precise method for the approximation of continuous service rating (CSR) is used in [7, 8, 13, 15]. It will be briefly described in the following sections of the paper.

Approximation of power by the function of a given shape [16] is carried out on the basis of data for the main engine brake power and the ship's speed within the range of design constraints of main dimensions (length between perpendiculars L_{pp}, breadth B, scantling draught d_s and block coefficient C_B). Data base may contain results of serial model testing, results of a large number of trial sailings or results of available programs for the calculation of the form drag and the speed of ship.

The SEAKING program based on the ITTC recommendations and the SSPA correction factors has been used in [7,8,13,15]. The required power of main engine is calculated for a selected area of basic design variables, L_{pp}, B, d_s, C_B, and for the speed area around the required speed as well as for the predicted propeller revolutions. By regression analysis [16], independent parameters in the approximation function ($a_1 – a_n$) are determined and the mean deviation from the data base results is minimized. Different general forms of approximation function are possible.

The form used in [7, 8, 13, 15] will be used in this paper. Thus, the CSR is defined by the following approximation:

$$\mathrm{CSR} = a_1\ L_{pp}^{\ a2}\ B^{a3}\ d_s^{\ a4}\ C_B^{\ a5}\ v_{tr}^{\ a6}\ (1 + a_7\ L_{pp}/d_s)\ (\mathrm{kW}) \tag{6.3}$$

In the case when there is only one choice of the main engine type, the calculated power in relation to the maximum continuous service rating that a selected main engine can deliver is verified, and the design solution is either accepted as satisfactory, or is discarded.

If there is a choice between two or more main engines, the correction of the calculated power for predicted revolutions of every particular alternative main engine has to be carried out.

6.5 Calculation of the Ship's Displacement, Light Ship and Deadweight

Displacement Δ is defined as:

$$\Delta = L_{pp}\, B\, d_s\, \gamma_{tot}\ (\mathrm{t}) \tag{6.4}$$

where γ_{tot} is defined as sea water density including the influence of ship's outside plating and appendages (t/m^3)

Deadweight is defined as a difference between displacement and light ship:

$$DW = \Delta - LS\ (\mathrm{t}) \tag{6.5}$$

The light ship LS is defined as a sum of the steel structure weight W_{st}, the weight of machinery W_m and the weight of other equipment W_o, that is:

$$LS = W_{st} + W_m + W_o\ (\mathrm{t}) \tag{6.6}$$

For the calculation of particular weights, there is a wide range of empirical data and formulae available in literature, e.g. [7,8,13,14,15]. Here, the following general forms of empirical formulae will be given:

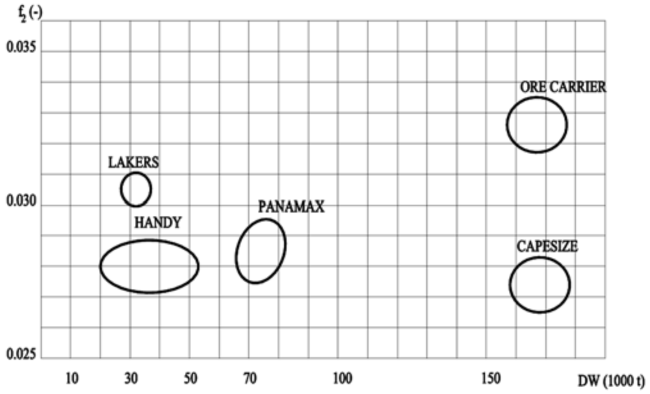
a) Steel structure weight

$$\begin{aligned} W_{st} = (1 - f_1/100)\ (f_2\ [L_{pp}\ (B + 0.85\ D + 0.15\ d_s)]^{1.36} \\ \{1 + 0.5\ [(C_B - 0.7) + \\ + (1 - C_B)\ (0.8\ D - d_s)\ /\ 3\ d_s]\} + f_3)\ (\mathrm{t}) \end{aligned} \tag{6.7}$$

where:

f_1 – factor of influence of high tensile steel on the reduction of steel structure weight
f_2 – empirical factor presented in Figures 10 and 11
f_3 – addition of the accomodation steel structure mass and specific features of a particular design (forecastle, ice class, etc.) (t)

Figure 10 **Factor f_2 (bulk carriers)**
Slika 10 **Faktor f_2 (brodovi za prijevoz rasutih tereta)**



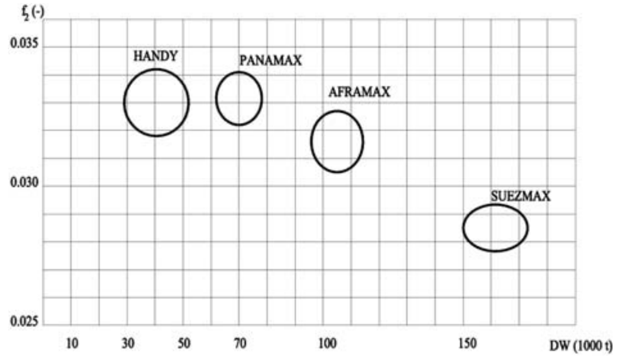


Figure 11 **Factor f_2 (tankers)**
Slika 11 **Faktor f_2 (tankeri)**

b) Weight of machinery

$$W_m = \mathrm{SMCR}\ (f_4 - 0.0034\ \mathrm{SMCR})\ /\ 7350\ (\mathrm{t}) \tag{6.8}$$

where:

SMCR = CSR / f_5 - maximum selected power of main engine (kW)
CSR - continuous service rating (kW)
f_4 – empirical factor presented in Figures 12 and 13
f_5 – CSR/ SMCR ratio, ranging from 0.85 to 0.9, depending on the optimization point of main engine

Figure 12 **Factor f_4 (bulk carriers)**
Slika 12 **Faktor f_4 (brodovi za prijevoz rasutih tereta)**

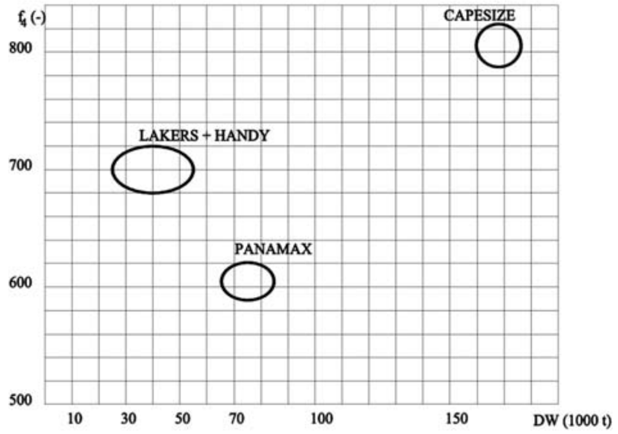
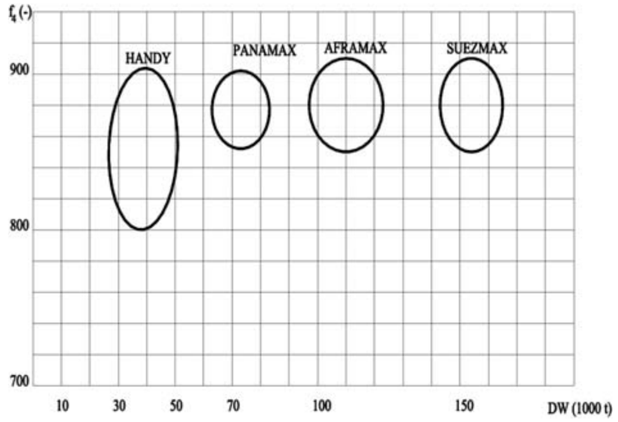


Figure 13 **Factor f_4 (tankers)**
Slika 13 **Faktor f_4 (tankeri)**



c) Weight of equipment

$$W_e = (f_6 - L_{pp} / 1620)\, L_{pp}\, B + f_7 \text{ (t)} \qquad (6.9)$$

where:

f_6 – empirical factor presented in Figures 14 and 15
f_7 – addition of the weight of ship equipment which is specific for a particular design (deck cranes, helicopter platform, etc.) (t)

Figure 14 **Factor f_6 (bulk carriers)**
Slika 14 **Faktor f_6 (brodovi za prijevoz rasutih tereta)**

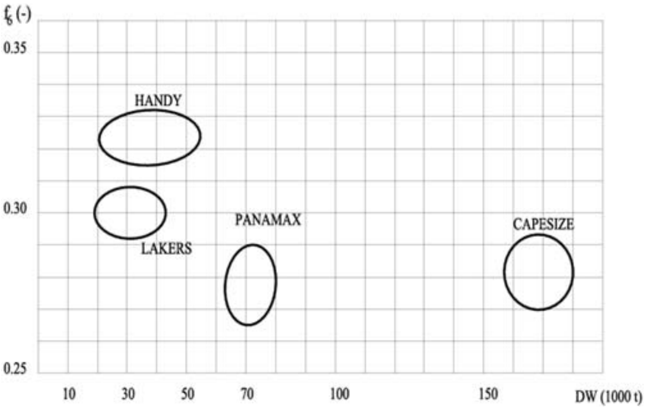
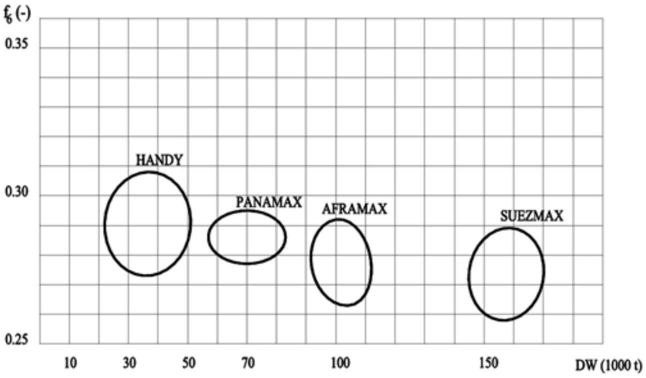


Figure 15 **Factor f_6 (tankers)**
Slika 15 **Faktor f_6 (tankeri)**



6.6 Calculation of costs of newbuilding

Costs of newbuilding C_{NB} comprise the costs of material C_M, costs of labour (process) C_L and other costs C_{oc}, i.e.:

$$C_{NB} = C_M + C_L + C_{oc} \text{ (US \$)} \qquad (6.10)$$

6.6.1 Calculation of costs of material

Costs of material C_M can be defined in the following way:

$$C_M = C_{ME} + C_{st} + C_{fix} \text{ (US \$)} \qquad (6.11)$$

where

C_{ME} – costs of main engine (US \$)

$$C_{st} = W_{gst}\, c_{st} \text{ (US \$)} \qquad (6.12)$$

W_{gst} – gross weight of steel (required quantity of steel increased by 10-15% in relation to the weight of steel structure W_{st} because of scraps produced in material processing) (t)
c_{st} – average unit price of steel (US \$/t)
C_{fix} – costs of other material and equipment (US \$)

6.6.2 Costs of labour (process)

Costs of labour C_L can be calculated as follows:

$$C_L = cGT\, P_{cGT}\, V_L \text{ (US \$)} \qquad (6.13)$$

where:

P_{cGT} – productivity (working hours/cGT)
V_L – unit hourly wage (US \$/working hour)
cGT – compensated gross tonnage, according to the OECD and defined as:

$$cGT = A * GT^B \qquad (6.14)$$

where:

GT – gross tonnage, defined as [17]:

$$GT = K_1 V \qquad (6.15)$$

$$K_1 = 0.2 + 0.02 \log V \qquad (6.16)$$

V – total ship volume (m^3)

Factors A' and B' are defined by the following table 3.

Table 3 **Factors A' and B' (excerpt)**
Tablica 3 **Faktori A' i B' (izvaci)**

Ship type	A'	B'
Oil tankers (double hull)	48	0.57
Chemical tankers	84	0.55
Bulk carriers	29	0.61
Combined carriers	33	0.62

6.6.3 Other costs

These costs (costs of financing, docking, hiring tugs, model testing, external services, etc.) can be considered as fixed at this design stage and are given as a design parameter.

7 Conclusions

Design procedure and mathematical models published in this paper are basis for development of modern design tools based on multiattribute optimisation methods. Standard design procedure traditionally represented with so called "design spiral" is replaced with presented design procedure which enables application of modern optimisation methods and algorithms.

The published procedure can be universally applied to the design of bulk carriers, tankers and other ship types with similar basic characteristics. The advantage of the presented procedure over standard procedures (e.g. design using a design spiral) is that it can be applied and adaped to different methods used for carrying out the design procedure.

A further development of the design procedure can take place in two parallel directions: extending data bases of mathematical models for the design of particular ship types and sizes and extending data bases to include the exploitation life of a ship. The former direction leads to the preparation of Croatian shipyards to move on to building more complex ships. The latter direction leads to the research of the field which has not been adequately researched in the world shipbuilding and marine practice, i.e. to the design optimization not only from the point of view of the shipyard and the prospective customer, but also to the design optimization with respect to the ship's life – from contracting and building, to exploitation and final sale or laying up.

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Appendices

Appendix A1: Basic elements of damage stability probabilistic calculation (e.g. environmental pollution problems)

Required subdivision index (for ships longer than 80 m)

$$R = (0.002 + 0.0009\, L_s)^{1/3} \quad (A1.1)$$

where L_s (subdivision length of the ship) is defined as the greatest projected moulded length of that part of a ship at or below deck, or as decks limiting the vertical extent of flooding with the ship at the deepest subdivision load line.

The attained subdivision index is

$$A = \Sigma\, p_i\, s_i \quad (A1.2)$$

where

i – represents each compartment or group of compartments under consideration,

p_i – accounts for the probability that only the compartment or a group of compartments under consideration may be flooded, disregarding any horizontal subdivision,

$s_i = C\,[0.5\,(GZ_{max})\,(\text{range of stability})]^{1/2}$ - accounts for the probability of survival probability after flooding the compartment or a group of compartments under consideration, including the effects of any horizontal subdivision.

$C = 1$ if $\theta_e \leq 25^o$

$C = 0$ if $\theta_e > 30^o$

$C = [(30 - \theta_e) / 5]^{1/2}$ otherwise

GZ_{max} – maximum positive righting lever (m) within the stability range, but not greater than 0.1 m

θ_e – final equilibrium angle of heel (^{o})

The stability range is taken maximally up to the angle of heel of 20°.

The attained subdivision index must be higher that the required one. If that is not the case, some interventions have to be made in the design, either by additional subdivisions, increased freeboard, rearrangement or heightening of hatch coamings or by using some other means.

Appendix A2: MARPOL rules of major importance in the design procedure

Minimum dimensions for the double side and double bottom are established in Chapter II, Regulation 13F. The minimum width (w) of the double side is defined in the following way:

$$w = 0.5 + DW / 20000 \text{ (m), or} \qquad \text{(A2.1)}$$

w = 2.0 (m) , whichever is the lesser. The minimum value is 1.0 m
where DW (t) is deadweight.

Minimum height (h) of the double bottom is determined in the following way:

$$h = B / 15 \text{ (m), or} \qquad \text{(A2.2)}$$

h = 2.0 (m), whichever is the lesser. The minimum value is 1.0 m
where B (m) is the moulded breadth of the ship.

Maximum dimensions of cargo tanks are defined in Chapter III. It will be briefly presented with in the following text.

Maximum length of a cargo tank is 10 m or any of the following values, whichever value is greater:

a) for tankers with no longitudinal bulkhead inside the cargo tanks
   $(0.5\, b_i / B + 0.1)\, L$ but not to exceed 0.2 L (A2.3)
b) for tankers with a centreline longitudinal bulkhead inside the cargo tanks
   $(0.25\, b_i / B + 0.15)\, L$ (A2.4)
c) for tankers with two or more longitudinal bulkheads inside the cargo tanks
   (i) for wing cargo tanks: 0.2 L (A2.5)
   (ii) for centre cargo tanks:
      (1) if b_i / B is equal to or greater than one fifth: 0.2 L (A2.6)
      (2) if b_i / B is less than one fifth:
         - with no centreline bulkhead:
           $(0.5\, b_i / B + 0.1)$ L (A2.7)
         - with a centreline bulkhead:
           $(0.25\, b_i / B + 0.15)$ L (A2.8)

where b_i is the minimum distance from the ship's side to the outer longitudinal bulkhead of the tank in question measured inboard at right angles to the centreline at the level corresponding to the assigned summer freeboard.

The length of a ship *L* (m) is defined as 96% of the total length on the waterline at 85% of the moulded depth, or as a distance from the stem to the axis of rudder stock on that waterline, whichever value is greater.

Maximum cargo tank capacity is defined in the way that a hypothetical oil outflow in the case of side damage of the ship O_c or the bottom damage of the ship O_s should not exceed 30,000 m^3 or 400 (DW)$^{1/3}$, whichever value is greater, but subject to a maximum of 40,000 m^3.

Basic calculations of a hypothetical cargo discharge in the case of ship damage are as follows:

(a) for side damages

$$O_c = \Sigma\, W_i + \Sigma\, K_i\, C_i \qquad \text{(A2.9)}$$

(b) for bottom damages

$$O_s = {}^1/_3\, (\Sigma\, Z_i\, W_i + \Sigma\, Z_i\, C_i) \qquad \text{(A2.10)}$$

where

W_i (m^3) = volume of a wing tank assumed to be breached by the damage

C_i (m^3) = volume of a centre tank assumed to be breached by the damage

$K_i = 1 - b_i / t_c$ when b_i is equal to or greater than t_c, K_i shall be taken as 0

$Z_i = 1 - h_i / v_s$ when h_i is equal to or greater than v_s, Z_i shall be taken as 0

b_i (m) = width of wing tank under consideration measured inboard from the ship's side at right angles to the centreline at the level corresponding to the assigned summer freeboard

h_i (m) = minimum depth of the double bottom under consideration

t_c, v_s are assumed damages defined in folowing text.

For the purpose of calculating hypothetical oil outflow following extent of damages are assumed:

(a) Side damage

(i) Longitudinal extent (l_c):	${}^1/_3\, L^{2/3}$ or 14.5 m, whichever is less	(A2.11)
(ii) Transverse extent (t_c):	*B*/5 ili 11.5 m, whichever is less	(A2.12)
(iii) Vertical extent (v_c):	from the baseline upwards without limit	

(b) Bottom damage	From 0.3 L from the forward perpendicular	Any other part of the ship	
(i) Longitudinal extent (l_s):	*L*/10	*L*/10 or 5 m, whichever is less	(A2.13)

(ii) Transverse extent (t_s):	B/6 or 10 m, whichever is less, but not less than 5 m	5 m	(A2.14)
(iii) Vertical extent from the baseline (v_s):	B/15 or 6 m, whichever is less		(A2.15)

Damage assumptions and stability criteria are established in Chapter III and Chapter II, Regulation 13F. It will be briefly presented with in the following text.

Damage stability criteria shall aply to:

- tankers of more than 225 m in length, anywhere in the ship's length
- tankers of more than 150 m, but not exceeding 225 m in length, anywhere in the ship's length, except involving either after or forward bulkhead bounding the machinery space located aft. The machinery space shall be treated as a single floodable compartment
- tankers not exceeding 150 m in length, anywhere in the ship's length between adjacent transverse bulkheads with the exception of the machinery space.

Damage cases:

(a) Side damage

(i) Longitudinal extent	$^1/_3\,L^{2/3}$ or 14.5 m, whichever is less;	(A2.16)
(ii) Transverse extent: (inboard from the ship's side at right angles to the centreline at the level of the summer load line)	B/5 or 11.5 m, whichever is less;	(A2.17)
(iii) Vertical extent:	from the moulded line of the bottom shell plating at centreline, upwards without limit	

(b) Bottom damage	For 0.3 L from the forward perpendicular	Any other part of the ship	
(i) Longitudinal extent:	$^1/_3\,L^{2/3}$ or 14.5 m, whichever is less	$^1/_3\,L^{2/3}$ or 5 m, whichever is less	(A2.18)
(ii) Transverse extent:	B/6 or 10 m, whichever is less	B/6 ili 5 m, whichever is less	(A2.19)

(iii) Vertical extent B/15 or 6 m, whichever is less, measured from the moulded line of the bottom shell plating at centreline (A2.20)

(c) Bottom raking damage (for oil tankers of 20,000 dwt and above)

(1) longitudinal extent
  (i) for ships of 75,000 dwt and above: 0.6 L measured from the forward perpendicular (A2.21)
  (ii) for ships of less than 75,000 dwt: 0.4 L measured from the forward perpendicular (A2.22)
(2) transverse extent: B/3 anywhere in the bottom (A2.23)
(3) vertical extent: breach of the outer hull. (A2.24)

Damage stability criteria are as follows:

(a) The final waterline, taking into account sinkage, heel and trim, shall be below the lower edge of any opening through which progressive flooding may take place.
(b) In the final stage of flooding, the angle of heel due to unsymmetrical flooding shall not exceed 25°, provided that this angle may be increased up to 30° if no deck edge immersion occurs.
(c) The stability in the final stage of flooding shall be investigated and may be regarded as sufficient if the righting lever curve has at least a range of 20° beyond the position of equilibrium in association with a maximum residual righting lever of at least 0.1 m within the 20° range; the area within this range shall not be less 0.0175 metre radian.

The requirement for minimum volume of ballast tanks is given in Chapter II, Regulation 13 by a definition of minimum ballast draughts. The minimum moulded amidships draught d_m is given as:

$$d_m = 2.0 + 0.02\,L\ \text{(m)} \qquad \text{(A2.25)}$$

in association with the maximum aft trim of 0.015 L and enabling full immersion of the propeller(s).

Appendix A3: Classification societies' rules having a influence on the general configuration of the ship

Further are presented DNV's requirements, other classification societies have similar requirements.

1) Minimum number of watertight transverse bulkheads

For ships without a longitudinal bulkhead and with the engine room located at the stern, the minimum number of bulkheads is defined by the following table A3.1.

Table A3.1 **Minimum number of transverse bulkheads**
Tablica A3.1 **Minimalni broj poprečnih pregrada**

Length of a ship (m)	Number of bulkheads
85 < L ≤ 105	4
105 < L ≤ 125	5
125 < L ≤ 145	6
145 < L ≤ 165	7
165 < L ≤ 190	8
190 < L ≤ 225	9
L > 225	considered individually

L (m) – length between perpendiculars (it should not be less than 96% or greater than 97% of the water line length at maximum draught).

The number of watertight transverse bulkheads may be lesser than the minimum number required. If that is case, the ship must satisfy the conditions of damage stability, and the problem of general configuration and strength of the ship should be given due attention.

2) Position of collision bulkhead

The position of collision bulkhead defines the length of the fore peak and the cargo space. It is defined as follows:

The distance from the forward perpendicular (x_c) must be within the values stated below:

$$x_{c\ (minimum)} = 0.05\,L - x_r\ (m) \qquad \text{for } L < 200\ m \qquad (A3.1)$$
$$x_{c\ (minimum)} = 10 - x_r\ (m) \qquad \text{for } L \geq 200\ m$$
$$x_{c\ (maximum)} = 0.08\,L - x_r\ (m)$$

where

L – is the length of a ship defined according to ICLL, i.e. 96% of the length overall at 85% of the moulded depth of the ship, or the distance between the stem and the centre of the rudder shaft at the same waterline, whichever length is greater.
x_r – reduction due to bulbous bow, defined as
$x_r = 0$ for a bow without bulb
or, as the least value of the following values for a bulbous bow:
$x_r = 0.5\ x_b$ (m)
$x_r = 0.015$ L (m)
$x_r = 3.0$ (m)

where
x_b – is the length of the bulbous bow.

3) Minimum height of double bottom

The minimum height of double bottom is defined by the requirement for the height of the double bottom centre girder and brackets at the centreline of the ship. The minimum height is defined in the following way:

$$h_{min} = 250 + 20\,B + 50\,d_s\ (mm),\ \text{minimum 650 mm} \qquad (A3.2)$$

where

B – breadth of the ship (m)
d_s – scantling draught (m).

Nomenclature

A	attained subdivision index
b_i	minimum distance from the ship's side to the outer longitudinal bulkhead of the tank in question measured inboard at right angles to the centreline at the level corresponding to the assigned summer freeboard, m
B	maximum breadth of the ship, m
c_{st}	average unit price of steel, US $/t
cGT	compensated gross tonnage
C	consistency level
C_B	block coefficient
C_{BD}	block coefficient at the moulded depth
$C_{B\ 0.85D}$	block coefficient at 85% of the moulded depth
C_{CB}	freeboard correction for the block coefficient
C_D	freeboard correction for the moulded depth, mm
C_i	volume of a centre tank assumed to be breached by the damage, m^3
C_{fix}	costs of other material and equipment, US $
C_{fc}	freeboard correction for forecastle, mm
C_L	cost of labour, US $
C_M	cost of material, US $
C_{ME}	cost of main engine, US $
C_{NB}	cost of newbuilding, US $
C_{sh}	freeboard correction for sheer, mm
C_{st}	cost of steel, US $
CSR	continuous service rating, kW
d_s	scantling draught, m
d_m	minimum ballast draught amidships, m
D	moulded depth of the, m
DW	deadweight, t
f_1	factor of influence of high tensile steel on the reduction of steel structure weight (%)
f_2	empirical factor presented in Figures 10 and 11
f_3	addition of the accommodation steel structure mass and specific features of a particular design, t
f_4	empirical factor presented in Figures 12 and 13
f_5	CSR/SMCR ratio
f_6	empirical factor presented in Figures 14 and 15
f_7	addition of the weight of ship equipment which is specific for a particular design, t
F_A	minimum freeboard for ships type A, mm
F_{B-60}	reduced minimum (B-60) freeboard, mm
F_{tA}	tabular freeboard for ships type A, mm
F_{tB}	tabular freeboard for ships type B, mm
F_{tB-60}	reduced minimum (B-60) tabular freeboard, mm
GT	gross tonnage
GZ_{max}	maximum positive righting lever, m
h	height of double bottom, m
I	unit matrix
I_{ME}	identificator of the main engine
IACS	International Association of Classification Societies
ICLL	International Convention on Load Lines
IMO	International Maritime Organization
ITTC	International Towing Tank Convention
l_c	longitudinal extent in the case of side damage, m
l_s	longitudinal extent in the case of bottom damage, m
L	length of the ship, m
L_F	length of the ship for the purpose of minimum freeboard calculation, m
L_{pp}	length between perpendiculars, m
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LS	lightweight of the ship, t
MARPOL	International Convention for the Prevention of Pollution from Ships
MCR	maximum continuous rating, kW
NA	number of attributes
O_c	hypothetical cargo discharge in the case of side ship damage, m^3
O_s	hypothetical cargo discharge in the case of bottom ship damage, m^3
OECD	Organisation for Economic Co-operation and Development
p	importance vector
p_i	importance of attribute i
p_i	probability that only the compartment or a group of compartments under consideration may be flooded
P	preference matrix
P_{cGT}	productivity, working hour/f_cGT
P_{ij}	ratio of importance of attributes i and j
P_{oc}	other costs, US $
R	required subdivision index
s_i	probability of survival probability after flooding the compartment or a group of compartments under consideration
SMCR	selected maximum continuous rating, kW

SOLAS	International Convention for the Safety of Life at Sea
SSPA	Swedish hydrodynamics institute
t_c	transversal extent in the case of side damage, m
t_s	transversal extent in the case of bottom damage, m
$U(y(x))$	fuzzy function of attribute y
v_c	vertical extent in the case of side damage, m
v_s	vertical extent in the case of bottom damage, m
v_{tr}	trial speed, kn
V	total ship volume, m^3
V_{car}	capacity of cargo holds (tanks), m^3
V_{fc}	volume of the forecastle, m^3
V_{sup}	volume of the accommodation, hatch coamings and hatch covers, m^3
V_{cam}	volume of the camber, m^3
V_D	ship´s volume up to moulded depth, m^3
V_L	unit hourly wage, US $/working hour
VLCC	very large crude oil carrier
w	minimum double side width, m
W_{gst}	gross weight of steel, t
W_i	volume of a wing tank assumed to be breached by the damage, m^3
W_m	weight of machinery, t
W_e	weight of equipment, t
W_{st}	weight of steel structure, t
x_b	length of the bulbous bow, m
x_c	distance from the forward perpendicular, m
x_r	reduction due to bulbous bow, m
γ_{tot}	sea water density including the influence of ship plating and appendages, t/m^3
Δ	displacement, t
θ_e	final equilibrium angle of heel, °
κ	specific voluminosity of the ship
λ_i	eigenvalues of the problem