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Multiattribute Decision Making Methodology in the Concept Design of Tankers and Bulk Carriers

Original scientific paper

An improved methodology for decision making for ship general design in concept design phase is presented. Multiattribute decision making method has been applied and executed by decision making shell *DeMak* developed at *Faculty of Mechanical Engineering and Naval Architecture in Zagreb*. Each attribute was defined through membership grade function based on fuzzy set theory. The consistent relative significance of attributes is obtained as an eigenvector of subjective decision making matrix and used as a weighting factor. Inadequate information about configuration of feasible designs´ subspace is overcome by sequential adaptive generation of design points in feasible region (via e.g. adaptive Monte Carlo method). The concept of nondominated designs was used for filtering efficient (Pareto) solutions which are the only significant ones from the designer point of view. Selection among efficient solutions is performed by MADM approach, thus expressing designer´s heuristic preference regarding multiple attributes. As "preferred design", the nondominated point having a minimal distance from the "utopia" or other target design in the subjective attribute space have to be selected. Method is presented for the basic design of Capesize bulk carrier and Handymax product tanker. Design procedure and mathematical models for basic design of tankers and bulk carriers has been taken over complementaty paper [B1].

Keywords: *tankers, bulk carriers, ship design*

Metodologija višeatributnog odlučivanja pri osnivanju tankera i *bulk carriera*

Izvorni znanstveni rad

U radu je prikazana suvremena metodologija sinteze projekta u konceptualnoj fazi osnivanja broda. Primijenjena je metoda višeatributne sinteze i korištena je programska aplikacija DeMak razvijena na *Fakultetu strojarstva i brodogradnje u Zagrebu*. Svakom je atributu (projektnom svojstvu) pridružena vlastita neizrazita funkcija kojom je definirana subjektivna mjera zadovoljenja kod ispunjavanja ciljanog iznosa pojedinog atributa. Konzistentnost relativnih međusobnih odnosa pojedinih projektnih atributa se postiže pomoću vektora vlastitih vrijednosti matrice subjektivnih relativnih preferencija. Nemogućnost spoznaje konfiguracije podprostora ostvarivih projekata se rješava generiranjem slučajnih projektnih rješenja (adaptivna Monte Carlo metoda). Izdvajanje projekata koji su značajni s projektanovog stajališta od ostalih podobnih rješenja se postiže primjenom kriterija nedominiranosti (Pareto). Selekcija među uspješnim projektnim rješenjima se vrši primjenom ciljnog programiranja tako da se poštuju projektantove preferencije međusobnih odnosa pojedinih atributa. Za "najbolji projekt" je određeno ono nedominirano projektno rješenje iz subjektivnog atributnog prostora koje je najmanje udaljeno od idealnog rješenja (utopije). Metoda je ilustrirana na primjerima osnivanja broda za prijevoz rasutih tereta *Capesize* veličine i tankera za prijevoz naftnih derivata *Handymax* veličine. Projektna procedura i matematički modeli osnivanja tankera i brodova za prijevoz rasutih tereta je preuzet iz [28].

Ključne riječi: *tankeri, bulk carrier* / brod za rasuti teret, *osnivanje broda*

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1 Introduction

Emergence of novel ship concepts, including advanced marine vehicles, has created a need for improvements in design methods. Improvements should be made both in applicable analysis tools and in synthesis techniques to form a balanced design procedure.

Methods should be capable of validating new concepts as well as generating competitive 'standard' ship designs, as presented in this paper. For the synthesis problems there is no universal technique to solve non-linear, fuzzy, multi-criteria problem of high dimensionality. The solution is to be found in the problem oriented approach achieved through team work on the decision support problem (DSP) formulation that should be the base for rational decision-making. DSP is formulated combining the insight into basic features of the design problem by the experienced designer and the mathematical formulation, solvable with available techniques and hardware, which is developed by the operations research specialist.

To promote such, not yet fully appreciated, cooperation the attempt is made in this paper to:

- define decision support procedure steps,
- list problem requirements for practical (non-academic) designs,
- provide basic nomenclature (terms/sets/spaces) of realistic DSP,
- present some useful problem manipulations and solution strategies for listed requirements,
- enable easy visualization of somewhat complex concepts and transformations,
- present an example of application.

Optimization based design process includes: problem identification, formulation of DSP methodology and problem solution (including sensitivity assessment) [1, 2].

Identification of DSP implies:

- selection of design variables and design criteria (constraints and attributes),
- determination of design objectives and corresponding measures of robustness.

DSP methodology can be efficiently formulated after the basic characteristics of design requirements and designer's preferences are revealed. It involves:

- DSP manipulation into equivalent but mathematically more convenient form,
- selection of solution strategy (e.g. optimization technique) for the manipulated problem,
- development of the final selection method for the generated design variants,
- sensitivity / uncertainty analysis.

DSP solution requires practical implementation of selected methodology through two basic calculation (mathematical) models:

- Design analysis model for technical (performance/response, safety) and economical (cost) evaluations,
- Synthesis model which includes a preferably interactive decision-making shell with design utilities (optimization and sensitivity modules, databases, graphics, etc.).

Basic requirements on calculation models for application in practical design are:

- Design criteria should include relevant aspects of design (performance measures, safety measures, cost, etc.) implying multi-criteria approach.
- Final selection of preferred design is influenced by subjective reasoning of general and structural designer, owners and shipyard management. Accommodation for subjective decisions should be part of the design process.
- Design method should be practical for use in design offices, easily modified and interactive.
- Design method should be applicable in case studies of advanced concepts and therefore capable of expansion to the new criteria and methods.
- Each good new design contains its own 'grain of salt' and the flexibility of the design model definition should be one of the first priorities to accommodate such design needs.

DSP advantages in meeting these conflicting requirements should also be taken into account, as well as the advances in modern engineering hardware:

- Design procedure requires only a comparison of competing designs, therefore relative and not absolute values of design attributes are needed. All considerations that are the same, or similar, for different designs could be excluded from the design process.
- The real quality of the design process is not based on inclusion of all possible or available complex calculations but, to the contrary, on a reasonable exclusion of all unnecessary considerations by concentrating on relevant ones used in the key decisions on the design characteristics.
- Development of parallel processing on modern computers or parallel work on workstations fit very well with design methods where, despite the spiral character of the overall design process, many of the calculation steps are parallel in nature. The increased speed of engineering workstations is opening the possibility of incorporating complex design criteria into realistic design procedure.

Complexity of synthesis procedure is shown through its dimensionality and complexity of analysis modules (nonlinearity of the response and feasibility models, stochastic definition of environment, subjectivity of quality assessments, etc.). However, only certain combinations of the analysis modules are possible at the present level of hardware development. Applicable combination of analytical and synthesis modules in DSP formulation is presented as a flowchart for general ship design model, see [3]. Elimination of infeasible designs on different levels of design analysis is performed to speed up DSP execution.

This paper presents the synthesis (design) procedure and methodology of decision making for the multicriterial ship design problems. This article is lean-to the article [B1]: "Design Procedures and Mathematical Models in the Concept Design of Tankers and Bulk Carriers".

In second section the general design procedure of full hull form merchant ships is given. Procedure is described and represented in the form of a block diagram. The presented procedure is a general one and can be used for various purposes: from checking a particular design solution by using the simplest tools [4,5,6,7] to using it as a basic algorithm of the ship design mathematical model in the ship optimization [8,9,10,11]. In addition, a short description and a comment on the standard design procedure using a "design spiral" are given.

The third section describes the application of the multiattribute optimization method. The program application has been developed at the *Faculty of Mechanical Engineering and Naval Architecture in Zagreb*, and it has been used as an optimization shell for a mathematical model of design procedure of numerous examples [3,12,13,14,15,16,17].

All the elements of the design problem are identified in accordance with the applied optimization method. Comments on particular design values are made and the designer's suggestions for their definition are explained.

The subsequent section represent mathematical models used in the design of two selected ship types and sizes: Capesize bulk carrier and Handymax product tanker. Data on modern ships built in shipyards specialized for building these particular ship types are presented.

Design requirements are defined and design tasks are identified accordingly. Mathematical models for both ship types are defined in detail. The figures containing output results are included, as well as comments on them and a synthesis of the applied design procedure.

The observed patterns are described together with the interrelations of particular values significantly affecting the obtained results.

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 Design procedures in the design of full hull form merchant ships

Ship design has been based on the so-called “design spiral” for years. The process has described in detail in professional literature since the very beginning of the scientific professional approach to the problem. The process involves basically a design cycle in which all calculations required for defining the ship design are carried out in a predetermined sequence. The results are then used for the iteration of calculations in the next design cycle, and so on. This produces a so-called “design spiral” in which the results of each new cycle come closer to an optimal solution. Figure 1 represents the design spiral taken from [18].

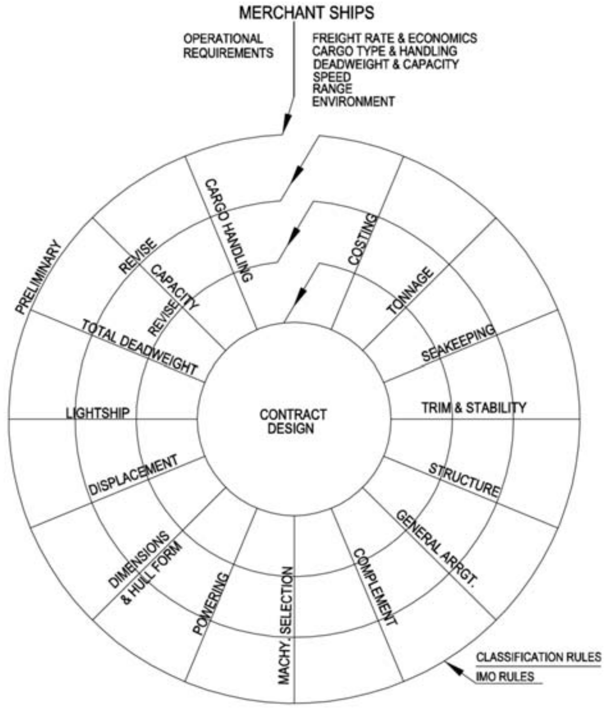


Figure 1 **Design spiral for the design of merchant ships**
Slika 1 **Projektna spirala osnivanja trgovačkih brodova**

The presented procedure is based on the methodology of ship design where calculations are carried out manually or using the tools available at the outset of the computer technology development. During the course of the process, the designer is concentrated on strictly following the set procedure of calculations and on making decisions on the direction the next design cycle is to take, or, on whether the obtained solution can be considered as a final one. This method cannot produce a good estimation of the influence of particular variables and parameters on the final solution; neither can it optimize the design regarding several possible goals.

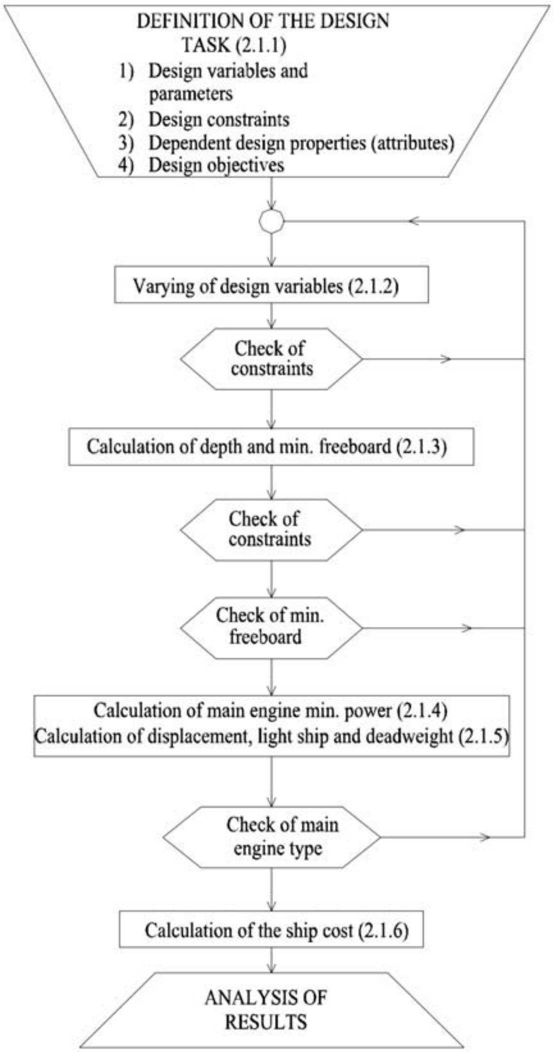
In following text a design procedure is presented which enables the use of the latest tools in design optimization.

Tankers and bulk carriers share a common design procedure [8,9,10,11]. The reason for that is that these two types of vessels (elaborated in [B1]) have common basic features. The procedures can generally be divided into two basic groups: a general design procedure and special design procedures.

2.1 General design procedure

The general design procedure incorporates the following steps:

Figure 2 **Block diagram of the general design procedure**
Slika 2 **Blok shema općeg projektnog postupka**



1. Definition of input data: design variables and parameters, design constraints, dependent design properties (attributes) and design objectives;
2. Variation of design variables and verification of constraints;
3. Calculation of the depth of the ship and verification of minimum freeboard;
4. Calculation of the main engine minimum power;
5. Calculation of the displacement, light ship and deadweight. Checking the type of main engine;
6. Calculation of costs of material, labour and total cost of the ship;
7. Analysis of obtained results.

The general design procedure is shown by a block diagram in Figure 2.

2.1.1 Ship design problem definition

Mathematical definition of design problem implies definition of the design parameters**,** design quality measures (or 'merits') and the corresponding structure of sets used for efficient design description and calculation.

Design parameters include design variables, open to designer, and tactical and technical constants usually fixed in the design problem (task) definition (e.g. mission profile).

Design quality measures are defined by using a set of design criteria functions (mappings), typically for performance, cost, weight, safety evaluations, etc.

In order to fully define the design task and the targets of the design process, the following groups of data need to be defined:

2.1.1.1 Design variables and parameters

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

b) identificator of the main engine I_{ME} (-);

c) design task should be fulfilled within particular parameter limits:
   - deadweight DW (t),
   - volume of cargo space V_{car} (m^3),
   - required trial speed v_{tr} (kn).

d) parameter denoted "specific voluminosity of the ship "κ" is defined as:

$$\kappa = V_{car} / (L_{pp}\, B\, D) \text{ (-)} \tag{2.1}$$

where D is the depth amidships (m).

e) parameters for estimating the influence of the use of high tensile steel on the mass reduction of the steel structure,

f) parameters required for the selection of main engine (maximum power of a particular engine MCR_i),

g) parameters required for the cost calculation of materials (costs of feasible main engines C_{MEi}, average unit cost of steel c_{st} and costs of other materials and equipment C_{fix}),

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

2.1.1.2 Design constraints

Design constraints are defined in two ways:

a) minimum and maximum values of basic design variables:
   - constraints on the ship length: $L_{pp\,min}$, $L_{pp\,max}$,
   - constraints on the ship breadth: B_{min}, B_{max},
   - constraints on the scantling draught: $d_{s\,min}$, $d_{s\,max}$,
   - constraints on the ship block coefficient: $C_{B\,min}$, $C_{B\,max}$.

b) limit values of ratios between main dimensions of the ship (they comprise empirical and design constraints which are not necessarily included in the previously listed minimum and maximum limitations of basic design variables):
   - constraints on the length/breadth ratio: $(L_{pp}/B)_{min}$, $(L_{pp}/B)_{max}$,
   - constraints on the length/ scantling draught ratio: $(L_{pp}/d_s)_{min}$, $(L_{pp}/d_s)_{max}$,
   - constraints on the breadth/ scantling draught ratio: $(B/d_s)_{min}$, $(B/d_s)_{max}$,
   - constraints on the length/depth ratio: $(L_{pp}/D)_{min}$, $(L_{pp}/D)_{max}$.

2.1.1.3 Dependent design properties (attributes)

Dependent design properties (attributes) depend upon the values of particular design variables and parameters. They are listed as follows:

a) mass of the steel structure W_{st} (t),
b) cost of materials C_M (US $),
c) cost of labour (process) C_L (US $),
d) cost of ship C_{NB} (US $),(kn).
e) obtained deadweight DW (t),
f) obtained volume of cargo space V_{car} (m^3),
g) obtained trial speed v_{tr}.

2.1.1.4 Design objectives

Design objectives depend upon primarily on the type of the ship and its special purposes. Potential design objectives can be the following:

a) minimize the weight of the steel structure,
b) minimize the power of the main engine,
c) minimize the cost of the material,
d) minimize the cost of labour (process),
e) minimize the cost of building,
f) minimize the own mass of the ship,
g) maximize the stability,
h) maximize the speed (at a given main engine power), etc.

The design solution quality is estimated by the quality of satisfying particular design objectives or design variables (attributes) – by a multi-target or multi-attribute synthesis of the design.

Relevant preferences determine the importance of a particular target or attribute in the multi-dimensional area of design solutions. Various methods can be applied for their definition: the method for associating particular influential factors, weighting factors, to each target (which can vary, depending on the target quality, from 0 to 1) [8,9,10,11], or the method used in this paper – a multi-attribute synthesis of the design in which each design characteristic is attributed with its own fuzzy function [B1], while the interrelations between importances of particular design characteristics are given by Saaty's method [B1,3,12,13, 14, 15, 16, 17].

2.1.2 Variation of design variables and verification of constraints

Main dimensions of a ship L_{pp}, B, d_s, C_B are varied within the design area in given steps: L_{step}, B_{step}, $d_{s\ step}$, C_{Bstep}. Each combination of design variables should be verified with respect to the design constraints and should be rejected if it fails to them.

2.1.3 Calculation of the depth and minimum freeboard of a ship

The depth D is obtained by a simple calculation from input data (required volume of cargo space V_{car} and the specific voluminosity of the ship κ) and the actual combination of design variables L_{pp}, B.

2.1.4 Calculation of the main engine minimum power

Approximate calculations of the main engine minimum power can be obtained in different ways, e.g. by empirical formulae [18,19,20], by more precise appreciative expressions for a particular area of main dimensions and speed of the ship [B1,8,9,10,11], or by some other method.

2.1.5 Calculation of the displacement, light ship and deadweight

Displacement is calculated as a product of main dimensions of the ship, i.e. L_{pp}, B, d_s, C_B, and γ_{tot} (sea water density including the influence of ship plating and appendages):

$$\Delta = L_{pp}\ B\ d_s\ \gamma_{tot}\ \text{(t)} \tag{2.2}$$

The weight of a ship can be divided into three groups: weight of the steel structure W_{st}, weight of machinery equipment W_m and weight of other equipment W_o. There is a wide range of empirical data and formulae available in literature for the calculation of particular weights, e.g. [B1,8,9,10,13,18,20].

$$LS = W_{st} + W_m + W_o\ \text{(t)} \tag{2.3}$$

Resulted deadweight is calculated as a difference between displacement and light ship:

$$DW = \Delta - LS\ \text{(t)} \tag{2.4}$$

2.1.6 Calculation of the ship's costs

The total cost of a ship C_{NB} comprise the cost of materials C_M, the cost of labour (process) C_L and other costs C_{oc}.

In the initial design stage, the calculation of the cost of the material required for building a ship is carried out by simply adding the most relevant elements which are included in the total cost of materials: cost of main engine C_{ME}, cost of steel C_{st}, and cost of other material and equipment C_{fix}.

The cost of the main engine is given as a fixed value or as a set of fixed values if there is a choice between various types of main engines, or various engine sizes.

The cost of steel is directly dependent of the main dimensions of the ship and of their ratios, and is calculated by using approximate empirical formulae.

The cost of other material comprises all other ship's equipment – cargo and ballast handling equipment, steering appliances, anchoring and mooring gear, crew accommodation, navigational equipment, auxiliary machinery and auxiliary units, automation, life saving equipment, etc. Since the listed equipment does not depend, or depends discreetly on the main dimensions of a ship, it can be considered as a fixed value at this design stage.

The cost of labour (process) is usually calculated according to the OECD methodology by which different ship types and sizes are reduced to a "standard" ship (detailed explanation in [B1]). The cost of the process per unit of product (the product of unit hourly wage V_L and the productivity of the shipyard P_{cGT}) is multiplied by the "product quantity" cGT.

Other costs (costs of a classification society, financing, docking, engagement of expert institutions, etc.) can be considered as fixed costs in the initial design stage.

2.2 Special design procedures

Special design procedures are developed for special, strictly defined designs. Generally, they are developed by simplifying the general procedure and are used in particular specific cases [4,5,6,7]. Special design procedures are used in a limited design space with most of main dimensions fixed.

3 Decision making methodology for merchant ship design

3.1 Mathematical model description for decision support [52]

Principles of design would require that for a good design (Axiom I), the qualities, are as much as possible uncoupled with respect to the parameters, and that (Axiom II) the information content describing a good design is minimal (simplicity), see [21].

'Best' design(s) can be determined by three classical ways of decision making, see [22]:

- lexicographical ordering of priorities (method selects among the 'best' candidates regarding the first priority those that are the 'best' regarding second priority, etc).;
- construction of value function (combination of attribute functions as the ultimate quality measure);
- goal seeking (construction of metric or 'distance' measure to the target design).

Full description of sets/spaces and transformations are given in Figs. 1a-d for the visual insight into concepts encountered in the realistic DS formulations (dominance, fuzziness, metrics).

*Design space **X***- (Figure 3a) is spanned by the free design variables x_i, i=1,.., nv. Each design k is represented as a point $\mathbf{x}^k = \{x_i\}$ (e.g. $\mathbf{x}^2$ or $\mathbf{x}^P$) in this space.

Designs in the subspace (subset if k is finite) of feasible designs $\mathbf{X}^{\geq}$ satisfy failure criteria $g_i(\mathbf{x}) \geq 0$, production or functionality requirements, min-max bounds x_i^L and x_i^U and other constraints. Note that $\mathbf{X}^{\geq}$ may be convex (line connecting two designs lies in $\mathbf{X}^{\geq}$) or non-convex as in Fig. 3a.

Note also that it can be multiply connected (containing holes for e.g. resonance avoidance in vibration problems) and that some of the variables are discrete (no. of stacks of containers, no. of stiffeners, standard profiles, etc.). That could strongly influence the problem formulation.

Dimensionality of the problem is given by the number of variables *nv*. The "curse of dimensionality" is tackled in detail in [23]. For concept design *nv*~5-30. Preliminary/Initial structural design would require *nv*~200/1000.

Most of the design variables in presented references on the structural design are structural scantlings and spacing of girders on 2D (midship section, bulkheads) or 3D structures. Dimensionality is higher (100-1000) only in few works. Constraints $g_i(.) \geq 0$ are either global and local strength formulae or Rules. Structural response is calculated using FEM or analytical methods.

*Attribute space **Y*** - (Figure 3b) is spanned by design attributes y_i. The mappings $\mathbf{y}^k = \mathbf{a}(\mathbf{x}^k)$ or $\mathbf{a} : \mathbf{X}^{\geq} \xrightarrow{} \mathbf{Y}^{\geq}$ are used to form the attribute space (or outcome space) $\mathbf{Y}^{\geq} = \{\mathbf{y}^k\}$. For each feasible design $\mathbf{x}^k$ in $\mathbf{X}$ the design quality measures (attribute values) $\mathbf{y}^k = \{y_i\}$ define its corresponding point in $\mathbf{Y}$ space.

Note that several points (designs) in **X** may map into a single point in **Y** (same performance, cost, etc.). In addition, x_i or y_j values are not mutually comparable and have different units and therefore **X** and **Y** are not metric spaces i.e. there is no distance measure among designs. The comparison of designs is possible only within each variable x_i or attribute y_j.

If direction is selected for the quality improvement (e.g. minimal cost, maximal safety) attributes are transferred to objectives. 'Ideal' $\mathbf{y}^*$ is a design (usually infeasible) with the coordinates of the best achieved quality for each objective.

Concept of nondominance (Figures 3a, 3b). The subspace $\mathbf{Y}^\mathbf{N}$ of nondominated or Pareto optimal or efficient designs can be identified when designer's preference structure is applied to designs (points) in $\mathbf{Y}^{\geq}$. Only those designs (usually only a small fraction of feasible designs) are of interest to designer since they dominate all other feasible designs.

Preference is a binary relation stating that design $\mathbf{y}^i$ is preferred to design $\mathbf{y}^j$. The "better set" can be defined with respect to given design $\mathbf{y}^0$ if all its elements are preferred to $\mathbf{y}^0$. Conversely, the "worse set" can be formed containing all designs that are worse than $\mathbf{y}^0$ in all attributes i.e. dominated by it. For the preference 'more is better' it is easy to visualize the "worse set" to e.g. design $\mathbf{y}^\mathbf{P}$ (see Fig. 3b) as a negative cone with an apex in $\mathbf{y}^\mathbf{P}$ containing points left of line y_1^P and below the line y_2^P. Finally, the set of nondominated designs $\mathbf{Y}^N$ is defined as a set of designs that have no "better set", hence they are not dominated by any design.

Alternatively, design is nondominated if it is better than any other design in $\mathbf{Y}^{\geq}$ in at least one objective. Points in Y^N have their design variable description in $\mathbf{X}^\mathbf{N}$ (see Figure 3a). Pareto concept is basic to most multi-criteria references today.

Subjectivity, sensitivity, analysis and robustness: Realistic *decision making* must include subjectivity of decision makers (different stake holder's point of view) particularly for novel designs. Objectives and measures of design quality are best represented in the attribute space but decision making is complicated due to lack of metric. Inclusion of subjectivity (see Figures $3b_1$ and $3b_2$) is basic to realistic decision-making. It implies:

- Subjective comparison of various designs can be performed using fuzzy functions $U_i(y_i)$. Membership grade (satisfaction level) $\mu_i = U_i(y_i)$ has range 0-1 (see dotted line). In vibration problems this function may consist of e.g. series of the inverse bell shaped functions centered at excitation frequencies ($\mu_i = 0$ for design in resonance). Concept is widely used in DSP.
- Determination of subjective importance of different attributes can be based on weighting factors w_i. For concepts of the preference ordering see [44].
- Combination of subjectivities - for attribute it can be achieved as e.g. product $u_i(y_i) = w_i\, U_i(y_i)$.

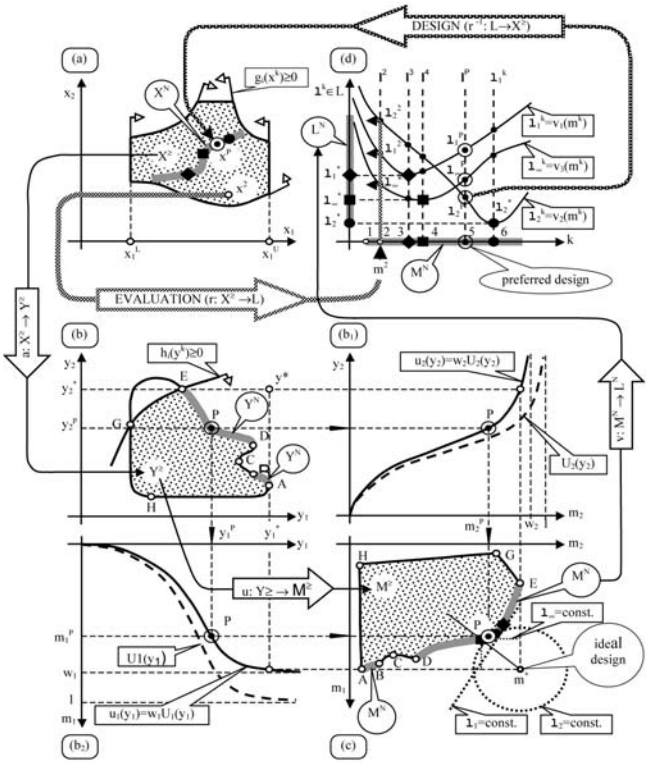
Subjective metric space (Figure 3c) is formed by using mappings $\mathbf{u}$: $\mathbf{Y}^{\geq} \xrightarrow{} \mathbf{M}^{\geq}$ where now it does exists possibility to introduce metric (distance measure) since all attribute values $m_i = u_i(y_i)$ are normalized and scaled to their relative importance. Subjective criteria functions **u** enable natural 'more is better' preference structure and make it even easier to filter the subset of nondominated designs $\mathbf{M}^N$ from $\mathbf{M}^{\geq}$ and then generate corresponding $\mathbf{Y}^\mathbf{N}$ and $\mathbf{X}^\mathbf{N}$.

Value and utility functions, (see [22]) **v** are defined as mappings $l_i = v_i(\mathbf{m})$. Vector $\mathbf{l}^k = \{l_i\}$ contains values obtained from different value functions and includes in its formulation the subjectivity of designer and others involved in decision making. The iso-value contours l_i = const. can be visualized in **M**-space. These contours (like in geography), may exhibit multiple peaks. Some of those peaks correspond to the local minima/maxima and some are global i.e. the best for the entire $\mathbf{M}^{\geq}$. Note that optimum in constrained problems is often achieved on boundaries of the feasible region.

Distance norms (metrics) L_p are commonly used as value functions. Distance to the specified target design m^*(e.g. ideal design) is given by standard expression:

$$l_i \equiv L_p(\mathbf{m}^k) = [\sum|m_i^k - m_i^*|^p]^{1/p}$$

Figure 3 **Basic formulation of Decision Support problem**
Slika 3 **Osnovna definicija postupka potpore donošenju odluke**



Exponent p in the norm definition is taken as 1, 2 (Euclidean norm) or ∞ (Chebisev norm). The iso-value contours for given distance norms are (see Fig.1c): (1) straight lines $\sum m_i$ = const for L_1, (2) circles around $\mathbf{m}^*$ for L_2 and (3) m_i = const for L_∞. The nondominated design for min L_∞ (marked ■) can be linked to so-called 'fuzzy optimum', i.e. a design for which the minimal m_i in $\mathbf{m}^k$ is maximal. Norms are used in many works, e.g. [24,25].

Selection of preferred design (Figure 1d). To make final selection of preferred design $\mathbf{d}^P = \{\mathbf{x}^P, \mathbf{y}^P, m^P, \mathbf{l}^P\}$ the values $\mathbf{l}^k$ are calculated for all designs in $\mathbf{M}^\mathbf{N}$. Since final decision is made only on the basis of $\mathbf{l}^k$, all l_i can be put on the same axis for each design k. A set of parallel axis for all candidate designs can be displayed to facilitate final subjective decision. Parallel axes can also correspond to all l_i. Lines connecting specific designs on all axes are used to facilitate ranking of designs.

3.2. Subjective decision making techniques

The previously described subjective metric space includes the stake holder's subjective preferences/prejudices implying comparisons of designs within the same attribute (intra-attribute preferences) and determination of relative importance of different attributes (inter-attribute preferences).

Intra-attribute preferences: Subjective comparison of various designs for given attribute can be performed, as described previously, using fuzzy functions for re-definition of design attribute value. Fuzzy approach softens the sharp transition from acceptable to unacceptable (uncertainty measures included) attribute values. At the same time the values of design attributes are normalized making them commensurable. Four principal types, named attracting, ascending, descending and averting are presented in Table 1. By selecting proper type and parameters of the fuzzy function, it is easy to express designer's aspirations, [see 3 and Sec 4 and 5].

Inter-attribute preferences: Determination of subjective relative importance of different attributes (performance parameters) is often expressed using weighting factors. In this respect Saaty's method, based on preference between attributes i and j, is the most common one. The rating of preference is from 1 to 9, see Table 2.

The consistent relative significance of attributes is obtained as an eigenvector of subjective preference matrix. The matrix is formed as a result of pair wise comparisons of attributes. Preference matrix $\mathbf{P}= [P_{ij}]$ is defined as:

$$P_{ij} = \frac{p_i}{p_j} = \frac{\text{Importance of attribute } i}{\text{Importance of attribute } j}; \qquad \mathrm{P}_{ji} = P_{ij}^{-1}$$

i, j = 1, ..., NA (number of attributes).

Table 2 **Subjective pairwise preferences inter (among) attributes**
Tablica 2 **Definicija odnosa među atributima**

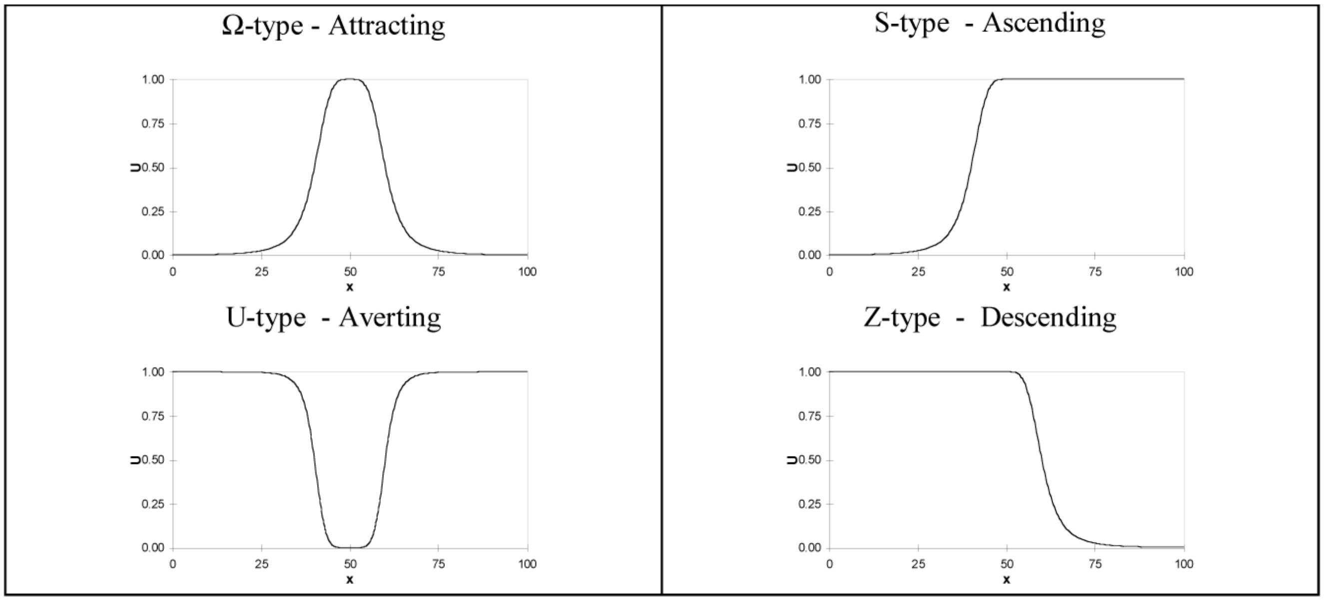
Pairwise preference attribute i vs. attribute j	P_{ij}	
	attribute i preferred	attribute j preferred
Equally important	1	1
Slightly preferred	3	1/3
Strongly preferred	5	1/5
Demonstrably preferred	7	1/7
Absolutely preferred	9	1/9

Importance vector reads $\mathbf{p} = \{p_i\}$. If the designer is fully consistent the following relation is obtained:

$$\mathbf{P} \cdot \mathbf{p} = \mathrm{NA} \cdot \mathbf{p}$$

In the case of the inconsistency of judgment the eigenvector $\Lambda = \{w_i\}$ corresponding to the largest eigenvalue (λ_{max}) of the problem:

Table 1 **Fuzzy definition of subjective preferences attributes**
Tablica 1 **Definicija subjektivnih prednosti atributa neizrazitim funkcijama**



$$(\mathbf{P} - \lambda\ \mathbf{I})\ \mathbf{p} = 0\ ;\ \mathbf{I} = \text{unit matrix},$$

is normalized and used as a vector of relative weights of attributes. Consistency of the preference may be estimated by the criterion: $C = (\lambda_{max}\text{-NA}) / (\text{NA-1}) < 0.1$. Alternatively, the normalized geometric mean of the row of the preference matrix may be used as weight:

$$w_i = (\Pi_{j=1,..NA}\ p_{i\,j})^{1/NA}$$

Sensitivity/ Robustness: For technical systems the existence of solution is often guaranteed but not its uniqueness and stability. Many parameters, held constant during optimization process, are subject to uncertainties causing variations of the values in the criteria set **Y** and/or violation of constraints (unfeasible designs). Robustness is defined as insensitivity (or stability) with respect to such changes.

Metric developed by Taguchi, see [26], is the ratio of the mean of the attribute value y_{mi} and of the standard deviation σ_{yi} resulting from uncertain parameter values. In fact, it is the ratio of predictability versus unpredictability. The 'signal-to-noise ratio'

$$SN_i = 20 \log (y_{mi}/\sigma_{yi})$$

is used to determine the relative importance of the various parameter effects. Robustness e.g. [23,27,28] and uncertainty e.g. [29] are becoming standard concept in many design references.

3.3 Design problem manipulations and solution strategies

Design mapping-(Figures 3a, 3d). Composite value function $l_i = r_i(\mathbf{x}^k)$, built from subjective criteria functions $r_i(\mathbf{x}^k) \equiv v_i(\mathbf{u}(\mathbf{a}(\mathbf{x}^k)))$, maps the feasible designs subspace $\mathbf{X}^{\geq}$ into designer's selection set **L**. The obtained values $\mathbf{l}^{\mathbf{k}}$ (cost, weight, etc.) are used for the final evaluation of the design. The described mapping **r**: $\mathbf{X}^{\geq} \longrightarrow \mathbf{L}$ is called evaluation mapping.

But in the design process the designer's task is to determine values of design variables $\mathbf{x}^{\mathbf{A}}$ for given aspired values $\mathbf{l}^{\mathbf{A}}$ of cost, weight, etc. Therefore the construction of the inverse or design mapping $\mathbf{r}^{-1} : \mathbf{l}^{\mathbf{A}} \longrightarrow \mathbf{X}^{\geq}$, that maps designer's aspirations to design parameters, is the essence of design.

The mappings used in the real design problems are almost always such that inverse functions r_i^{-1} for the inverse mapping $\mathbf{x}^A = r_i^{-1}(\mathbf{l}^A)$ do not exist and that only so called inverse image can be constructed. Basic problems are:

- x_i is often discrete or integer,
- subjective value function may not be consistent or even exist,
- criteria sets contain non-linear functions or even procedures,
- factors w have multiple values since they are subjective to all involved in design process,
- feasible domain $\mathbf{X}^{\geq}$ is non-convex and often multiply connected (vibration problems),
- no insight is provided in the design space.

Emergence of new generation of structural optimization techniques is discussed in the excellent surveys in [30] regarding current status and new directions and in [31] regarding non-gradient methods. Basic trends are:

- Multiple Criteria Decision Making (MCDM) is accepted as the only realistic general approach. Selection of MADM (Multi Attribute) or MODM (Multi Objective) formulation depends on dimensionality and mathematical complexity of the problem (see below);
- Computer speed is used for generation of large number of design variants. Parallel processing is also an important option for such 'workload';
- Approximate problem formulation is based on sensitivity and perturbation analysis. For particularly complex dynamic problems, see [32];
- Emergence of second generation of approximation techniques in structural design, see refs. from [31] imply: (a) usage of intermediate variables, (b) force approximations for stress constraints, (c) Rayleigh quotient for freq. constraints, (d) incorporation of stress recovery routines during optimization process, etc. Move limits in such processes can be raised reducing drastically number of FEM reanalysis (main measure of process efficiency);
- Meta-modeling of criteria functions or entire subspaces (e.g. $\mathbf{X}^{\mathbf{N}}$) for inexpensive-to-run approximations of expensive-to-run computer analysis is obtained using: (1) response surfaces e.g. [33], (2) neural networks, e.g. [31] and (3) kriging e.g. [23]. Neural networks are special form of response surfaces using nested squashing function. Kriging technique is a combination of fixed criteria function and departure from it described as realization of stochastic process with zero mean and spatial correlation function. Other techniques are compared in [34];
- Synergetic Multi Disciplinary Optimization (MDO) in [35] combines parameters and criteria from hydrodynamics, structures, production etc.;
- Multilevel problem decomposition (hierarchical or not) to global and local (subsystem) levels is a must for large MDO design problems. Basic to such developments are the 'agentification' of DSP to enable communication (knowledge exchange), e.g. [36] and decomposition strategy where sensitivity analysis can play a dominant role.
- Emerging techniques for large scale problems are: Simultaneous Analysis and Design (SAND), Nested Analysis and Design (NAND), All-at-once (AAO), Individual Discipline Feasible (IDF), Multi Discipline Feasible (MDF) and multilevel Concurrent Subspace Optimization (CSSO). Standard decomposition techniques used are goal coordination (modifying objective functions of subsystems) and model coordination (using coordinating variables);
- The linear combinations of prescribed (basis) designs can drastically reduce number of design variables, problem complexity and even enable coupling of shape and scantling optimizations, e.g. [33].

Manipulations and Solution strategies 1 - MODM approach: The techniques for the highly non-linear and high-dimensional problems are necessarily leading to variety of methods in operations research closely tailored to the characteristics of objective and constraint functions of the problem at hand.

Design mapping in MODM is usually transformed to the standard mathematical programming formulation: max $\mathbf{r}(\mathbf{x})$ such that $x \in \mathbf{X}^{\geq}$. If a value function combining multiple objectives can be constructed the methods for single compound objective could be used e.g. compromise and goal programming methods, see Refs. from [23]. MODM formulations can be further manipulated as follows:

(M1) Problem is projected (partitioned) to the subset of design variables (others fixed).

(M2) Linearizations and meta-modeling techniques can replace failure surfaces or their envelopes.

(M3) Many successful formulations are given in dual form. Dualization is based on combination of objective function and constraint functions via Lagrange multipliers. They are the dual variables entering the problem linearly.

Basic MODM strategies used to solve manipulated problems are:

(S1) Iterative and piecewise strategy (leading to sequence of simple problems e.g. feasible directions, penalty function approach, etc.),

(S2) Relaxation s. (temporarily removing some constraints e.g. in dualization),

(S3) Restriction s. (fixing of some variables temporarily to zero e.g. in linear programming).

Standard useful combinations of {Manipulation(s)/Strategies} are: {projection, outer linearization/relaxation e.g. cutting plane}, {projection/piecewise}, {inner linearization/restriction e.g. Dantzig-Wolfe}, {projection/feasible directions} or {dualization/feasible directions}. Methods described under (M3) are basically application of {dualization, linearization/relaxation}.

Solution strategies 2 - MADM approach: The selection of the best design is done among the discrete number of design alternatives via straightforward evaluation. The increased speed of workstations provides the opportunity to model the complex design problem as a multiple evaluation process by intentionally creating a large number of design variants. It is done through the enumeration or random search methods as the simplest and the most robust of non-gradient techniques. If sufficient density of non-dominated points is generated, one may obtain a 'discrete' inversion of the evaluation mapping for the most important parts of design space. Therefore, it is possible to replace optimization oriented MODM approach with much simpler MADM. It implies generation, evaluation and filtering of nondominated designs in affine space and final selection procedure in metric space.

In this way, problems of discrete variables and disjoint domain, prohibiting application of most analytical methods, become irrelevant. MADM approach is particularly efficient in concept design phase and in design of subsystems in preliminary/initial design phase.

Design generation and evaluation strategies: Some MADM methods and their combinations for the generation of good parent designs (e.g. on the nondominated hyper-surfaces $\mathbf{X}^N$, $\mathbf{Y}^N$ or $\mathbf{M}^N$) are listed. Classical deterministic search methods (e.g. Nelder-Mead simplex strategy used in MODM), may also be applied, particularly for exploration of the design space shape. Local and global search methods may differ and hybrid methods may emerge in the future, e.g. [2,37]. Six approaches of stochastic search are presented as example. The emerging computational paradigm is to follow processes in nature ("superb designer") and the last three methods are modeled accordingly. These methods are also more robust to local minima.

(S1) Monte Carlo sampling in design space generates *n* non-dominated designs in *t* trials. It is used for start in S2-S3 and for multiple starting points in MODM.

(S2) Sequential adaptive generation of non-dominated designs implies testing of feasible designs for the dominance in the Pareto sense. Nondominated ones are used as centers of subspaces (minicubes) in the design space for further sequential ("chain") generation of non-dominated candidates for final design selection e.g. [25]. Parallel processing was applied. Basic differences to S1 are adaptive bounds as functions of current non-dominated point $\mathbf{x}^k$.

(S3) Fractional Factorial Design (FFD) uses orthogonal arrays (OA) constructed from the Latin squares, see [26]. It is applied for efficient generation of designs and has proven efficient in higher cycles of adaptive design generation in subspaces around the non-dominated designs. The number of factor (variable, parameter) levels is from 2 to 5. Orthogonal arrays (e.g. L9, L27) with 3 levels accommodating up to 8 and 13 design variables are commonly used. They permit parallel efficient building of response surfaces, e.g. [23].

(S4) Genetic Algorithms (GA) include (a) crossover i.e. exchange of parts of chromosome contents (string of decimal or binary values of the design variables $\mathbf{x}$), (b) mutation of chromosome content and (c) statistical selection of surviving designs.

- GA are modeled following natural selection with Darwinian survival of the fittest, see [38]. They correspond to randomized adaptive search. They differ from S1-S3 by coding of the parameter set, not the parameters themselves. They use probabilistic and not deterministic transition rules regarding design fitness.
- For large scale MCDM, see [31], the multistage methods and Parallel (processing) GA are used.
- Immune Network Modeling, e.g. [39], with the antigen strings and generalist antibody strings can be used to coordinate subsystems into cooperative system. Fitness function is a bit-by-bit match-score got from the comparison of strings.

(S5) Evolution Strategies (ES) (crossover not very important) e.g. [40] are similar to S4. Strategies 4-5, like S2, search from a population of points (one generation is recombined to generate new one), not a single point. Different heuristic methods (Taboo search, Expert and Classifier systems) can be used for streamlining and guiding the design process using developed population of designs to develop new rules and/or actions, see [31].

(S6) Simulated annealing is patterned on the physical process of optimum layout of molecules due to annealing e.g. [41]. The objective function of the optimization problem is taken as the energy corresponding to a given system state (i.e. design). The design variations ($\mathbf{x}^k$) for given 'temperature' (process control parameter) are treated as the probable states with Boltzman distribution. The number of random variations at each temperature and the rate at which temperature is lowered is called the annealing schedule.

The strategies S1-S6 are used combined with predictive task performed by meta-modeling techniques. Parallel processing is easily applicable to S1-S6 strategies with the 'processor farming' (independent work) applied in generation of feasible designs. The algorithmic parallelism of processors can speed up the process of filtration of nondominated designs or the GA population selection. Since S4-S6 are basically unconstrained optimization techniques the constraint set $\mathbf{g}(\mathbf{x})$ has to be included. Special procedures, e.g. [42], or penalty function approach: $r^P(\mathbf{x}) = r(\mathbf{x}) + F(\mathbf{g}(\mathbf{x}))$, are used. Function F is penalizing the objective regarding level of constraint satisfaction**.** Immune simulation (gene repair) is also used in S4-5 to generate feasible ‘children’, see [33].

Selection strategies imply simple and fast calculation of $\mathbf{L}^N$ for known $\mathbf{M}^N$. Minimization problem is thus reduced to simple comparison of $\mathbf{l}^k$ values. For selection strategies see [24].

3.4 General design procedure and interactivity with the designer and design environment

General design shell *DeMak* is presented in Figure 4. Two phases of decision making are identified:
(a) design generation phase,
(b) design selection phase.

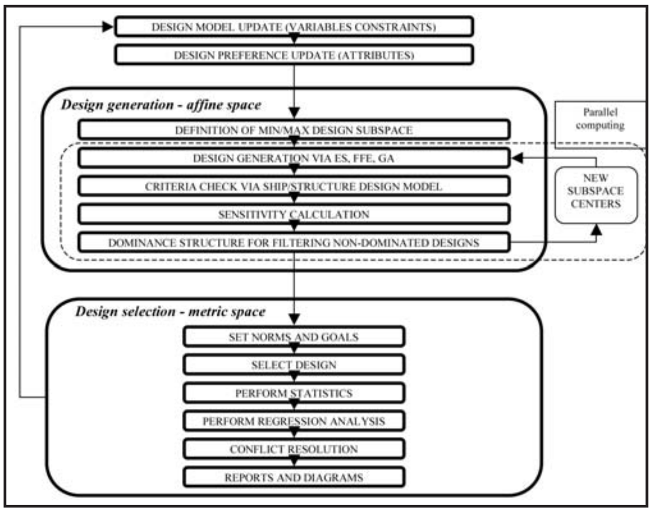


Figure 4 **DeMak environment for decision Support problem**
Slika 4 **DeMak okolina za postupak potpore donošenju odluke**

Different evolution and generation techniques (described previously) are implemented.

Basic analytical ship design model described in Section 2 is inserted into the generation phase of the shell with the minimal interface data (only values of current design variables - input and achieved criteria values - output).

Principal steps of the second phase (rational design selection) using this multi-attribute environment are:

a. Determination of criteria/attribute values e.g. cost, weight, robustness, reliability, redundancy, ultimate carrying capacity, etc.
b. Interactive definition of the preference information regarding relationship between attributes.
c. Selection of attribute type (original, membership grade). Normalization of attribute value (vector, linear scale, fuzzy functions):
d. Extraction of weight factors from subjective preference matrix. (Saaty’s method, least squares method, entropy method). The main problem is to achieve consistency of the preference definition.
e. Removal of implicit weighting by the post-optimal analysis of the attained levels of attributes for generated non-dominated designs.
f. Calculation of the L_1, L_2 and L_∞ norms with respect to the given ideal point or prescribed target for all non-dominated designs, using the selected attribute weights. Construction of other value functions, if required.
g. Stratification of the set of non-dominated solutions into layers according to the value- function value and interactive visualization of design and attribute spaces.
h. Extraction of the preferred solutions according to the given preference structure.

Interactivity, including visualization (Figure 5) gives the most powerful tool for designer's understanding of the DSP.

Stratified distances from the ideal design (Figure 3-c), calculated by L_p metric can be used as a means of visualizing multidimensional space of design attributes and/or free variables It generates expert knowledge about the problem for all participants involved, helps the designer to identify advantageous combinations of variables, other feasible options and clusters of nondominated designs thus enabling realistic decision support to the principal and structural designer.

An example of the newly developed 5D interactive visualization tool *DeView,* an utility of the *DeMak* optimizer, is shown in the presented figures applied to the design of a substructure.

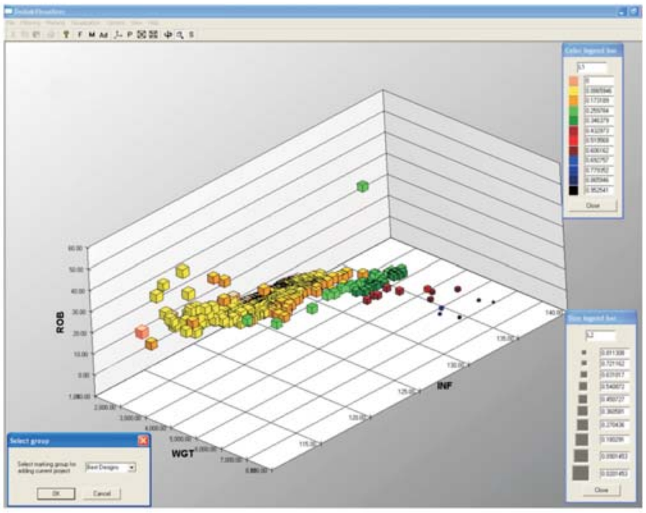


Figure 5 **Attribute space visualization in 5D view (WGT = substr. weight; ROB = substr. robustness measure; INF = information content of design; color/size = distance from ‘Ideal’ in L_1 / L_2 norms)**
Slika 5 **Peterodimenzijska vizualizacija prostora atributa (WGT = masa podv. konstr.; ROB = mjera robusnosti podv. konstr.; INF = informatički sadržaj projekta; color/size = udaljenost od idealnog rješenja u L_1 / L_2 normama)**

Present references show that ship design optimization (including interactivity/visualization) is a mature tool offering significant savings to the shipyard and ship owner: (a) increase of deadweight, (b) decrease in price and weight of construction steel, (c) increase of safety (and robustness), particularly so in the vessel concept design phase (e.g. given route, multi-model and/or multi-attribute fleet design, etc.) requiring fully multi-criteria DSP definition.

Rational definition of DSP problem is in the interest of all involved in the very competitive ship building and shipping market.

It is particularly important for the novel transport concepts for which the classical ‘evolutionary’ development of designs in Naval Architecture is not applicable.

3.5 Setting of design margins through definition of intra-attribute preferences

Very important part of the mature design procedure, regarding modelling of subjectivity, is the treatment of design margins that are used to ensure performance of design related to different design model uncertainties. Optimal selection of margins is related to designers talent but in presented Decision Support Methodology it is possible to accommodate those aspects.

Dependent design properties (attributes) consist of two groups: attributes which are guaranteed ship's characteristics (deadweight DW, trial speed v_{tr} and cargo holds/tanks volume V_{car}) and attributes which are design objectives or are used in calculation of design objectives (mass of steel structure W_{st}, cost of material C_M, cost of labour C_L and cost of newbuilding C_{NB}). Designer usually has different approach to definition of intra-attribute preferences for this two attribute groups.

Guaranteed ship's characteristics must be fulfilled within design margins arising from the shipbuilding contract. Shortage in obtaining guaranteed ship's characteristics is normally free of penalties up to some level. From that point to some higher level of deficiency shipyard is subjected to payment of agreed penalties related to level of deficiency. Shortage of obtained ship's characteristics of even larger scale is reason for newbuilding nonacceptance from the buyer's side. That situation is very unfavourable for the shipyard because is causing serious problems for the shipyard, so designer must set design margins in a way to avoid any chance of ship's nonacceptance.

Excess of obtained ship's characteristics usually is not subjected to any bonus, so it is not of interest for the shipyard and designer. Besides, fulfilling guaranteed ship's characteristics with significant excess has a consequence of reaching higher cost of newbuilding and possible problems in design development (higher ship's speed may cause difficulties in design of propeller, shafting and steering gear, torsional vibrations, determining selected maximum continuous rating and continuous service rating of the main engine, fulfilling required manoeuvring standards, etc.).

Based on these reasons selection of Ω-shape fuzzy functions is recommended for definition of intra-attribute preferences of guaranteed ship's characteristics. Lower limits can be set on the level of guaranteed figures, or on the level expected to be free of penalties, or on the level expected that newbuilding is still acceptable (or somewhere in between). Final decision of design margins definition is complex problem: more "secure" margins have a consequence of more expensive and unfavourable design for the shipyard, "insecure" margins are leading to the cheaper design, but also are increasing the risk of failure in achieving the main goal – delivery of the newbuilding. Setting the upper limits totally depend on designer's discretion, considering, of course, intention to avoid previously explained possible design problems.

Designer's interest is to minimize other attributes (mass of steel structure W_{st}, cost of material C_M, cost of labour C_L and cost of newbuilding C_{NB}) as much as possible. That leads to recommendation of Z-shaped fuzzy functions for definition of intra-attribute preferences. In that case lower limits have not to be set. Setting the upper limits is again depending on designer's decision based on his experience and actual newbuilding cost level. Upper limits must be set on the position which enables selection of nondominated designs based on inter-attribute preferences, and, in the same time, level which supports optimization procedure in reaching the global optimum or designs close to the global optimum.

Definition of intra-attribute preferences through fuzzy functions enables ship's designers to introduce their own approach to problem of design margins in the ship design algorithm. In this novel approach the designer is capable, through assigning intra-attribute preferences to each attribute, to guide final design solution to area of a priori defined risk level. Definition of intra-attribute preferences through fuzzy functions enables investigation of interconnectivity between design margins and achieved risk level of resulted attributes/objectives. Also, it enables normalization of design attributes and consistent definition of inter-attribute preferences.

4 Application to concept design of bulk carriers

4.1 Overview of modern Capesize bulk carriers

Capesize bulk carriers are the largest ships for the carriage of bulk cargo. They are built exclusively in the Far East shipyards. The following table gives some modern, high-quality designs.

Table 3 **Modern Capesize bulk carriers**
Tablica 3 **Suvremeni Capesize bulk carrieri**

Shipyard	*IHHI*	*Sasebo H.I.*	*Koyo Dock.*	*Namura*	*NKK*
L_{oa} (m)	289.0	289.0	288.93	287.64	289.0
L_{pp} (m)	277.0	279.0	280.0	277.0	279.0
B (m)	45.0	44.98	45.0	45.0	45.0
D (m)	23.8	24.4	23.8	24.1	24.1
d_s (m)	17.6	17.95	17.6	17.7	17.81
DW (t)	170780	170415	171199	171191	172510
GT	83849	87407	85379	85868	87522
Capacity of cargo holds (m^3)	186668		188205	191255	191582
Main engine	6RTA72	6S70MC	6S70MC	6S70MC	6S70MC
SMCR (kW/rev.)	16040/93	16860/91	16100/87	16370/90.1	14705/80
CSR (kW/rev.)	13636/88.1	13700/85	13695/82.4	13910/85.3	12500/75.8
$v_{tr,\ ballast}$ (kn)	17.53	16.34	16.79	16.67	
$v_{service}$ (kn)	14.8	14.5	14.6	14.8	14.7

From the data presented in Table 3, the following conclusions can be drawn:

- Deadweight ranges from 170,000 to 172,500 t;
- Cargo holds capacity is from 186,000 to 191,500 m^3;
- Specific voluminosity [B1] of the ship is in the range from 0.6243 to 0.6367;
- Length between perpendiculars ranges between 277 to 280 m;
- Breadth is the same in all presented designs - 45 (m);
- Draught ranges from 16.5 to 17.95 (m);
- Trial speed is from 16.3 to 17.5 (kn).

4.2 Design requirements

Based on the data presented above, the following design requirements are set:

- Deadweight is 172,000 t;
- Cargo holds capacity is 190,000 m^3;
- Maximum length between perpendiculars is 280 m;
- Maximum breadth is 45 m;
- Maximum scantling draught is 17.95 m;
- Trial speed at the scantling draught will be 15.2 knots.

4.3 Identification of the design task

Design procedure follows mathematical model published in [B1], section 6. Problem is solved using DeMak multicriterial solver and inbuilt Evolution strategy based on adaptive MC and FFE. Experiments were also done with MOPSO (multiobjective particle swarm optimization).

4.3.1 Design variables and parameters

Design variables and parameters identified for Bulk-Carrier project:

- length between perpendiculars L_{pp},
- breadth B,
- scantling draught d_s,
- block coefficient C_B,
- selection of the main engine between the following two main engines:
- *MAN B&W* 6S70MC-C, mark 7,
- *MAN B&W* 5S70MC-C, mark 7,
- deadweight DW,
- volume of cargo holds V_{car},
- trial speed v_{tr},
- specific voluminosity of the ship $\kappa = 0.64$,
- parameters required for the calculation of the ship's light weight:
  a) estimated percentage of high tensile steel is about 30%, so that its application affects the reduction of the total weight of steel structure by approximately 5%, i.e. $f_1 = 5$;
  b) set factor f_2, in accordance with [B1], Figure 10, at the value of 0.0282;
  c) estimated weight of the steel of accommodation and hatch coamings, hatch cover and forecastle is $f_3 = 450$ t;
  d) factor f_4 is given, according to [B1], Figure 12, at the value of 800;
  e) set CSR at 90% SMCR, i.e. f_5 factor is 0.9;
  f) set f_6 factor, according [B1], Figure 14, at the value of 0.28.
- maximum powers and prices of main engines:
  a) 6S70MC-C, mark 7 (MCR 18660 kW/91 rpm), C_{ME1} = 8.4 m US $
  b) 5S70MC-C, mark 7 (MCR 15550 kW/91 rpm), C_{ME2} = 7.4 m US $
- data for the calculation of costs of materials and of ship building:
  a) average unit price of steel c_{st} = 1000 US $/t
  b) ratio between the gross mass of steel and the weight of steel structure $W_{gst}/W_{st} = 1.12$
  c) other costs for materials and equipment C_{fix} = 26.0 m US $
  d) compensation factors A and B for calculation of cGT according to [B1], Table 4 A = 29 B = 0.61
  e) set the productivity at the value of P_{cGT} = 35 wh/cGT
  f) set unit hourly wage at the value of V_L = 30 US $/wh
  g) other costs C_{oc} = 7.0 m US $

4.3.2 Design constraints

Min-max constraints with steps within the range are given as:

$265 \le L_{pp} \le 280$ m, step of 1.0 m
$43 \le B \le 45$ m step of 0.2 m
$17.5 \le d_s \le 17.95$ m step of 0.05 m
$0.85 \le C_B \le 0.875$ step of 0.0025

Constraints of basic dimensions are defined as follows:

$5.8 \le L_{pp}/B \le 6.5$
$15.3 \le L_{pp}/d_s \le 16.2$
$2.3 \le B/d_s \le 2.7$
$11.0 \le L_{pp}/D \le 11.9$

4.3.3 Design attributes

Summary of the attributes listed and described in section 2.1.1.3 and [B1], section 6.1.3:

a) weight of the steel structure W_{st},
b) cost of material C_M,
c) cost of labour (process) C_L,
d) cost of newbuilding C_{NB},
e) deadweight DW,
f) trial speed v_{tr},
g) cargo space capacity V_{car}.

Subjective preference matrix (section 3.2) in accordance with the optimization method described in section 3 is presented in Table 4:

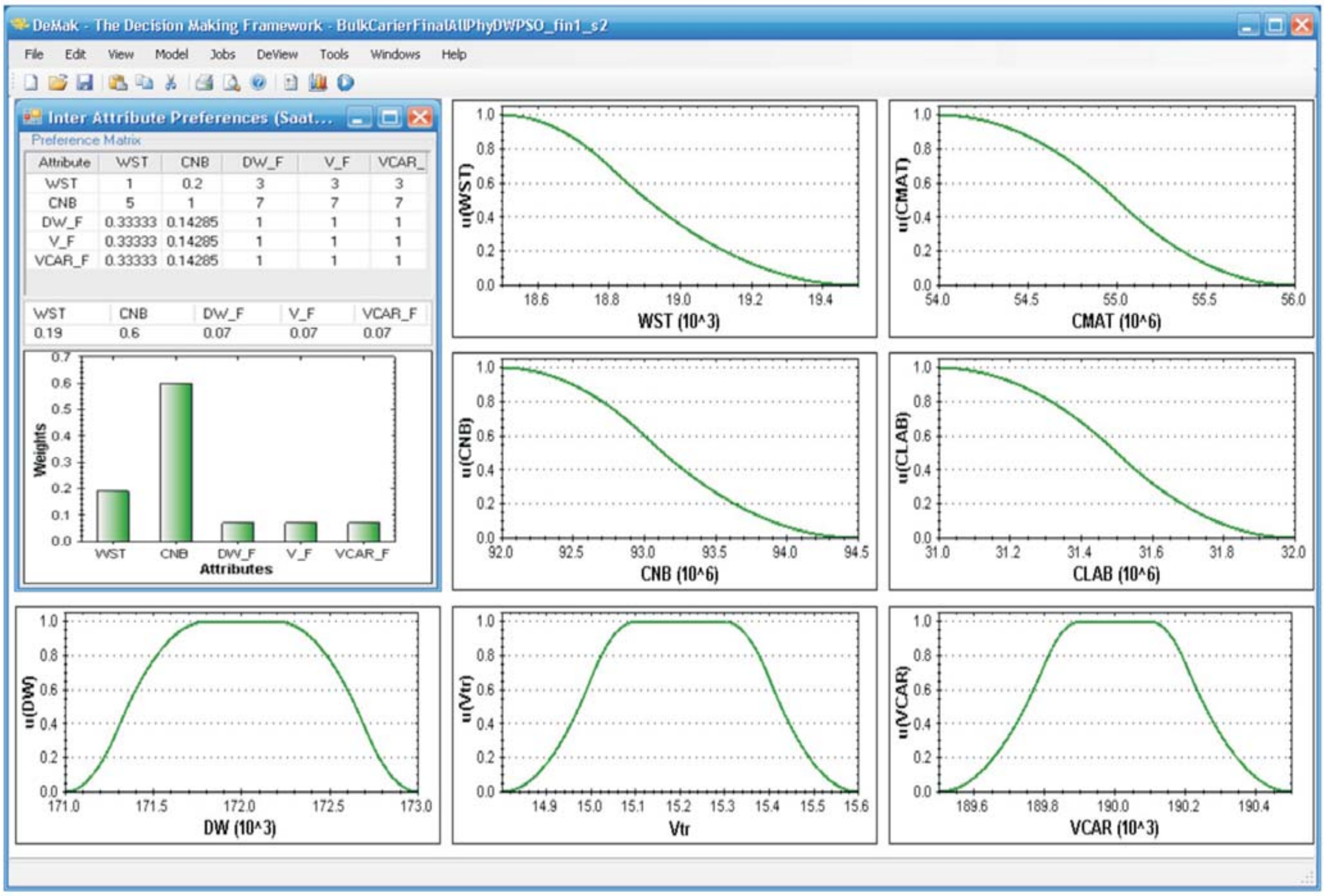
Table 4 **Determined intra-attribute preferences**
Tablica 4 **Zadane prednosti među atributima**

	DW	v_{tr}	V_{car}	W_{st}	C_M	C_L	C_{NB}
DW	1	1	1	1/3	1/5	1/5	1/7
v_{tr}	1	1	1	1/3	1/5	1/5	1/7
V_{car}	1	1	1	1/3	1/5	1/5	1/7
W_{st}	3	3	3	1	1/3	1/3	1/5
C_M	5	5	5	3	1	1	1/3
C_L	5	5	5	3	1	1	1/3
C_{NB}	7	7	7	5	3	3	1

Associated fuzzy functions for particular design variables [43] are given as follows (section 3.2) using six characteristic values of the membership grade μ (from left to right).

Table 5 **Determined fuzzy functions**
Tablica 5 **Zadane neizrazite funkcije**

Attribute	Type of function	a_1	b_1	c_1	c_2	b_2	a_2
DW (t)	Ω	171000	171300	171800	172000	172700	173000
v_{tr} (kn)	Ω	14.8	15.0	15.1	15.3	15.4	15.6
V_{car} (m^3)	Ω	189500	189800	189900	190100	190200	190500
W_{st} (t)	Z				18500	18800	19500
C_M (m US \$)	Z				54.0	55.0	56.0
C_L (m US \$)	Z				31.0	31.5	32.0
C_{NB} (m US \$)	Z				92.0	93.0	94.5



Attribute	WST	CNB	DW_F	V_F	VCAR_
WST	1	0.2	3	3	3
CNB	5	1	7	7	7
DW_F	0.33333	0.14285	1	1	1
V_F	0.33333	0.14285	1	1	1
VCAR_F	0.33333	0.14285	1	1	1

WST	CNB	DW_F	V_F	VCAR_F
0.19	0.6	0.07	0.07	0.07

Figure 6 **Graphical representation of preferences**
Slika 6 **Grafički prikaz prednosti**

Figure 6 gives a graphical representation of selected inter-attribute preferences among attributes relevant for decision making process (upper part- left) and fuzzy function graphs for all attributes (intra-attribute preferences based on values from Table 5).

In the right and lower part of the figure, numerical data and a graphical representation of fuzzy functions associated to the attributes are shown. Weight of steel structure W_{st}, cost of material C_M, cost of labour (process) C_L and the total cost of newbuilding C_{NB} are Z-shaped and have no lower limits defined since with the presented attributes, the option of “dissatisfaction” with the associated minimal values does not exist. Attributes which are additionally guaranteed ship’s characteristics (deadweight DW, trial speed v_{tr} and cargo tanks volume V_{car}) have Ω-shaped fuzzy functions with lower limits defined on the level expected to be free of penalties.

In the upper left part of the figure there is a subjective preference matrix and a graphical representation of weighting factors of attributes relevant for decision making process.

4.3.4 Design objectives

In accordance with section 2.1.1.4 and [B1], section 6.1.4, the following design objectives may be identified:

- minimize the weight of steel structure,
- minimize the power of main engine (using catalogue main engines),
- minimize the cost of newbuilding.
- additional objectives used for satisfaction of the constraints within given margins:

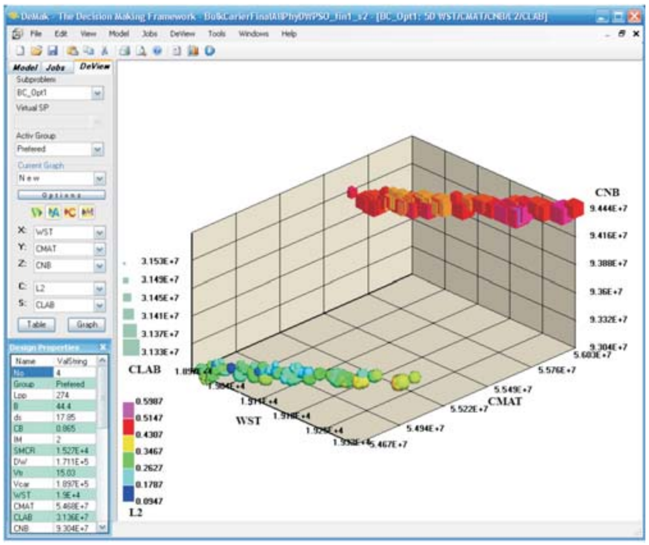
(a) Trial speed v_{tr}; (b) Volume of cargo V_{car} (c) Deadweight DW

4.4 Results and discussion

Approximate calculations of minimum freeboard, main engine minimum power and building cost are given in appendices A1, A2 and A3. The result of the applied design process is a number of nondominated designs (Pareto frontier). Figure 7 gives nondominated designs in a 3D coordinate system with the weight of steel W_{st}, costs of material C_M and costs of newbuilding C_{NB} on the three coordinates. The shape designating a particular design (cube or sphere) is attributed to the associated main engine (the designs designated by a sphere have a 5S70MC-C main engine, and those by a cube a 6S70MC-C). The size of the cube, or a sphere represents the costs of labour (lower costs are represented by a bigger cube, or a sphere, respectively). Thus, a 5D space of design attributes has been defined. The colour spectrum represents the remoteness from the utopia.

One can notice that the designs are grouped in two major groups with respect to the selected main engine (below, to the left, there are designs designated by a sphere, which are characterized by 5-cylindre main engines, and up, to the right, there are designs designated by a cube, which are characterized by 6-cylindre main engines). The designs with a smaller main engine are closer to the utopia (coloured in azure, blue and green), which means that the costs of newbuildings are dominant and preferred with respect to other design attributes.

Figure 7 **Nondominated designs (Pareto frontier)**
Slika 7 **Nedominirani projekti (Pareto fronta)**



Subproblem: BC_Opt1
Activ Group: Prefered
Current Graph: New
X: WST
Y: CMAT
Z: CNB
C: L2
S: CLAB

Name	ValString
No	4
Group	Prefered
Lpp	274
B	44.4
ds	17.85
CB	0.865
IM	2
SMCR	1.527E+4
DW	1.711E+5
Vtr	15.03
Vcar	1.897E+5
WST	1.9E+4
CMAT	5.468E+7
CLAB	3.136E+7
CNB	9.304E+7

This leads to a conclusion that the increase in the main engine costs has a greater influence on the total costs of newbuildings than other influential factors. The difference in the main engine costs in section 4.3.1 is given at a level of 1.0 m US $, which cannot be matched by the difference in the costs of steel and those of labour.

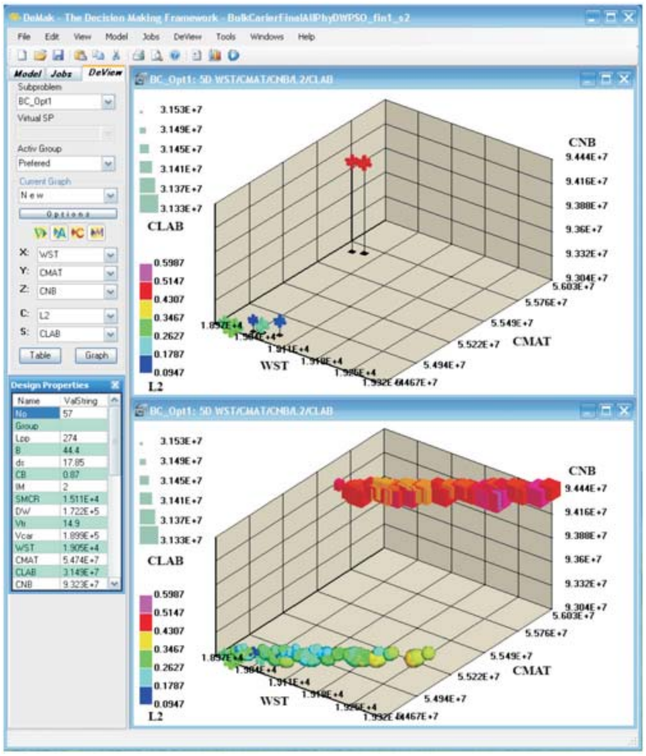
In the lower left corner there are data pertaining to any of nondominated designs presented in the figure. In the upper left corner, there are all the values defining the presented 5D space.

In the lower part of the Figure 8, the previous figure is repeated, i.e. nondominated designs in a 3D coordinate system are given, with the weight of steel W_{st}, cost of materials C_M and the cost of newbuildings C_{NB} on each coordinate, respectively. The shape designating a particular design (cube or sphere) also designates the associated main engine (designs designated by a sphere have a 5S70MC-C main engine, while those by a cube have a 6S70MC-C). The size of the cube, or the sphere, represents the costs of labour (lower costs of labour are represented by a bigger cube, or a smaller sphere). Thus, a 5D space of design tasks has been defined. The colour spectrum represents the remoteness from the utopia.

The upper part of the figure represents only the designs preferred by a certain criterion – in this case four designs with lowest cost of newbuilding are selected, two designs according to selected metrics which is as close to the utopia as possible and two best designs with bigger main engines; all the designs are designated by 3D pluses.

The data referring to one of the presented designs are given in the left part of the figure. It is important to note that when us-

Figure 8 **Nondominated designs (Pareto frontier)**
Slika 8 **Nedominirani projekti (Pareto fronta)**



Subproblem: BC_Opt1
Activ Group: Prefered
Current Graph: New
X: WST
Y: CMAT
Z: CNB
C: L2
S: CLAB

Name	ValString
No	57
Group	
Lpp	274
B	44.4
ds	17.85
CB	0.87
IM	2
SMCR	1.511E+4
DW	1.722E+5
Vtr	14.9
Vcar	1.899E+5
WST	1.905E+4
CMAT	5.474E+7
CLAB	3.149E+7
CNB	9.323E+7

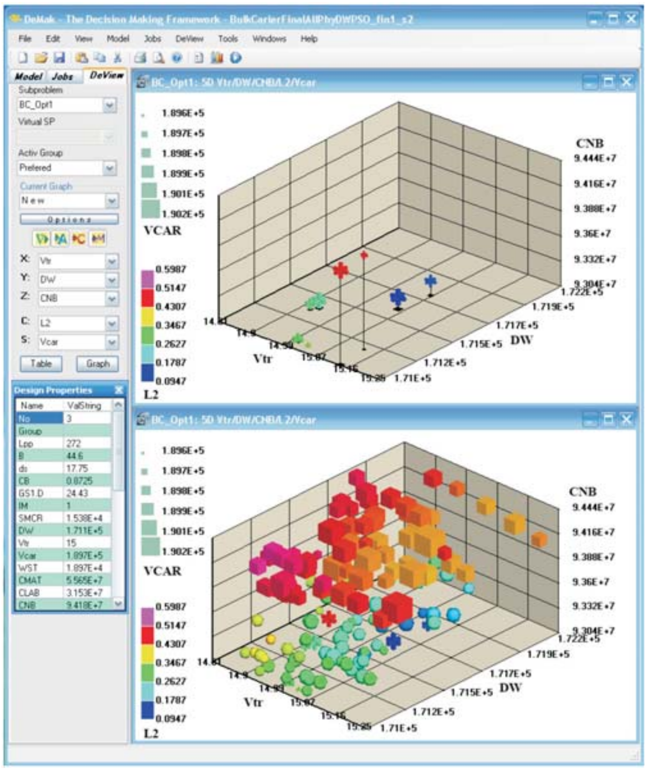
ing the visualization program it is possible to define in different ways the space in which designs are presented, to select preferred designs according to different criteria and to obtain alphanumeric data for any of the presented designs. The coordinate system can be freely rotated in space and put into a position (or positions) in which particular features of a design can be observed best.

Figure 9 represents nondominated designs (Pareto frontier) in coordinate systems: trial speed v_{tr}, deadweight DW and cost of newbuildings C_{NB} with the cargo holds capacity expressed by the size of designation.

From this figure one can easily notice the division of designs into two major groups according to the selected main engine. In both figures designs with smaller main engines (closer to an ideal solution) are marked by azure, blue and green. The size of the cube, or sphere, (volume of cargo holds) is fairly uniformly distributed. This leads to a conclusion that meeting this requirement within given associated fuzzy functions has no significant influence on the costs of newbuildings as a dominant attribute.

Figure 10 gives a representation of subjective space of design attributes. In the lower part of the figure there are eight preferred designs. The upper diagram has designs presented in different colours, and subjective satisfactions of each attribute are given on the abscissa. The lower diagram has a reversed situation with attributes on the ordinate.

A table with alphanumeric data of all preferred designs is given in the upper part of the figure. It can be noted again that the cost of main engine has a major share in the total costs of material, while the differences in the costs of labour (process) are of a lesser degree. The presented figures give design information required for the final selection of one of nondominated or subjectively preferred designs.



Subproblem: BC_Opt1

Virtual SP

Activ Group: Prefered

Current Graph: New

X: Vtr

Y: DW

Z: CNB

C: L2

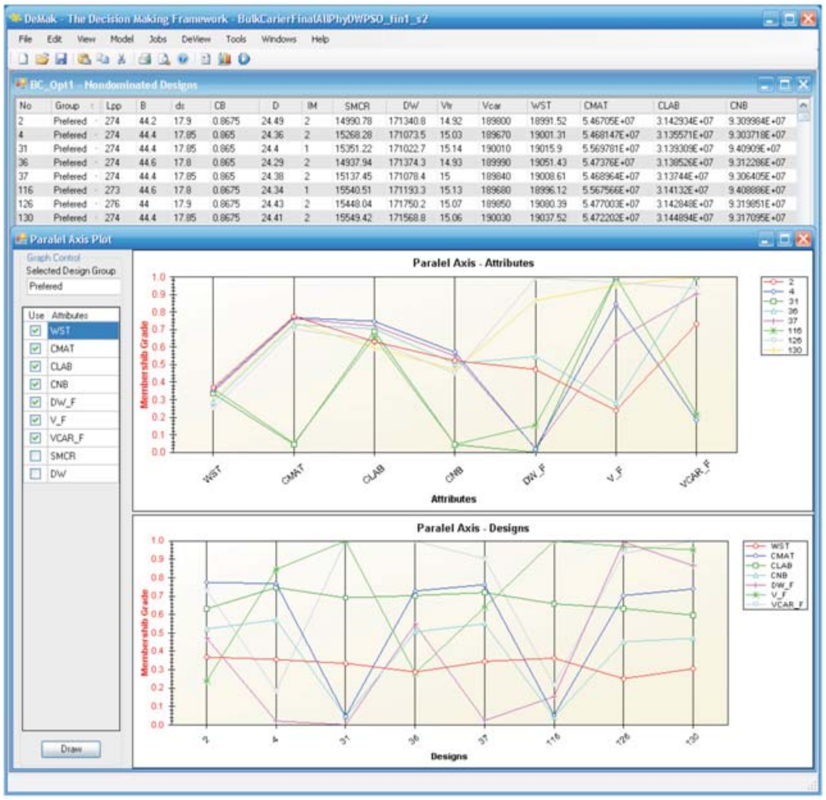
S: Vcar

Design Properties

Name	ValString
No	3
Group	
Lpp	272
B	44.6
ds	17.75
CB	0.8725
GS1.D	24.43
IM	1
SMCR	1.538E+4
DW	1.711E+5
Vtr	15
Vcar	1.897E+5
WST	1.897E+4
CMAT	5.565E+7
CLAB	3.153E+7
CNB	9.418E+7

Figure 9 **Nondominated designs (Pareto frontier)**
Slika 9 **Nedominirani projekti (Pareto fronta)**

Figure 10 **Subjective decision making by means of parallel axes**
Slika 10 **Subjektivno odlučivanje putem paralelenih osi**



BC_Opt1 - Nondominated Designs

No	Group	Lpp	B	ds	CB	D	IM	SMCR	DW	Vtr	Vcar	WST	CMAT	CLAB	CNB
2	Prefered	274	44.2	17.9	0.8675	24.49	2	14990.78	171340.8	14.92	189800	18991.52	5.46705E+07	3.142934E+07	9.309984E+07
4	Prefered	274	44.4	17.85	0.865	24.36	2	15268.28	171073.5	15.03	189670	19001.31	5.468147E+07	3.135571E+07	9.303718E+07
31	Prefered	274	44.4	17.85	0.865	24.4	1	15351.22	171022.7	15.14	190010	19015.9	5.569781E+07	3.139309E+07	9.40909E+07
36	Prefered	274	44.6	17.8	0.865	24.29	2	14937.94	171374.3	14.93	189990	19051.43	5.47376E+07	3.138526E+07	9.312286E+07
37	Prefered	274	44.4	17.85	0.865	24.38	2	15137.45	171078.4	15	189840	19008.61	5.468964E+07	3.13744E+07	9.306405E+07
116	Prefered	273	44.6	17.8	0.8675	24.34	1	15540.51	171193.3	15.13	189680	18996.12	5.567566E+07	3.14132E+07	9.408886E+07
126	Prefered	276	44	17.9	0.8675	24.43	2	15448.04	171750.2	15.07	189850	19080.39	5.477003E+07	3.142848E+07	9.319851E+07
130	Prefered	274	44.4	17.85	0.8675	24.41	2	15549.42	171568.8	15.06	190030	19037.52	5.472202E+07	3.144894E+07	9.317095E+07

Selected Design Group: Prefered

Use	Attributes
☑	WST
☑	CMAT
☑	CLAB
☑	CNB
☑	DW_F
☑	V_F
☑	VCAR_F
☐	SMCR
☐	DW

It is possible to select a design with lowest costs of building as a subjectively preferred design, which is a desired design solution for the shipyard as a stakeholder. Figure 10 gives the design no. 4 as a selected design: it is presented on the diagram in the upper part of the figure by a blue line with little squares and it has the highest value on the ordinate of newbuildings; the diagram in the lower part gives the costs of newbuildings in a light blue line with little triangles with the highest value on the ordinate of design no. 4. Basic characteristics of the design are as follows:

L_{pp} = 274.0 m
B = 44.4 m
d_s = 17.85 m
D = 24.36 m
C_B = 0.865
Main engine:
MAN B&W
5S70MC-C, mark 7
SMCR = 15268 kW

DW = 171073 t
v_{tr} = 15.03 kn
V_{car} = 189670 m^3
W_{st} = 19001 t
C_M = 54.681 m US $
C_L = 31.356 m US $
C_{NB} = 93.037 m US $

As far as the design requirement is concerned, one can notice that the preferred design falls short of the obtained deadweight and cargo holds volume. It leads to conclusion that, during the further design development, actions related to cargo holds geometry and all weight groups must be performed with special care. Obtained trial speed is close to the required one and it is not needed to pay extra attention during further design development. Such a quality of the preferred design could have been expected since this solution minimizes the costs of newbuildings which are given as a dominant attribute in determining relations among design attributes.

Presented design of Capesize bulk carrier is a preferred design due to its basic characteristics and especially due to its commercial effects (smaller and cheaper main engine) and it is superior to the designs presented in Table 3.

5 Application to concept design of tankers

5.1 Overview of modern Handymax product tankers

The best modern Handymax product tankers are built in the Far East and Croatian shipyards. Therefore, Table 6 gives examples of three good quality newbuildings from Japanese shipyards and two from Croatian shipyards.

Table 6 **Modern Handymax product tankers**
Tablica 6 **Suvremeni *Handymax product* tankeri**

Shipyard	*Mizushima*	*Onomichi*	*Shin Kurus.*	*Brodosplit*	*Brodotrogir*
L_{oa} (m)	182.0	182.5	179.88	183.4	182.5
L_{pp} (m)	174.0	172.0	172.0	175.0	174.8
B (m)	32.20	32.20	32.20	32.0	32.20
D (m)	17.80	19.10	18.70	17.95	17.50
d_s (m)	12.65	12.65	12.0	12.0	12.2
DW (t)	48338	47131	45908	44881	47400
GT	27185	28534	28077	27533	27526
Cargo tank vol. (m^3)	52180	53609	53562	55926	53100
Main engine	6RTA48T	6S50MC	6UEC60LA	6S50MC	6S50MC
SMCR (kW/rev.)	8160/124	8580/127	9267/110	8240/122	8310/123
CSR (kW/rev.)	7460/122.4	7705/123	7877/104	7415/117.8	7480/118.8
$v_{tr,\ ballast}$ (kn)	15.35	16.28	16.82	16.5	16.5
$v_{service}$ (kn)	14.25	15.0	14.6	14.5	14.7

Based on the data presented above, the following conclusions can be drawn:

- Deadweight is in the range between 45000 and 48300 t;
- Cargo tanks capacity is from 52200 to 56000 m^3;
- Specific voluminosity of the ship ranges from 0.5068 to 0.5564;
- Length between perpendiculars is from172 to 175 m;
- Breadth is the same in all designs, except in that of *Brodosplit*, where it is 32.2 m;
- Scantling draught ranges from 12.0 to 12.65 m;
- Service speed is from 14.25 to 15.0 knots.

5.2 Design requirements

Based on the data presented above, the following design requirement can be set:

- Deadweight of 50000 t;
- Cargo holds capacity of 58000 m^3;
- Maximum length over all of 182.88 m, and length between perpendiculars of 174.8 m;
- Maximum breadth of 32.24 m;
- Maximum scantling draught of 12.65 m;
- Speed at scantling draught and in trial conditions of 15.0 knots.

5.3 Design task identification

Design procedure follows mathematical model published in [B1], section 6. Problem is solved using *DeMak* multicriterial solver and inbuilt Evolution strategy based on adaptive MC and FFE. Experiments were also done with MOPSO (particle swarm).

5.3.1 Design variables and parameters

The following design variables and parameters are identified:

- length between perpendiculars L_{pp},
- breadth *B*,
- scantling draught d_s,
- block coefficient C_B,
- selection between two potential main engines:
- *MAN B&W* 6S50MC-C, mark 7,
- *MAN B&W* 7S50MC-C, mark 7,
- deadweight *DW*,
- cargo holds volume V_{car},
- trial speed v_{tr},
- specific voluminosity [B1], of the ship $\kappa = 0.56$;
- parameters required for the calculation of light ship:
  a) estimated percentage of high tensile steel is approximately 15%; thus its use has an impact on the reduction of the steel structure total weight of approximately 3%, i.e. $f_1 = 3$;

  b) set f_2 factor, in accordance with [B1], Figure 11, at the value of 0.034;
  c) estimated steel weight of accomodation and hatch coamings is f_3= 350 t;
  d) set f_4 factor, according to [B1], Figure 13, at the value of 860;
  e) set CSR of main engine at 90% SMCR, i.e. set the f_5 factor at 0.9;
  f) set f_6 factor, in accordance with [B1], Figure 15, at the value of 0.29.
- maximum powers and costs of main engines:
  a) 6S50MC-C, mark 7 (MCR 9480 kW/127 RPM), C_{ME1} = 4.7 m US $
  b) 7S50MC-C, mark 7 (MCR 11060 kW/127 RPM), C_{ME2} = 5.2 m US $
- data for the calculation of costs of material and building of a ship:
  a) average unit price of steel c_{st} = 1000 US $/t
  b) gross weight of steel/ weight of steel structure ratio W_{gst}/W_{st} = 1.15
  c) cost of other materials and equipment C_{fix} = 16.0 m US $
  d) compensation factors A and B for calculation of cGT according to [B1], table 4 A = 48 B = 0.57
  e) productivity is set at the value of P_{cGT} = 35 wh/cGT
  f) unit hourly wage V_L = 30 US $/wh
  g) other costs C_{oc} = 4.0 m US $

5.3.2 Design constraints

The min-max constraints with steps within the range are given as follows:

$170 \leq L_{pp} \leq 174.8$ m	step 0.2 m
$32.0 \leq B \leq 32.24$ m	step 0.04 m
$12.2 \leq d_s \leq 12.65$ m	step 0.05 m
$0.82 \leq C_B \leq 0.845$	step 0.001

The following constraints of main dimension ratios are:

$$5.3 \leq L_{pp}/B \leq 5.6$$
$$13.7 \leq L_{pp}/d_s \leq 14.2$$
$$2.5 \leq B/d_s \leq 2.8$$
$$9.2 \leq L_{pp}/D \leq 10.0$$

5.3.3 Design attributes

The list the attributes described in section 2.1.1.3 and [B1], section 6.1.3 reads:

a) weight of steel structure W_{st},
b) cost of material C_M,
c) cost of labour (process) C_L,
d) cost of newbuildings C_{NB},
e) deadweight *DW*,
f) trial speed v_{tr},
g) cargo tanks volume V_{car}.

In accordance with the design methodology described in Section 3, the subjective preference matrix (section 3.2) is given in Table 7.

Table 7 **Subjective preference matrix**
Tablica 7 **Zadane prednosti među atributima**

	DW	v_{tr}	V_{car}	W_{st}	C_M	C_L	C_{NB}
DW	1	1	1	1/3	1/5	1/5	1/7
v_{tr}	1	1	1	1/3	1/5	1/5	1/7
V_{car}	1	1	1	1/3	1/5	1/5	1/7
W_{st}	3	3	3	1	1/3	1/3	1/5
C_M	5	5	5	3	1	1	1/3
C_L	5	5	5	3	1	1	1/3
C_{NB}	7	7	7	5	3	3	1

The associated fuzzy functions [43] for particular design variables (section 3.2) are presented in Table 8.

Table 8 **Fuzzy functions**
Tablica 8 **Zadane neizrazite funkcije**

Attribute	Type of function	a_1	b_1	c_1	c_2	b_2	a_2
DW (t)	Ω	49600	49800	49900	50100	50200	50400
v_{tr} (kn)	Ω	14.7	14.8	14.9	15.1	15.2	15.4
V_{car} (m^3)	Ω	57800	57900	57950	58050	58100	58200
W_{st} (t)	Z				8200	8250	8400
C_M (m US $)	Z				30.0	30.5	31.0
C_L (m US $)	Z				17.0	17.5	18.0
C_{NB} (m US $)	Z				51.0	52.0	53.5

Figure 11 gives a graphical representation of selected inter-attribute preferences among attributes relevant for decision making process (upper part left) and fuzzy function graphs for all attributes (intra-attribute preferences based on values from Table 8).

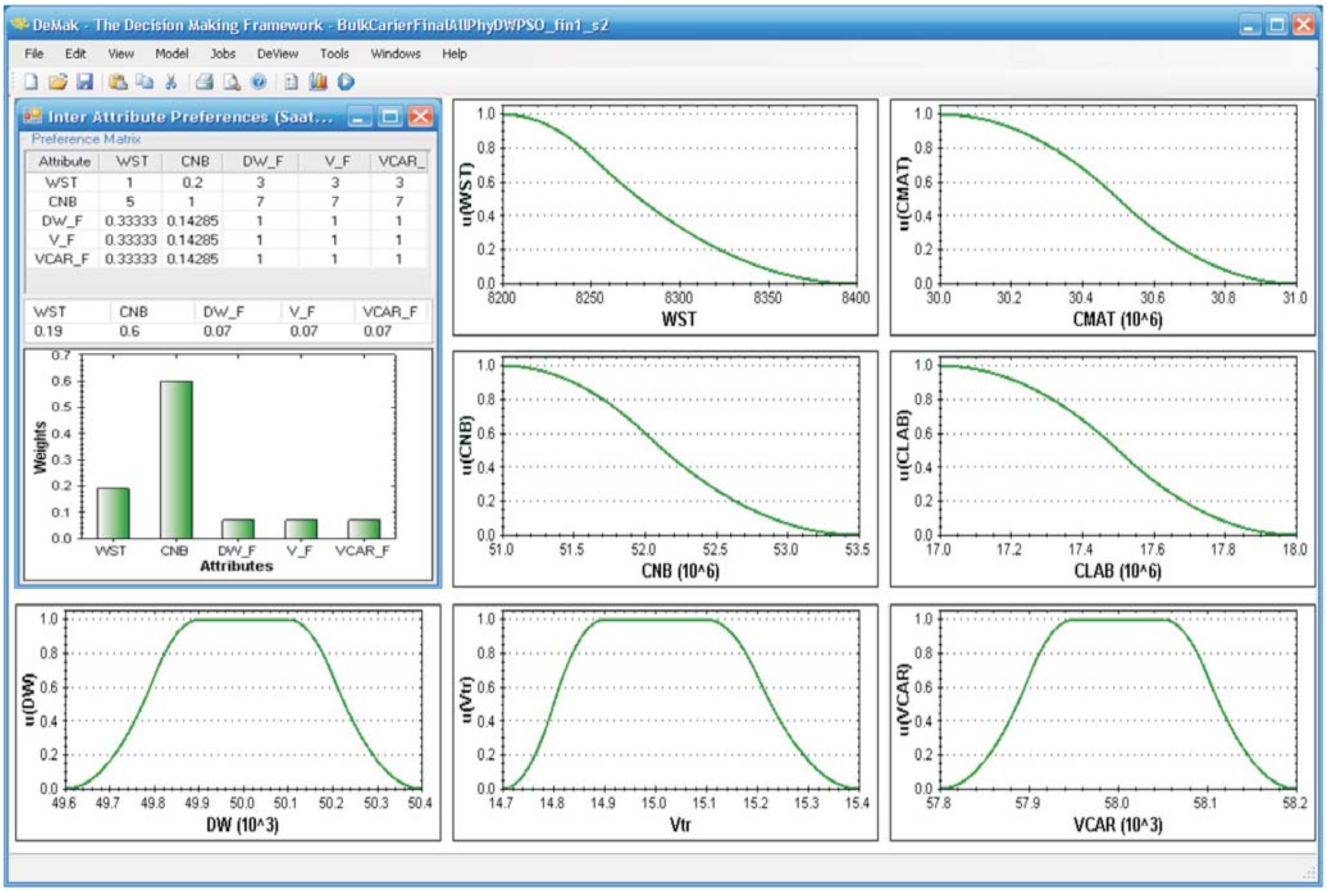
Numerical data and a graphical representation of fuzzy functions associated to the attributes are shown in the right and lower part of the figure. Weight of steel structure W_{st}, cost of material C_M, cost of labour (process) C_L and the total cost of newbuilding C_{NB} are Z-shaped and have no lower limits defined. Other attributes (deadweight *DW*, trial speed v_{tr} and cargo tanks volume V_{car}) are the additionally guaranteed ship's characteristics and they have Ω-shaped fuzzy functions with lower limits defined on the level expected to be free of penalties.

In the upper left part of the figure there is a subjective preference matrix and a graphical representation of weighting factors of attributes relevant for decision making process.

5.3.4 Design objectives

As already stated in section 2.1.1.4 and [B1], section 6.1.4, the following design attributes may be identified. By adding improvement direction they are transferd to objectives:

- minimize the steel structure weight,
- minimize the main engine power,



Attribute	WST	CNB	DW_F	V_F	VCAR_
WST	1	0.2	3	3	3
CNB	5	1	7	7	7
DW_F	0.33333	0.14285	1	1	1
V_F	0.33333	0.14285	1	1	1
VCAR_F	0.33333	0.14285	1	1	1

WST	CNB	DW_F	V_F	VCAR_F
0.19	0.6	0.07	0.07	0.07

Figure 11 **Graphical representation of preferences**
Slika 11 **Grafički prikaz prednosti**

- minimize the costs of newbuilding

- additional objectives used for satisfaction of the constraints within given margins:

(a) Trial speed v_{tr}; (b) Volume of cargo V_{car} (c) Deadweight *DW*

5.4 Results and discussion

Approximate calculations of minimum freeboard, main engine minimum power and building cost are given in appendices A4, A5 and A6. The design process has resulted in a number of nondominated designs.

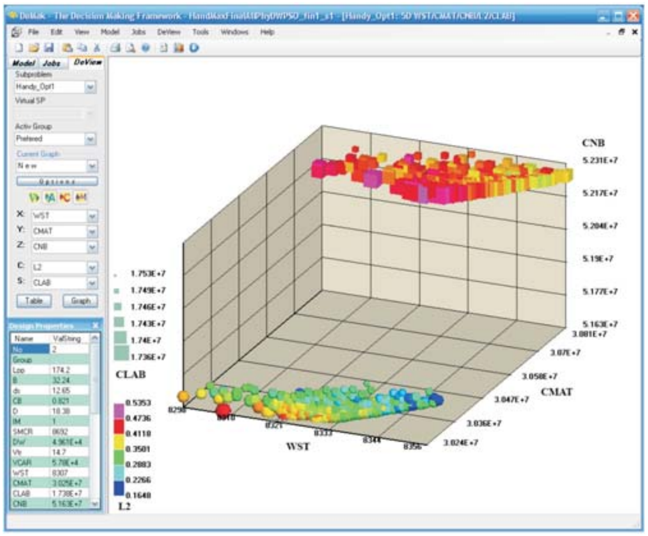
Figure 12 shows nondominated designs in a 3D coordinate system: weight of the steel structure W_{st}, costs of material C_M, and costs of newbuilding C_{NB} on the three coordinates. The shape of designation identifies the main engine type (sphere - 6S50MC-C, cube - 7S50MC-C). The size of designation represents the cost of labour C_L, and the colour spectrum represents the remoteness from the utopia.

The figure illustrates possible combinations of design dimensions for the purpose of analyzing interrelations of particular attributes and their impacts. In this figure, one can also notice two major groups of designs classified according to the selected main engine type (low, left – designs designated by a sphere and characterized by six-cylinder main engines). Designs with smaller main engines are closer to the utopia (coloured in azure, blue and green). This means, more or less as in the previous example, that the cost of newbuilding is dominant and preferred with respect to other design attributes. In this case it leads to a conclusion that the rise in costs of main engine has a greater influence on the total costs of newbuilding than other influential factors. The difference in the price of main engines which is determined in section 5.3.1 at the level of 0.5 m US $ cannot be matched by the difference in the cost of steel and cost of labour.

The data referring to any of nondominated designs presented in the figure are in the lower left part. Values which define the presented 5-D space are recapitulated in the upper left part.

Figure 13 represents nondominated designs in the same coordinate system as in Figure 12. The lower parts of figures represent all nondominated designs, and the upper parts represent only preferred designs - four designs with lowest cost of newbuilding are selected, two designs according to selected metrics which is as close to the utopia as possible and two best designs with bigger main engines; all the designs are designated by 3D pluses.

As in the previous example, in these two figures one can also notice the division of designs into two major groups according to the selected main engine. In both figures, designs with smaller main engines are designated by the colour, i.e. azure, blue and green (they are closer to an ideal solution). One can also notice that the size of sphere, or cube (cost of labour), is rather uniformly distributed, which leads us to a conclusion that, in this case, the



Subproblem: Handy_Opt1

Virtual SP

Activ Group: Prefered

Current Graph: New

X: WST

Y: CMAT

Z: CNB

C: L2

S: CLAB

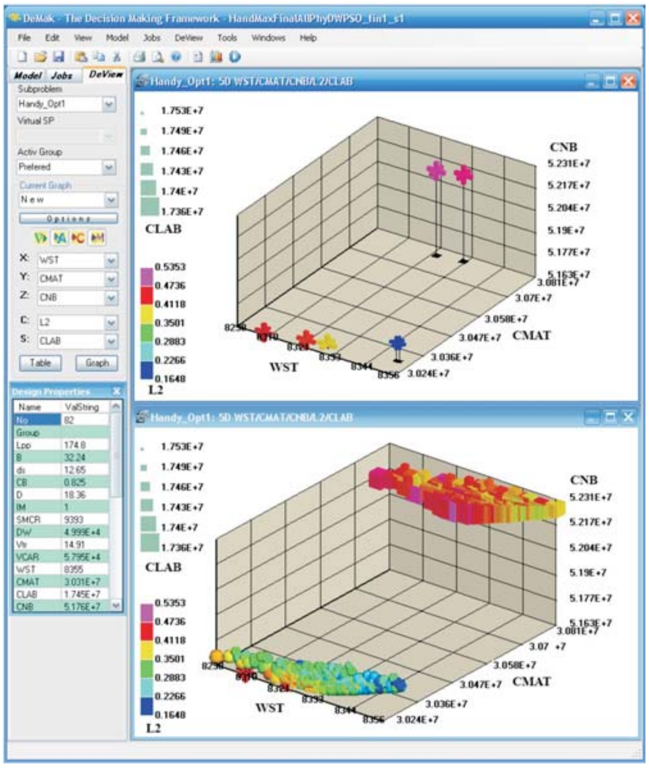
Name	ValString
No	2
Group	
Lpp	174.2
B	32.24
ds	12.65
CB	0.821
D	18.38
IM	1
SMCR	8692
DW	4.961E+4
Vtr	14.7
VCAR	5.78E+4
WST	8307
CMAT	3.025E+7
CLAB	1.738E+7
CNB	5.163E+7

Figure 12 **Nondominated designs (Pareto frontier)**
Slika 12 **Nedominirani projekti (Pareto fronta)**

influence of costs of material is stronger than that of costs of labour (process). This conclusion is expected because, again, the difference in the costs of main engines is dominant with respect to other influential factors.

In the lower part of Figure 14 nondominated designs are presented in a 3-D space with trial speed v_{tr}, deadweight DW and costs of newbuilding C_{NB} on the three coordinates. The shape of designations (cube or sphere) designates the associated main engine (designs designated by a sphere have a 6S50MC-C main engine, and those by a cube a 7S50MC-C). The size of cube, or sphere, represents the volume of cargo tanks V_{car} (lower volume - smaller cube or sphere). Thus, a 5-D space of design objectives has been defined. The colour spectrum represents the remoteness from the utopia. The upper part of the figure represents only the preferred designs. These designs are designated by 3-D pluses.

Figure 13 **Nondominated designs (Pareto frontier)**
Slika 13 **Nedominirani projekti (Pareto fronta)**



Subproblem: Handy_Opt1

Virtual SP

Activ Group: Prefered

Current Graph: New

X: WST

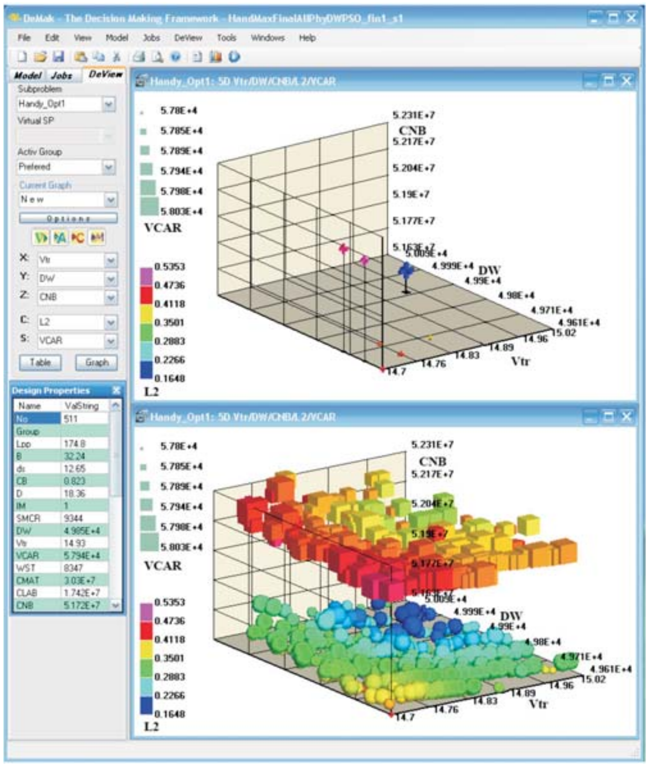
Y: CMAT

Z: CNB

C: L2

S: CLAB

Name	ValString
No	82
Group	
Lpp	174.8
B	32.24
ds	12.65
CB	0.825
D	18.36
IM	1
SMCR	9393
DW	4.999E+4
Vtr	14.91
VCAR	5.795E+4
WST	8355
CMAT	3.031E+7
CLAB	1.745E+7
CNB	5.176E+7



Subproblem: Handy_Opt1

Virtual SP

Activ Group: Prefered

Current Graph: New

X: Vtr

Y: DW

Z: CNB

C: L2

S: VCAR

Name	ValString
No	511
Group	
Lpp	174.8
B	32.24
ds	12.65
CB	0.823
D	18.36
IM	1
SMCR	9344
DW	4.985E+4
Vtr	14.93
VCAR	5.794E+4
WST	8347
CMAT	3.03E+7
CLAB	1.742E+7
CNB	5.172E+7

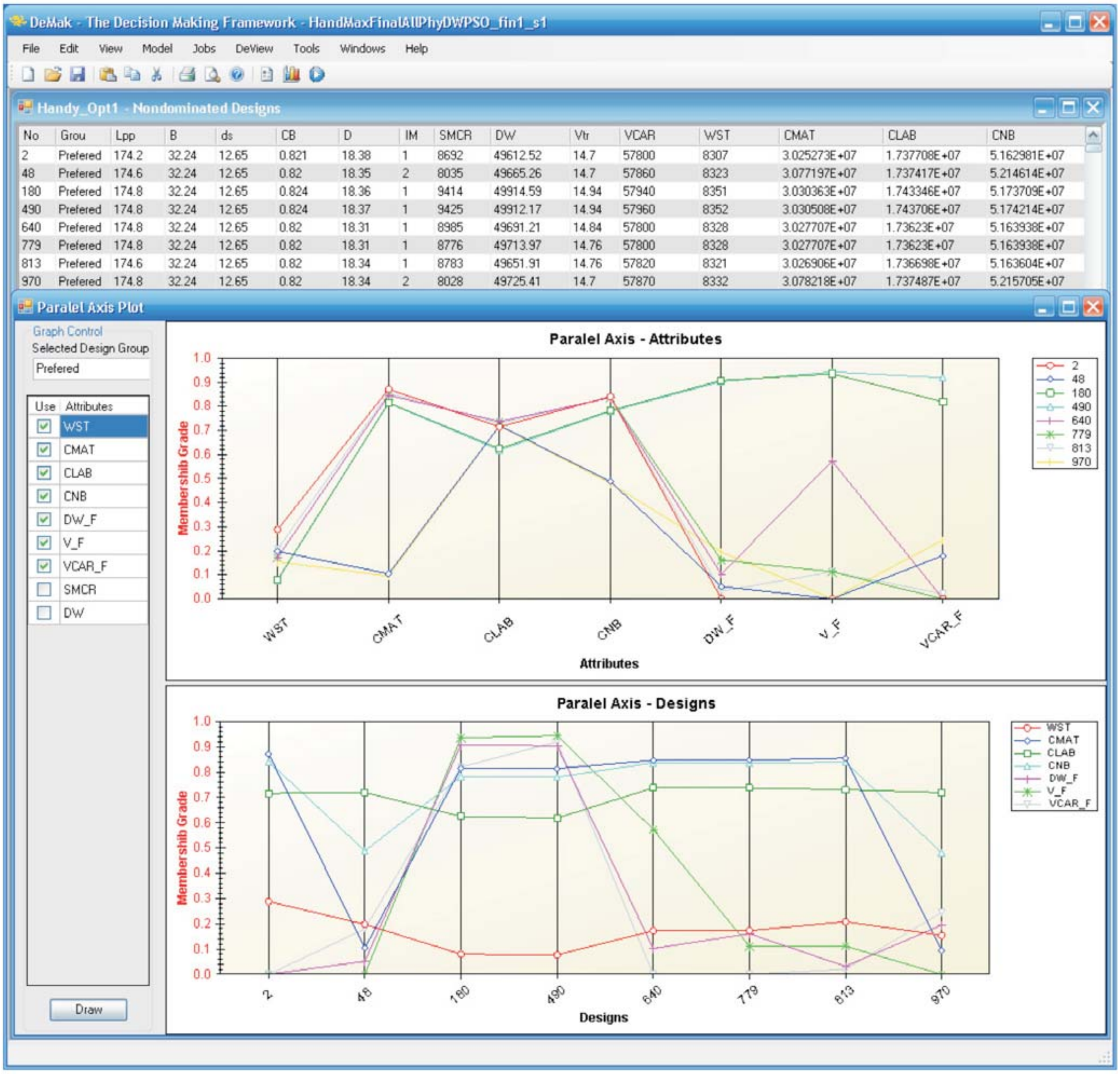
Figure 14 **Nondominated designs (Pareto frontier)**
Slika 14 **Nedominirani projekti (Pareto fronta)**

The left part of the figure represents the data of a selected design.

Nondominated designs presented in this figure are divided into two major groups according to the selected main engine. From this figure, one can conclude that, also in this case, the difference in price of main engines has a major influence on the costs of newbuilding, and that all other elements which are involved in the cost of newbuilding are of minor importance.

Since the costs of newbuilding represent the attribute which is preferred with respect to other design attributes, its influence on determining the remoteness from an ideal design („utopia“) is dominant, so that designs with lowest cost are at the same time closest to the ideal, i.e. they are coloured in blue in the figure.

Figure 15 represents the subjective space of design attributes. In the lower part of the figure there are preferred designs. Four of preferred eight designs have been selected according to the minimal building cost, two designs have been selected according to the minimal remoteness from the utopia, and the remaining two are the best among the designs with bigger main engines. The upper diagram has designs presented in different colours, and attributes are given on the abscissa. The lower diagram has



No	Grou	Lpp	B	ds	CB	D	IM	SMCR	DW	Vtr	VCAR	WST	CMAT	CLAB	CNB
2	Prefered	174.2	32.24	12.65	0.821	18.38	1	8692	49612.52	14.7	57800	8307	3.025273E+07	1.737708E+07	5.162981E+07
48	Prefered	174.6	32.24	12.65	0.82	18.35	2	8035	49665.26	14.7	57860	8323	3.077197E+07	1.737417E+07	5.214614E+07
180	Prefered	174.8	32.24	12.65	0.824	18.36	1	9414	49914.59	14.94	57940	8351	3.030363E+07	1.743346E+07	5.173709E+07
490	Prefered	174.8	32.24	12.65	0.824	18.37	1	9425	49912.17	14.94	57960	8352	3.030508E+07	1.743706E+07	5.174214E+07
640	Prefered	174.8	32.24	12.65	0.82	18.31	1	8985	49691.21	14.84	57800	8328	3.027707E+07	1.73623E+07	5.163938E+07
779	Prefered	174.8	32.24	12.65	0.82	18.31	1	8776	49713.97	14.76	57800	8328	3.027707E+07	1.73623E+07	5.163938E+07
813	Prefered	174.6	32.24	12.65	0.82	18.34	1	8783	49651.91	14.76	57820	8321	3.026906E+07	1.736698E+07	5.163604E+07
970	Prefered	174.8	32.24	12.65	0.82	18.34	2	8028	49725.41	14.7	57870	8332	3.078218E+07	1.737487E+07	5.215705E+07

Selected Design Group: Prefered

Use	Attributes
☑	WST
☑	CMAT
☑	CLAB
☑	CNB
☑	DW_F
☑	V_F
☑	VCAR_F
☐	SMCR
☐	DW

Figure 15 **Subjective decision making by parallel axes**
Slika 15 **Subjektivno odlučivanje putem paralelnih osi**

a reversed situation with attributes on the ordinate. The upper part of the figure represents a table of alphanumerical data of all preferred designs.

The comment made in the previous example can be repeated: costs of the main engine are dominant in the total costs of materials, while the differences in costs of labour (process) are of lesser importance.

When particular designs fulfilling particular design attributes with respective minima of subjective satisfaction are selected (especially those designs which fulfil the contracted requirements – deadweight *DW*, trial speed v_{tr} and cargo tanks volume V_{car}), then, in the next design phase, due attention should be given to "endangered" attributes.

The figures used in this example give the design information required for the final selection of one of nondominated or subjectively preferred designs.

It is possible again to select design with lowest costs of building as a subjectively preferred design, which is a desired design solution on the part of the shipyard. Design no. 2 represents a selected design from the Figure 15: it is presented on the diagram in the upper part of the figure by a red line with little circles and it has the highest value on the ordinate of newbuildings; the diagram in the lower part gives the costs of newbuildings in a light blue line with little triangles with the highest value on the ordinate of design no. 2 Basic characteristics of the design are as follows:

L_{pp} = 174.2 m
B = 32.24 m
d_s = 12.65 m
D = 18.38 m
C_B = 0.821
Main engine *MAN B&W*
6S50MC-C, mark 7
SMCR = 8692 kW

DW = 49613 t
v_{tr} = 14.7 kn
V_{car} = 57800 m^3
W_{st} = 8307 t
C_M = 30.253 m US $
C_L = 17.377 m US $
C_{NB} = 51.630 m US $

It can be noticed that the preferred design does not fully meet the required deadweight, volume of cargo holds and the trial speed, but it still meets the design requirements on the level expected to be free of penalties. Therefore, special attention must be payed with in the further design stages of selected design.

Related to the modern designs of Handymax product tankers presented in Table 6 one can notice that the preferred design is superior as far as the achieved deadweight and cargo tanks capacity are concerned. The design has reached the maximum beam and draught, as expected, which has entailed the lower gross tonnage, and consequently the lower costs of newbuilding as a dominant criterion.

6 Conclusions

By following the steps of the design procedure presented in Figure 2, the ship general design procedure, in the concept design phase, can be carried out by using the simplest tools and a ship design which fulfils all basic design requirements and constraints can be made. Naturally, the quality of such a design cannot be considered as optimal, and its remoteness from the ideal or target design solution cannot be precisely determined since multicriterial formulation of objective and subjective preferences is not fully revealed.

The applied optimization method (multi-attribute design synthesis) and the application of the adapted design procedure and associated mathematical models has resulted in a breakthrough in ship design, which makes this design approach superior to the traditional ship design and ranks it among the best modern approaches to ship design. The developed computer program can be used for the design of a wide range of ships in yards and RTD institutions. The adaptation of the mathematical model of ship design is very simple; therefore, it is possible to build in subjective experience in design of any shipyard with its particular features and the personal experience and attitudes of a particular designer.

Further work in application of fuzzy functions for definition of intra-attribute preferences should be in examination of connections between design margins and obtained risk level and also in further development of design optimization methodology that includes optimal margins selection enabled with the presented approach.

The program developed on the basis of the novel methodology presented in this paper is equipped with a good quality output graphics offering the designer unprecedented possibilities for the design analysis and synthesis. The methodology enables the designer (or a design team) to rely on his own subjective estimation of the importance of particular design attributes, to analyse their interrelations and to make a synthesis of the whole design, and finally to reveal some patterns of the applied design procedure.

When selecting the final design solution, the designer has at his disposal a large amount of information and possibilities which enable creation of a comprehensive picture of the design: the quality of satisfying the conditions of every particular attribute; the relation of attributes with corresponding attributes in other design solutions; and information on what should be considered with special attention in further phases of the design development. The methodology also enables the selection of final design in co-operation with other project stakeholders e.g. shipowner, as all technical and commercial data for all nondominated designs are available.

Finally, the presented procedure and the method developed, give a basis for futher recognition of products of Croatian shipbuilding industry and may help Croatian shipyards to maintain or gain the more profitable businesses in projects of higher added value where concept design is very demanding.

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Complementary article to this paper

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Appendices

Appendix A1: Approximate calculation of Capesize bulk carrier minimum freeboard

The approximate calculation of minimum reduced freeboard (B-60) for a typical configuration of a Capesize bulk carrier comprises the following procedure:

1. The length of a ship for the purpose of minimum freeboard calculation can be approximately set as the length between perpendiculars increased by one metre, i.e.:

$$L_F = L_{pp} + 1 \text{ (m)}. \qquad \text{(A1.1)}$$

2. "B" tabular freeboard can be described in the range of given lengths by the following approximation:

$$F_{tB} = 4227 + 12.067\,(L_F - 266) \text{ (mm)} \qquad \text{(A1.2)}$$

3. "A" tabular freeboard can be described in the range of given lengths by the following approximation:

$$F_{tA} = 3106 + 5.0\,(L_F - 266) \text{ (mm)} \qquad \text{(A1.3)}$$

4. Reduced (B-60) tabular freeboard:

$$F_{tB\text{-}60} = \mathrm{v}_{tB} - 0.6\,(F_{tB} - F_{tA}) \text{ (mm)} \qquad \text{(A1.4)}$$

5. Approximation of the block coefficient at 0.85% of the moulded depth is performed by the following expression (according to the properties of a similar hull form):

$$C_{B\,0.85D} = 0.9963\,C_B\,[1 + 0.005285\,(0.85D - \mathrm{d}_s)] \qquad \text{(A1.5)}$$

6. Correction for the block coefficient:

$$C_{CB} = (C_{B\,0.85D} + 0.68)/1.36 \qquad \text{(A1.6)}$$

7. Correction for depth:

$$C_D = 250\,(D - L_F/15 + 0.02) \text{ (mm)} \qquad \text{(A1.7)}$$

8. Correction for sheer - due to the assumed camber of 800 (mm):

$$C_{sh} = 0.75\,[200.1\,(L_F/3 + 10) - 1100] / 16 \text{ (mm)} \qquad \text{(A1.8)}$$

9. Correction for forecastle:

$$C_{fc} = 1070\,[0.5\,l_k/L_F - 0.05(0.07L_F - l_k)/(0.07L_F)] \text{ (mm)} \qquad \text{(A1.9)}$$

10. Minimum freeboard:

$$F_{B\text{-}60} = C_{CB}\,F_{tB\text{-}60} + C_D + C_{sh} - C_{fc} \text{ (mm)} \qquad \text{(A1.10)}$$

Appendix A2: Calculation of the Capesize bulk carrier main engine minimum power

In order to evaluate the accurate approximation function for continuous service rating, within previously determined design area bounds, it is necessary to build a data base.

The data base has been created in a way that the SEAKING calculation results of the power delivered to the ship propeller are increased by mechanical losses, and then correlated on the basis of empirical data in using the SEAKING program and results obtained at trial sailings (modern, optimized hull forms can reach the trial speed increased by 0.3 to 0.6 knots compared to the speed predicted by the SEAKING program). The data base uses the results of approximately 140 ship speed calculations within the following range:

$$185000 \le V_D \le 192000 \text{ m}^3$$
$$14.8 \le v_{tr} \le 15.4 \text{ kn}$$
$$265 \le L_{pp} \le 280 \text{ m}$$
$$43 \le B \le 45 \text{ m}$$
$$17.5 \le d_s \le 17.95 \text{ m}$$
$$0.85 \le C_B \le 0.875$$

with expected propeller revolutions of approximately 82 rpm.

The regression analysis results [44]show the following values of independent parameters:

$a_1 = 5.171 * 10^{-3}$
$a_2 = -1.465 * 10^{-1}$
$a_3 = 1.072$
$a_4 = 8.145 * 10^{-1}$
$a_5 = 3.843$
$a_6 = 3.589$
$a_7 = 6.634 * 10^{-4}$

so that the approximation function of continuous service rating is defined as follows:

$$\mathrm{CSR} = 0.005171\,L_{pp}^{\;-0.1465}\,B^{1.072}\,d_s^{\;0.8145}\,C_B^{\;3.843}\,v_{tr}^{\;3.589} \cdot \cdot\,(1 + 0.0006634\,L_{pp}/d_s) \qquad \text{(A2.1)}$$

Calculation of continuous service rating for the purpose of determining the main engine power (and not the weight of machinery equipment), if *MAN B&W* 5S70MC-C is selected, needs to be increased by 2-3% due to lower efficiency of propulsion system at a higher propeller revolutions (expected revolutions for that case are approximately 90 rpm).

Appendix A3: Calculation of the building costs of Capsize bulk carrier

In order to calculate ship costs in accordance with the calculation presented in [B1], section 6.6, the total ship volume V has to be determined. It can be defined in the following way:

$$V = V_D + V_{cam} + V_{sup} \text{ (m}^3\text{)} \tag{A3.1}$$

where

V_D – ship's volume up to moulded depth (m^3);
V_{cam} – volume of the camber (m^3);
V_{sup} – volume of the accommodation, hatch coamings and hatch covers (m^3).

The ship's volume up to moulded depth is defined in the following way:

$$V_D = L_{pp}\, B\, D\, C_{BD} \text{ (m}^3\text{)} \tag{A3.2}$$

where C_{BD} is the block coefficient at the moulded depth, defined for this case by the following approximation (according to the properties of a similar hull form:

$$C_{BD} = C_B\, [1 + 0.005285\, (D - d_s)] \tag{A3.3}$$

The volume of the camber and of the accommodation can be approximated as follows:

$V_{cam} = 5000$ m^3
$V_{sup} = 11000$ m^3

Appendix A4: Approximate calculation of Handymax product tanker minimum freeboard

Approximate calculation of minimum freeboard (A) for the configuration of a Handymax oil product tanker with a forecastle consists of the following procedure:

1. For the purpose of the minimum freeboard calculation, the ship's length can be approximately determined as the length between perpendiculars increased by 1 m, i.e.:

$$L_F = L_{pp} + 1 \text{ (m)} \tag{A4.1}$$

2. "A" tabular freeboard for the range of given lengths can be approximated with the following approximate expression:

$$F_{tA} = 2307 + 12.67\, (L_F - 173) \text{ (mm)} \tag{A4.2}$$

3. Approximation of the block coefficient at 0.85% of moulded depth can be performed with the following expression (according to the features of a similar hull form):

$$C_{B\,0.85D} = 0.9943\, C_B\, [1 + 0.005686\, (0.85D - d_s)] \tag{A4.3}$$

4. Correction for block coefficient:

$$C_{CB} = (C_{B\,0.85D} + 0.68)/1.36 \tag{A4.4}$$

5. Correction for depth:

$$C_D = 250\, (D - L_F/15 + 0.02) \text{ (mm)} \tag{A4.5}$$

6. Correction for sheer – due to the assumed sheer of 500 mm:

$$C_{sh} = 0.75\, [200.1\, (L_F/3 + 10) - 600] / 16 \text{ (mm)} \tag{A4.6}$$

7. Correction for forecastle:

$$C_{fc} = 1070\, [0.7\, l_k/L_F - 0.05(0.07L_F - l_k)/(0.07L_F)] \text{ (mm)} \tag{A4.7}$$

8. Minimum freeboard:

$$F_A = C_{CB}\, F_{tA} + C_D + C_{sh} - C_{fc} \text{ (mm)} \tag{A4.8}$$

Appendix A5: Calculation of the Handymax product tanker main engine minimum power

The database was set in a similar way as in the previous example. The SEAKING calculation results for the power delivered to the ship propeller are increased by the value of mechanical losses, and then correlated on the basis of empirical data in using the SEAKING program and the obtained results during trials (a 0.4 knot higher speed than the speed predicted by the SEAKING program can be expected). Database contains the results of approximately 100 ship speed calculations within the following range:

$57000 \leq V_D \leq 60000$ m^3
$14.8 \leq v_{tr} \leq 15.2$ kn
$170 \leq L_{pp} \leq 175$ m
$32 \leq B \leq 32.3$ m
$12.2 \leq d_s \leq 12.65$ m
$0.82 \leq C_B \leq 0.845$

and predicted propeller revolutions of approximately 127 rev./min.

The regression analysis result [44] has given the following values of free parameters:

$a_1 = 7.997 * 10^{-3}$
$a_2 = -5.697 * 10^{-2}$
$a_3 = 1.048$
$a_4 = 1.141 * 10^{-1}$
$a_5 = 3.826$
$a_6 = 4.251$
$a_7 = -2.913 * 10^{-2}$

so that the CSR approximation function is defined as follows:

$$\text{CSR} = 0.007997\, L_{pp}^{-0.05697}\, B^{1.048}\, d_s^{0.1141}\, C_B^{3.826}\, v_{tr}^{4.251} \\ (1 - 0.02913\, L_{pp}/d_s \tag{A5.1}$$

The CSR estimation for the purpose of the main engine power determination (and not of the weight of machinery equipment), in the case when a *MAN B&W* 7S50MC-C is selected, should be reduced by 7-8% because of a better propulsion system efficiency at a lower number of revolutions (predicted revolutions for this case are 100-105 rev./min).

Appendix A6: Calculation of the building costs of Handymax product tanker

For the calculation of costs of newbuilding in accordance with the calculation in [B1], section 6.6, the total ship volume V can be defined in the following way:

$$V = V_D + V_{cam} + V_{sup} + V_k \text{ (m}^3\text{)} \tag{A6.1}$$

where

V_D = ship's volume up to moulded depth (m³);
V_{cam} = volume of the camber (m³);
V_{sup} = volume of the accommodation and construction below the funnel (m³);
V_{fc} = volume of the forecastle (m³).

The ship's volume up to moulded depth is defined in the same way as in the previous example:

$$V_D = L_{pp}\, B\, D\, C_{BD}\ (\mathrm{m}^3) \qquad \text{(A6.2)}$$

C_{BD} is defined for this case by the following approximation (according to the features of a similar hull form):

$$C_{BD} = C_B\, [1 + 0.005686\, (D - d_s)] \qquad \text{(A6.3)}$$

The volume of the sheer and accommodation is determined as follows:

$V_{cam} = 1500\ (\mathrm{m}^3)$
$V_{sup} = 5000\ (\mathrm{m}^3)$
$V_{fc} = 500\ (\mathrm{m}^3)$

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, m³
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
$F_{B\text{-}60}$	reduced minimum (B-60) freeboard, mm
F_{tA}	tabular freeboard for ships type A, mm
F_{tB}	tabular freeboard for ships type B, mm
$F_{tB\text{-}60}$	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, m³
O_s	hypothetical cargo discharge in the case of bottom ship damage, m³
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, m³
V_{car}	capacity of cargo holds (tanks), m³
V_{fc}	volume of the forecastle, m³
V_{sup}	volume of the accommodation, hatch coamings and hatch covers, m³
V_{cam}	volume of the camber, m³
V_D	ship´s volume up to moulded depth, m³
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, m³
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/m³
Δ	displacement, t
θ_e	final equilibrium angle of heel, °
κ	specific voluminosity of the ship, defined as $\kappa = V_{car} / (L_{pp}\, B\, D)$
λ_i	eigenvalues of the problem