HOLISTIC DESIGN AND OPTIMISATION OF HIGH-SPEED MARINE VEHICLES

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ABSTRACT

The present paper provides a brief introduction to a holistic approach to ship design optimization, defines the generic ship design optimization problem and demonstrates its solution by use of advanced optimization techniques for the computer-aided generation, exploration and selection of optimal designs. It discusses proposed methods on the basis of some typical ship design optimization problems of high-speed marine vehicles related to multiple objectives and leading to improved and partly innovative designs with increased cargo carrying capacity, enhanced safety, survivability and comfort, reduced required powering and improved environmental protection.

Keywords: Holistic Ship Design; Parametric Design; Multi-criteria Optimisation; High Speed Craft

1 INTRODUCTION TO HOLISTIC SHIP DESIGN OPTIMIZATION (Papanikolaou 2009)

Inherently coupled with the design process is design optimization, namely the selection of the best solution out of many feasible ones on the basis of a criterion, or rather a set of criteria. A systemic approach to ship design may consider the ship as a complex system integrating a variety of subsystems and their components, e.g. subsystems for cargo storage and handling, energy/power generation and ship propulsion, accommodation of crew/passengers and ship navigation. They are all serving well defined ship functions. Ship functions may be divided into two main categories, namely payload functions and inherent ship functions. E.g., for Ro-Ro passenger ships, the payload functions are all those related to the provision of public and private accommodation spaces for the passengers and spaces/handling & access equipment for the cargo (Ro-Ro decks, ramps, ventilation etc.); inherent ship functions are those related to the transport of the passengers and cargo safely from port to port with certain speed, namely the ship as a system, consisting of ship’s hull (main and superstructure), facilities of crew, navigation control (bridge), machinery, tanks (fuel and lub oil, water and sewage, ballast and voids), comfort systems (air conditioning, water and sewage, electrical), mooring and life-saving equipment, etc.

Independently, considering that ship design should actually address the whole ship’s life cycle, it may be split into various stages that are traditionally composed of the concept/preliminary design, the contractual and detailed design, the ship construction/fabrication process, and ship operation for an economic life and scrapping/recycling. It is evident that the optimal ship with respect to her whole life cycle is the outcome of a holistic optimization of the entire, above defined ship system for its life-cycle. It is noted that mathematically, every constituent of the above defined life-cycle ship system forms evidently itself a complex nonlinear optimization problem for the design variables, with a variety of constraints and criteria/objective functions to be jointly optimized. Even the simplest component of the ship design process, namely the 1st loop (conceptual/preliminary design), is complex enough to be simplified (reduced) in practice. Also, inherent to ship design optimization are the conflicting requirements resulting from the design constraints and optimization criteria (merit or objective functions), reflecting the interests of the various ship design stakeholders: ship owners/operators, ship builders, classification society/coast guard, regulators, insurers, cargo owners/forwarders, port operators etc.

Assuming a specific set of requirements (usually the shipowner’s requirements for merchant ships or mission statement for naval ships), a ship needs to be optimized for lowest construction cost, for highest operational efficiency or lowest Required

1 Principle of holism according to Aristotle (Metaphysics): “The whole is more than the sum of the parts”

2 Principle of reductionism may be seen as the opposite of holism, implying that a complex system can be approached by reduction to its fundamental parts. However, holism and reductionism should be regarded as complementary approaches, as they are both needed to satisfactorily address complex systems in practice.
Freight Rate (RFR), for highest safety and comfort of passengers/crew, for satisfactory protection of cargo and the ship herself as hardware and last but not least, for minimum environmental impact, particularly for oil carriers with respect to marine pollution in case of accidents and for high-speed vessels with respect to generated wave wash. Recently, even aspects of ship engine emissions and air pollution need to be considered in the optimization of ship design and operation, though, for the time being, high-speed vessels have been left out of current discussions about the Energy Efficiency Design Index (EEDI) (see, IMO 2008 and Koepke & Sames 2010). Many of these requirements are clearly conflicting and a decision regarding the optimal ship design needs to be rationally made.

To make things more complex but coming closer to reality, even the specification of a set of design requirements with respect to ship type, cargo capacity, speed, range, etc. is complex enough to require another optimization procedure that satisfactorily considers the interests of all shareholders of the ship as an industrial product and service vehicle of international markets or others. Actually, the initial set of ship design requirements is the outcome of a compromise of intensive discussions between highly experienced decision makers, mainly on the shipbuilder’s side, and end-users who attempt to articulate their desires and tradeoffs they are willing to allow. A way to undertake and consolidate this kind of discussion in a rational way has been advanced by the EU funded project LOGBASED (see LOGBASED 2004 and Papanikolaou(ed.) 2009).

Since the middle sixties with the advance of computer hard- and software more and more parts of the design process were taken over by computers, particularly the heavy calculatory and drafting elements of ship design. Simultaneously, the first computer-aided preliminary design software systems were introduced, dealing with the mathematical parametric exploration of the design space on the basis of empirical/simplified ship models for specific ship types or the optimization of design variables for specific economic criteria by gradient based search techniques. With the further and faster advance of computer hard- and software tools, along with their integration into powerful hard- and software design systems, the time has come to look at the way ahead in ship design optimization in a holistic way, namely by addressing and optimizing several and gradually all aspects of ship’s life (or all elements of the entire ship life cycle system), at least the stages of design, construction and operation; within a holistic ship design optimization we should herein also understand exhaustive multi-objective and multi-constrained ship design optimisation procedures even for individual stages of ship’s life (e.g. conceptual design) with least reduction of the entire real problem (Nowacki 2009, Andrews et al. 2009, Papanikolaou et al. 2009).

The use of Genetic Algorithms (GA), combined with gradient based search techniques in micro-scale exploration and with a utility functions technique for the design evaluation, is advanced in the present paper as a generic type optimization technique for generating and identifying optimized designs through effective exploration of the large-scale, nonlinear design space and a multitude of evaluation criteria. Several applications of this generic, multi-objective ship design optimization approach by use the design software platform of the Ship Design Laboratory of NTUA, integrating well established naval architectural and optimization software packages with various application methods and software tools, as necessary for the evaluation of stability, resistance, seakeeping, structural integrity etc. may be found in the listed references. The following examples, deduced from recently completed projects of NTUA-SDL, which are related to high-speed marine vehicles, may be highlighted:

-Hull form optimization of high-speed mono- and twin hulls for least wave resistance and wave wash (FLOWMART 2000 and Zaraphonitis et al. 2003).

2 THE GENERIC SHIP DESIGN OPTIMIZATION PROBLEM

Within a holistic ship design optimization we should herein mathematically understand exhaustive multi-objective and multi-constrained optimisation procedures with least reduction of the entire real design problem. The generic ship design optimization problem and its basic elements may be defined as following (Fig. 1).

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Optimisation Criteria (Merit Functions, Goals):

It refers to a list of mathematically defined performance/efficiency indicators that may be eventually reduced to an economic criterion, namely the profit of the initial investment. Independently, there may be optimization criteria (merit functions or goals) that may be formulated without direct reference to economic indicators, see, e.g., optimization studies for a specific X ship function, like ship performance in calm water and in seaways, ship safety, ship’s strength including fatigue, etc. The ship design optimization criteria are in general complex nonlinear functions of the design parameters (vector of design variables) and are in general defined by algorithmic routines in a computer-aided design procedure.

Constraints: It mainly refers to a list of mathematically defined criteria (in the form of mathematical inequalities or equalities) resulting from regulatory frameworks pertaining to safety (for ships mainly the international SOLAS and MARPOL regulations). This list may be extended by a second set of criteria characterized by uncertainty with respect to their actual values and being determined by the market conditions (demand and supply data for merchant ships), by the cost of major materials (for ships: cost of steel, fuel, workmanship), by the anticipated financial conditions (cost of money, interest rates) and other case specific constraints. It should be noted that the latter set of criteria is often regarded as a set of input data with uncertainty to the optimization problem and may be assessed on the basis of probabilistic assessment models.

Design Parameters: It refers to a list of parameters (vector of design variables) characterizing the design under optimization; for ship design this includes ship’s main dimensions, unless specified by the shipowner’s requirements (length, beam, side depth, draft) and may be extended to include ship’s hull form, the arrangement of spaces and of (main) outfitting, of (main) structural elements and of (main) networking elements (piping, electrical, etc), depending on the availability of topological-geometry models relating ship’s design parameters to a generic ship model to be optimized.

Input Data: This includes first the traditional owner’s specifications/requirements, which for a merchant ship are the required cargo capacity (deadweight and payload), service speed, range etc. and may be complemented by a variety of further data affecting ship design and its economic life, like financial data (profit expectations, interest rates), market conditions (demand and supply data), costs for major materials (steel and fuel) etc. The input data set may include besides numerals of quantities also more general type of knowledge data, like drawings (of ship general arrangements) and qualitative information that needs to be properly translated for inclusion in a computer-aided optimisation procedure.

Output: It includes the entire set of design parameters (vector of design variables) for which the specified optimization criteria/merit functions obtain mathematically extreme values (minima or maxima); for multi-criteria optimization problems optimal design solutions are on the so-called Pareto front and may be selected on the basis of tradeoffs by the decision maker/designer. For the exploration and
The final selection of Pareto design solutions is a variety of strategies and techniques that may be employed. In mathematical terms, the multiobjective optimisation problem may be formulated as:

$$\min \{\mu_1(x), \mu_2(x), \ldots, \mu_n(x)\}^T,$$

subject to $$g(x) \leq 0$$ and $$h(x) = 0$$ and $$x_l \leq x \leq x_u$$

where $$\mu_i$$ is the $$i$$-th objective function, $$g$$ and $$h$$ are a set of inequality and equality constraints, respectively, and $$x$$ is the vector of optimization or vector of design variables. The solution to the above problem is a set of Pareto solutions, namely solutions for which improvement in one objective cannot be achieved without worsening of at least one other objective. Thus, instead of a unique solution, a multiobjective optimization problem has (theoretically) infinite solutions, namely the Pareto set of solutions.

The use of MultiObjective Genetic Algorithms (MOGA), combined with gradient based search techniques in micro-scale exploration and with a utility functions technique for the design evaluation, is advanced in the present paper as a generic type optimization technique for generating and identifying optimized designs through effective exploration of the large-scale, nonlinear design space and a multitude of evaluation criteria occurring in ship design. Several applications of this generic, multi-objective ship design optimization approach by use of NTUA-SDL’s design software system, integrating the naval architectural software package NAPA®4 the optimization software modeFRONTIER®5 and various application software tools, as necessary for the evaluation of stability, resistance, seakeeping etc. may be found in the listed references.

3 EXAMPLES OF OPTIMIZATION OF HIGH-SPEED MARINE VEHICLES

3.1 Hull-form optimization of high speed monohull with respect to powering and wash (Zaraphonitis et al. 2003)

The ship hydrodynamic performance in terms of speed, powering, seakeeping characteristics, maneuverability is of paramount importance, especially for High Speed Craft (HSC). Wash waves generation has worried neither the designers nor the ship operators until very recently. It is the introduction of numerous large high-speed vessels that is currently driving maritime authorities to consider applying to the extent possible rational wash criteria to the operation of HSC, because of the impact on the marine environment and the safety of activities in coastal areas. Therefore, at least for HSC designs, wash reduction has become a major requirement of the vessel’s hydrodynamic performance, along with other traditional hydrodynamic objectives.

From the conceptual point of view, long and slender hull forms are recognized for their favorable resistance and wash characteristics. Increased separation distance of twin-hull vessels will generally result to wave resistance and wash waves’ reduction. Unfortunately, the selection of a vessel’s main particulars is a compromise of numerous considerations and constraints, thus cannot be dictated by low wash requirements only. Therefore, the integration of a wash minimization methodology in the design process, preferably in the very first stages, when the vessel’s main particulars are defined and the hull form is developed, is becoming eventually a prerequisite to reduce the impact of regulatory speed limitations that will drastically impair the vessel’s ultimate economic potential. If such a methodology is to be efficient, a reliable wash prediction numerical method has to be available.

Although wash waves prediction is not at all a simple problem, particularly for vessels in the semi-planning and planning condition, recent progress in CFD resulted in the development of software tools, either based on the Kelvin or Rankine sources distribution, that can be used with a good degree of confidence. Incorporation of such numerical tools within an integrated design environment is the main goal of the work presented herein. Formulation of the ship design procedure in the framework of a multi-objective optimization problem, where wash reduction is one of the objective functions, allows the application of formal optimization methods to

3 National Technical University of Athens – Ship Design Laboratory, NTUA-SDL, http://www.naval.ntua.gr/sdl
4 NAPA Oy (2005), NAPA software, http://www.NAPA.fi/
5 E.STE.CO (2003), "modeFrontier software v.2.5.x", http://www.esteco.it/
derive the optimum hull form subject to the owner’s requirements and technical and regulatory constraints. Other objective functions might be the vessel’s total resistance, seaworthiness, dynamic stability and so on, provided that adequate numerical tools are available for their reliable and efficient calculation. In addition, optimization criteria reflecting the vessel’s economic potential, like the building and operational costs, transport capacity, net present value or required freight rate may as well be used.

The present study is focusing primarily on the minimization of powering and the environmental impacts caused by excessive wash waves. Thus the selected objective functions are limited to total resistance and minimization of the impact of wash waves. To further simplify the calculations, the effect of the vessel’s propulsion system, either water-jets or propellers, on the generated wash waves is herein omitted. Omission of objective functions reflecting the economic performance of the vessels is partly justified by the imposed condition of constant transport capacity. In practice this is ascertained by the requirements for a specified minimum RoRo cargo deck area and constant displacement.

The selected objectives have been approached as following:

1. The total resistance is approximated by the sum of frictional plus wave resistance, where the frictional resistance is calculated by use of the ITTC frictional drag coefficient formula. Shipflow®, a well-known commercial CFD code of Flowtech is employed for the wave resistance and wash waves calculation. Nonlinear iterative calculations are performed, since it is considered necessary to take into account the effect of sinkage and running trim on the wave resistance and wash waves.

2. For the second objective function, an appropriate wash waves measuring criterion should be selected for each particular application, depending on the kind of wash effects to be assessed. In the present study, basically aiming to demonstrate the potential of the optimization concept, a simple wash measure has been adopted, in the form of an ‘average’ wave height along a longitudinal wave-cut at a certain distance from the vessel’s center line:

\[ W = \frac{1}{x_2 - x_1} \int_{x_1}^{x_2} \zeta(x, y)^2 \, dx \]

where \( \zeta(x, y) \) is the wave elevation, while \( x_1 \) and \( x_2 \) are the starting and end points of the integration interval along a wave cut. Alternative wash criteria can be easily introduced in the optimization procedure, like for example the maximum occurring local wave height. Wave period or wave length may be also introduced, combined with wave height to obtain a wash criterion expressing the local wave energy density. For the solution of this optimization problem, the generic procedure outlined in Fig. 2 has been applied.

Reference Vessel

A high-speed monohull vessel has been selected for the demonstration of the outlined optimization procedure. Relevant work was conducted within the EU funded project FLOWMART 2000-2003. The basis-reference monohull vessel is the Corsaire 11000 built by the former Leroux-Navele yard. The vessel’s main technical characteristics are listed in Table 1.

<table>
<thead>
<tr>
<th>Main characteristics of the selected monohull vessel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length over all</td>
</tr>
<tr>
<td>Length at waterline</td>
</tr>
<tr>
<td>Beam over all</td>
</tr>
<tr>
<td>Draught</td>
</tr>
<tr>
<td>Service speed</td>
</tr>
<tr>
<td>Transport Capacity</td>
</tr>
<tr>
<td>Propulsion Power</td>
</tr>
<tr>
<td>Main Engines</td>
</tr>
<tr>
<td>Propulsors</td>
</tr>
</tbody>
</table>

Model tests for the above vessel were performed by SIRHENA within the FLOWMART project at a model scale of 1:30, in a towing tank with a beam of 5m and depth of 3m corresponding to a depth Froude number \( F_{nh} = 0.641 \). Due to the narrow beam of the towing tank, significant reflections were expected to affect the measured wash waves. Therefore, calculations have been performed for the vessel in unrestricted water width and 90m depth (full scale) and also in a channel of width and depth corresponding to the dimensions of the towing tank. Typical comparisons of the predicted vs. measured wave cuts at 0.25L and 0.5L transverse distance off centerline are presented in Figures 3 and 4.

In the first part of the wave cuts and for approximately three ship lengths from the bow, the effect from the limited channel width on the numerical predictions is comparatively weak. Further aft this effect increases significantly with the predictions for the vessel in the channel comparing much better with the experimental measurements. A very steep wave crest, approximately two ship lengths from the bow can be observed in the experimental results for the wave cut at 0.25L. This
wave crest is approximately 50% higher compared to the numerical predictions. The same phenomenon is visible in the wave cut at 0.5L, where a steep wave observed in the experimental measurements between 300m and 400m from the bow, is significantly underpredicted by the numerical results.

![Graph 3: Comparison of measured and predicted wave cuts at 0.25L off CL for the monohull vessel](image)

![Graph 4: Comparison of measured and predicted wave cuts at 0.5L off CL for the monohull vessel](image)

![Fig. 5: Grid definition and resulting hull form for monohull vessel](image)

![Fig. 6: Monohull vessel, total resistance vs. wash waves measure vessel, total resistance vs. wash waves measure](image)
Hull-form development

The developed optimization procedure is based on the parametric generation of alternative hullforms by use of NAPA®. Careful identification of the most suitable design parameters, along with their appropriate range of variation is needed to ascertain the generation of feasible and efficient hull-forms. For the monohull case the hull-form generation is controlled by a set of points and inclination angles. Through these points a grid is created that defines the hull. In Fig. 5 a perspective view of a typical hull form is presented, where the grid and the definition points are shown. Details of this parametric design procedure may be found in Zaraphonotis et al. 2003.

Results of optimisation

Typical results of the hull-form optimization of the above-mentioned semi-displacement monohull are discussed in the following. In Fig. 6, a scatter diagram of the wash waves measure $W$ versus total resistance $R_T$ (approximated by: $R_T = R_F + R_W$) for the generated designs is shown. The corresponding values of the original vessel (according to Shipflow calculations) are presented with the thick solid circle at the upper right corner of the diagram.

A number of designs with favorable hydrodynamic characteristics are identified. The obtained reductions in resistance, wash waves measure and maximum wave height, compared to the original vessel are presented in Table 2. Similar comparisons were obtained from the results calculated for the wave cuts located at 0.25L and 0.75L transverse distance from the vessel’s centerline. The boundary line (‘Pareto Frontier’) shown in Fig. 6 corresponds to the best obtainable results. All the designs located on that line are considered ‘optimal’, since it is impossible to improve the vessel’s performance with respect to one criterion without impairing its performance with respect to the others. It is the designer’s responsibility to select the most preferable solution among the designs located on this line, based on his experience and possibly further evaluation criteria. Decision support tools, like the Utility Functions Technique, are available within modeFrontier to assist the designer in this selection procedure.

The results presented in Fig. 6 were calculated using 2x686 panels on the wetted surface and 2x3345 panels on the free surface. The results presented in Table 2 have been recalculated with a larger free surface panelization area (2x7742 free surface panels). Convergence has been obtained after 9 iterations for all vessels. Note that the wash measure $W$ in Table 2 was also recalculated for a larger integration interval (with its aft end at the zero down-crossing point of the wave cut, situated closer to the point at 500m behind the vessel’s bow). The corresponding free surface elevation at a wave cut located LPP/2 from the vessel’s track is presented in Fig. 7.

Table 2: Comparison of obtained results

<table>
<thead>
<tr>
<th></th>
<th>Original vessel</th>
<th>Hull no.47</th>
<th>Hull no.118</th>
<th>Hull no.282</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_T$ (kN)</td>
<td>500.5</td>
<td>449.3</td>
<td>464.3</td>
<td>494.4</td>
</tr>
<tr>
<td>Diff. %</td>
<td>0</td>
<td>-10.2%</td>
<td>-7.2%</td>
<td>-1.2%</td>
</tr>
<tr>
<td>$W$ (m)</td>
<td>0.205</td>
<td>0.173</td>
<td>0.160</td>
<td>0.155</td>
</tr>
<tr>
<td>Diff. %</td>
<td>0</td>
<td>-15.6%</td>
<td>-22.0%</td>
<td>24.4%</td>
</tr>
<tr>
<td>$H_{max}$ (m)</td>
<td>1.0515</td>
<td>0.8840</td>
<td>0.789</td>
<td>0.7473</td>
</tr>
<tr>
<td>Diff. %</td>
<td>0</td>
<td>-15.9%</td>
<td>-24.9%</td>
<td>-28.9%</td>
</tr>
</tbody>
</table>

![Fig. 7: Monohull vessels, comparison of free surface elevation at LPP/2 off CL](image_url)

3.2 Parametric design and optimization of high speed twin hull ROPAX ship

Further building-up on the methodology presented in section 3.1, an integrated methodology for the parametric design and holistic optimization of high-speed mono- and twin-hull ROPAX vessels was developed. Additional external software tools were linked with the NAPA® design software platform, to perform specific calculations (i.e. besides the calm water hydrodynamic performance, ship’s seakeeping behaviour and her preliminary structural design, etc.). The implemented procedure includes the following classical steps of ship design:

1. Hull form development
2. Resistance and propulsion estimations
3. Development of internal layout
4. Preliminary structural design
5. Weights estimation
6. Intact and damaged stability calculations
7. (Seakeeping behaviour)
8. Assessment of economic performance
Development of the hull form

The first step of the implemented parametric design procedure is the development of the hull form. Considering of increased importance for high-speed passenger vessels their seaworthiness, we focused in this study on twin hull vessels of SemiSWATH type. A set of NAPA macros was developed, enabling the fully automatic hullform generation. The derivation of the SemiSWATH type hullform is based on 3 sets of design parameters (for details see Skoupas et al. 2009 and Skoupas 2011):  
- the 1st set consists of 11 design parameters defining the overall characteristics of the demihull  
- the 2nd set defines through 7 design parameters the local details of the forebody, while  
- the 3rd set of 5 parameters defines the shape of the aftbody

Based on the above 23 design parameters, a grid of definition curves is created (Figure 8), from which the demihull’s surface is derived (Figure 9). From the 23 design variables, only 5 are defined explicitly and are independent parameters. The remaining variables are defined indirectly from their ratio with respect to other variables, mainly the demihull’s immersed length \( L_{HI} \), width \( B_{HI} \) and draught \( T \), which are 3 of the 5 independent variables.

Resistance and Propulsion Calculations

With the shape of the underwater part of the vessel already defined, the procedure continues with the estimation of the calm water resistance. The total resistance coefficient of the single hull is approximated by the following equation:

\[
C_r = (1 + r) C_F + C_W \quad (3)
\]

where the coefficient \( r \) is introduced to account for the viscous form and other effects on resistance. A series of experiments were performed in the towing tank of the Laboratory for Ship and Marine Hydrodynamics of National Technical University of Athens for the estimation of this coefficient, using two SemiSWATH models of equal length and displacement but of different hull shapes, for various draught and trim values. Based on these measurements and simplifying the calculations, when assessing various designs parametrically, an average value of \( r=0.45 \) was assumed. For a twin hull configuration, the total resistance coefficient is calculated by the following expression:

\[
C_r = (1 + \beta r) C_F + C_W \quad (4)
\]

where the coefficient \( \beta \) in equ. 4 is introduced to account for the additional viscous form and other interaction effects due to the presence of the second demihull. This coefficient depends mainly on the separation distance between the two demihulls (and Froude number); based on the analysis of conducted experimental measurements, a rough approximation of \( \beta=1.4 \) was herein obtained and used in the parametric calculations. The frictional resistance coefficient \( C_F \) in equations 3 and 4 corresponds to the demihull in isolation and is calculated according to the ITTC 1957 formula, whereas the wave resistance coefficient \( C_W \) in Equation 1 corresponds also to the single hull configuration, while the corresponding coefficient appearing in equ. 4 refers to the twin-hull configuration. In both cases, \( C_W \) is calculated by an external CFD software, namely herein SHIPFLOW®. Although SHIPFLOW can be used both for potential flow and viscous flow calculations, we preferred in the present study the former option in order to keep the calculation time within acceptable limits for optimisation purposes. The use of potential flow calculations may be also justified to a certain extent by the following observations:

- Potential flow calculations are generally considered fairly accurate, or at least satisfactory, for the particular vessel type having very slender demihulls, and operating at very high speeds \( F_n \approx 0.6 \) to 0.7.
- Within an optimisation procedure, a systematic error/inaccuracy in the prediction of the calm water resistance, may have an impact on the absolute performance of each particular design alternative, but it may not alter the ranking of the various designs, provided of course that the error is always systematic and on the same side; we have good reason to believe that this is the present case, at least for the considered range of hullform alternatives.
Based on the total resistance coefficient, as derived by equ. 4, the bare hull calm water resistance is obtained. The calculation is based on the vessel’s wetted surface at zero speed. The calculated calm water resistance, properly corrected to account for appendage drag, hull fouling and added resistance in waves is used for the calculation of the required propulsion power. A user-supplied value for the resistance increase coefficient is used; otherwise, the internally specified default value of 25% is used. Assuming water jet propulsion, an estimation of the propulsion efficiency is obtained, applying the following equation according to Skoupas et al., 2009:

\[
 n = aV^a + bV^b + cV^c + d
\]

In the above equation, \(V\) is the vessel’s speed in knots (10kn \(\leq V \leq 80\)kn) and the values of the coefficients are: \(a=2.963e-19\), \(b=-0.0003\), \(c=0.0295\), \(d=-0.0250\). The resulting propulsion power is increased by a suitable power margin, to derive the required MCR of the engine. User-supplied values for the mechanical losses and the engine’s loading factor are used; otherwise, the default values of 97% mechanical power transmission efficiency and 87.5% engine’s loading factor are used.

**Generation of the Internal Arrangement**

Before proceeding to the definition of the internal arrangement, the vessel’s “envelope” (i.e. the complete outer profile, both below and above water) is created. The required decks are generated at the deck heights specified by the corresponding design variables: the wet deck of the cross-structure, the bulkhead deck (main vehicles deck), the platform deck (if existing), the main passengers’ deck and the bridge deck. A frame table is created using constant frame spacing throughout the entire length of the vessel, specified by the user. Subsequently, the vessel’s internal arrangement is generated, based on the values of the corresponding design parameters. The process starts with the definition the watertight subdivision below the main vehicles deck. The type of arrangement of the compartments where the propulsion plant is installed is specified by the user. The following options are available:

- One or two engine rooms and one pump room in each hull.
- Two engine rooms, one auxiliary room and one pump room in each hull.
- One engine room, one gear room, one auxiliary room and one pump room in each hull.

The length of each compartment is specified by the corresponding design variables. Starting from the vessel’s aft end, the pump room, gear room, engines rooms and auxiliary room are created, according to the selected propulsion plant arrangement. The collision bulkhead is then positioned according to regulations and the remaining part of the lower hulls from the engines rooms to the collision bulkhead is subdivided in the specified number of watertight compartments. The tank top is created from piecewise horizontal plane elements between successive transverse watertight bulkheads, with increasing height from midship towards the bow, in order to ensure effective protection of the upper compartments in the event of racking damage. The provisions of Chapter 2, Regulation 2.6 of the HSC Code are applied to define the bottom area that is vulnerable to racking damage.

In total, 24 design variables are controlling the definition of the vessel’s cross-structure and its internal arrangement. The General Arrangement Drawing of a typical vessel created by the developed parametric design software (\(L_{OA}=71.49m\), \(L_{HL}=70.0m\), \(B_{OA}=22.2m\), \(T_{D}=3.3m\), \(D=7.3m\)), is presented in Figure 10. This vessel has a transport capacity of 601 passengers, 4 trucks and 137 private cars, and a service speed of 30.5kn.

Figure 10: Typical internal arrangement of semi SWATH ROPAX
Preliminary Structural Design

The preliminary structural design is performed by an external software code, namely herein implementing DNV rules for the Classification of High-Speed, Light Craft and Naval Surface Craft. This code is called by the NAPA design environment and calculates the required plate thickness, the section modulus and other cross-sectional characteristics of the primary and secondary stiffeners of hull’s structure. The construction material may be selected by the user. The available options include construction of the entire vessel with high tensile steel or aluminum alloy. This evaluation is considered only a rough approximation of the final structural design and is mainly used for the preliminary estimation of the vessel’s steel weight.

Weights Estimation

The vessel’s light weight is subdivided into the various basic weight components, namely weights of hull structure, propulsion, auxiliaries, deck machinery and outfitting, electrical, piping, heating and air-conditioning, accommodation and miscellaneous. The structural weight is readily obtained by direct calculation, namely based on the readily available three-dimensional geometric NAPA model and on the results of the preliminary structural design calculations. The machinery weight is assumed decomposed into four main components (main engines, gear-boxes, shafting, water-jets). The remaining basic weight categories are also further decomposed into the required items and sub-items and relevant expressions have been developed for the estimation of the corresponding weights and weight centres. The vessel’s payload is determined by subtracting the light ship weight and the various deadweight components (fuel, consumables, provisions, stores etc.) from vessel’s displacement.

Intact and Damaged Stability Calculations

Stability calculations are performed for the vessel both in intact and damaged condition (either for side damage or bottom racking) to verify its compliance with the requirements of the 2000 HSC Code. A series of NAPA macros were prepared to control the process flow, including the intact and damage cases definition, while the actual stability analysis is performed using the calculation capabilities provided by the NAPA software. Calculations are performed for a predetermined range of initial draughts at zero trim and also for specific loading cases, with 100% passengers and variable vehicles loadings, both in the departure and arrival condition, assuming 10% consumables for the latter case.

The required metacentric height to satisfy relevant regulations ($G_M$) is subtracted from the actual metacentric height to obtain the corresponding stability margin. Thus, the overall minimum value of the calculated stability margins for the considered loadings, both in intact and damaged condition, is obtained, which is denoted as the metacentric height margin ($G_{MTRG}$). A minimum positive value for the $G_{MTRG}$ is usually required, in the order of 10cm to 30cm, to ensure fulfilment of the stability requirements in all cases, even in case of a small underestimation of the vessel’s vertical centre of gravity. As expected, due to the inherently large transverse stability margins of twin-hull vessels, the fulfilment of the transverse stability regulations with significantly large safety margins was easily accomplished in most cases.

Assessment of the Vessel’s Economic Performance

The calculation of the vessel’s building costs is based on its decomposition into major cost items and sub-items, along with the development of suitable expressions for their calculation. In general, calculations are based on unit construction or procurement costs (for example, cost of fabricated steel or aluminum per ton, cost of public spaces outfitting per square meter, cost of propulsion machinery per kW). A similar procedure is applied for the calculation of the vessel’s operating cost. Here again many cost items are estimated on the basis of corresponding unit cost values (e.g. cost of fuel oil, diesel oil and lubricating oil per ton, crew wages, maintenance and insurance costs, etc.). Unless otherwise specified by the user, the crew synthesis and the corresponding costs are determined according to Greek statutory regulations. Since the various unit costs vary significantly from year to year or from one shipyard to another, the software user may provide the corresponding values to ascertain satisfactory accuracy of calculations. Otherwise, calculations are performed using internally defined default values. The annual operating income and also many items of the annual operating cost are calculated for the particular service conditions specified by the user (route length, number of trips per week in the low, medium and high season, the corresponding passenger and vehicles occupancies, passenger fare and vehicles freight etc.). In addition, the expected years of operation should be provided by the user, along with an estimation for the price of the vessel at the end of the operation period (as a percentage of the corresponding acquisition cost), the percentage of the initial acquisition cost covered by loan, the loan interest and the payback period, the discount rate
and tax rate. Based on these data, the vessel’s economic performance is assessed using appropriate economic indices, such as the Required Freight Rate (RFR), or the Net Present Value (NPV). Those two criteria are encompassing the building, capital and operating costs as well as the annual revenues in a rational way. Transport capacity and propulsion power are also directly accounted for in the RFR and NPV calculation, via the annual income, the fuel costs and the acquisition cost of the propulsion plant.

INTEGRATION WITH OPTIMISATION SOFTWARE
The main objective of the presented work was the successful linking of the developed parametric design software for high-speed vessels with a commercial multicriteria optimisation software, namely herein modeFRONTIER®, to form an integrated design and optimisation environment for the preliminary design and optimisation of high-speed mono- and twin-hull ROPAX vessels. Genetic Algorithms were selected as the most suitable optimisation method for the specific design problem, in view of their inherent capability to deal with multi-objective and multi-constrained optimisation problems, with mixed continuous-discrete design variables and non-convex design space solutions.

A series of technical or economic quantities are available for the formulation of the most suitable objective functions fitting to the requirements of the user in each particular study. The minimisation of building cost is an obvious choice, particularly when the optimisation study is performed on behalf of the yard, seeking to find the most economical design solution, to a specified set of operational requirements. In addition to the minimisation of building cost, other criteria such as the minimisation of the required propulsion power, or the annual operating costs, or the Energy Efficiency Design Index or the maximisation of annual revenue on a selected route are of particular interest to the ship operator. Accounting for all these objectives simultaneously, requires the formulation and solution of a multicriteria optimisation problem. On the other hand, more complex economic criteria, such as the maximisation of the Required Freight Rate (RFR) or the maximisation of the Net Present Value (NPV) may be used, revealing the vessel’s economic performance on a specified route in a seaway (estimation of motion and acceleration levels). Once again, the user has the choice of treating seakeeping performance as an objective function (see, Boulougouris et al. [10]), or as a constraint, specifying acceptable limits regarding the vessel’s performance (motions, accelerations or sea-sickness indexes) in specific sea-states. Other objective functions can also be used if required, since the design software architecture is very flexible.

DEMONSTRATION STUDY
The developed parametric design and optimisation methodology has been applied to the design and optimisation of a series of high-speed ROPAX vessels of various sizes and on selected routes, between a number of Aegean islands and the Greek mainland. In the following, a typical example is briefly presented and discussed.

This example corresponds to an optimisation study for a medium size vessel, operating between the port of Lavrion, located 60km southeast of Athens and the island of Mykonos in the central Aegean Archipelagos (Figure 11). The length of the one way trip is 75sea miles. With a desired service speed of 32kn the time at sea for a one-way trip is approximately 2.5 hours. Only one objective function (i.e. the maximisation of the vessel’s Net Present Value) was used in this example. A minimum metacentric height margin $GM_{MRG} \geq 0.30m$, above the requirements of the intact and damaged stability regulations has been specified. The 5083 aluminum alloy was selected as the construction material. From the various design parameters, some were kept constant during this optimisation exercise, while 12 of them were treated as free variables. These design parameters, along
with their range of variation are presented in Table 3. The actual transport capacity of each design alternative is calculated by the design software, based on the available deck area and the vessel’s weight carrying capacity, assuming an average truck weight of 20t (a maximum number of two trucks per one-way trip was used for the calculation of the vessel’s revenue). The calculation of the Net Present Value index has been performed for an average fare of 45€ per passenger, and a freight rate of 67.5€ for the private cars and 168.75€ for the trucks. The Required Freight Rate calculations were performed for a standard ratio of the private cars freight rate to the passenger’s fare equal to 1.5. The ratio of the freight rate of trucks to that of the private cars has been kept constant, equal to 2.5. The vessels have been considered operating for a period of twelve years. The depreciated value of each vessel at the end of the twelve years period was set at 33% of the corresponding acquisition cost. A 50% loan with a 7% interest and a ten years payback period has been considered. The discount rate was set at 8%, while a 30% tax rate was assumed. The fuel oil price was set at 500€/t. Some additional assumptions regarding the seasonal conditions on the route are summarized in Table 4.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Internal Code Names</th>
<th>Range</th>
<th>Intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td>VA.1 Demihull length below the water line, L_{HL} (m)</td>
<td>LHULL</td>
<td>60.0</td>
<td>70.0</td>
</tr>
<tr>
<td>VA.2 Strut length, L_{SR} (% L_{HL})</td>
<td>LSTRUT</td>
<td>90.0</td>
<td>95.0</td>
</tr>
<tr>
<td>VA.3 Draught, T (m)</td>
<td>DRAFT</td>
<td>2.9</td>
<td>3.3</td>
</tr>
<tr>
<td>VA.7 Run length, L_{R} (% L_{HL})</td>
<td>LRUN</td>
<td>48.0</td>
<td>52.0</td>
</tr>
<tr>
<td>VA.11 Required demihull volume, V (m³)</td>
<td>VOLREQ</td>
<td>475</td>
<td>525</td>
</tr>
<tr>
<td>VB.1 Vertical coordinate of the bulbous bow end point, Z_{B} (%T)</td>
<td>BOWIM</td>
<td>45.0</td>
<td>55.0</td>
</tr>
<tr>
<td>VC.1 Transom immersion, T_{IM} (%T)</td>
<td>TRANSIM</td>
<td>55.0</td>
<td>65.0</td>
</tr>
<tr>
<td>VD.1 Distance between demihulls, S_{DH} (m)</td>
<td>SPACE</td>
<td>15.0</td>
<td>18.0</td>
</tr>
<tr>
<td>VD.8 Accommodation deck aft limit, (%B_{OA})</td>
<td>ODCL</td>
<td>30.0</td>
<td>50.0</td>
</tr>
<tr>
<td>VD.9 Bridge deck aft limit (%L_{HL})</td>
<td>BDCL</td>
<td>30.0</td>
<td>50.0</td>
</tr>
<tr>
<td>VD.11 Spacing of transverse frames, F_{SP} (m)</td>
<td>FRSPAC</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>VD.12 Number of transverse watertight bulkheads, N_{BK}</td>
<td>BHDS</td>
<td>6</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 4: Seasonal conditions (Lavrion – Mykonos route)

<table>
<thead>
<tr>
<th>Season</th>
<th>High</th>
<th>Medium</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Months per year</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Round trips per day</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Passengers loading</td>
<td>90%</td>
<td>60%</td>
<td>30%</td>
</tr>
<tr>
<td>Private cars loading</td>
<td>90%</td>
<td>50%</td>
<td>20%</td>
</tr>
</tbody>
</table>

The Multiple Objectives Genetic Algorithm optimisation scheduler of modeFRONTIER has been applied in these optimisation studies. Using the steady-state GA algorithm MOGA, 200 design generations were derived with a population of 50 designs per generation. The genetic operations were executed with a 5% probability of selection, 50% probability of directional crossover, 10% probability of mutation, 10% DNA string mutation ratio and
penalize objectives for treating constraints. Some of the obtained results from this optimisation example are presented in the following.

The attained NPV index of the feasible designs varies from -21.6m€ to 12.93m€, while their corresponding RFR value varies from 72.07€ to 33.74€. The design maximising NPV is found in the 69th generation (design number 3441). The same design exhibits also the maximum ratio of NPV vs. the acquisition cost. Figure 12 presents the scatter diagram of the obtained NPV versus the total Propulsion Power. As expected, there is an inverse relation between the installed Propulsion Power and NPV, with an increase of Propulsion Power generally leading to a reduction of the NPV index. Figures 13 and 14 present the scatter diagrams of the obtained NPV index versus the building cost and the vessel’s DWT respectively. As may be observed from these diagrams, for the particular operational scenario and for the considered range of vessels, the best performance is exhibited in general by the larger vessels (economy of scale). Finally, in Figure 15, a “parallel diagram” is given, showing the relationship between the design variables of the obtained designs and the corresponding values of their NPV index. Each line in this graph corresponds to a particular design. Disregarding all the designs with NPV less than 9m€ (Figure 16) we may observe some trends among the design variables of the remaining vessels: they all have comparatively larger length and transverse spacing between demiuhulls, a strut length greater or equal to the 92% of their hull length, combined with relatively small draught and frame spacing. The values of the remaining design variables of the selected vessels are equally distributed in the considered range, indicating that the impact of these variables on the vessel’s performance is relatively weak.

CONCLUSIONS

The present paper provided a brief introduction to the holistic approach to ship design optimization, defined the generic ship design optimization problem and demonstrated its solution by use of Genetic Algorithms and a developed integrated ship design optimization procedure. This was applied to two distinct examples, namely the optimization of hydrodynamic performance and environmental impact of a high-speed monohull passenger ship and the optimization of the economic performance of high-speed twin hull ROPAX ship.

It was shown that multi-objective mathematical optimization approaches are very valuable tools and greatly enhance the quality of ship design, even if applied to vessel concepts already optimized by traditional methods. The developed design and optimisation methodology may be a useful tool for the designer in the preliminary design stage, facilitating the elaboration of a large number of design alternatives quickly and with little effort. The designer may explore this possibility to investigate the effect of crucial decisions on the vessel’s operating performance before proceeding to the detailed design stage. The design methodology may be also effectively used in feasibility studies, providing assistance for the determination on a rational basis of the most suitable vessel’s size, transport capacity, speed and other operating characteristics, for a selected service. The integration of the parametric ship design application with a multi-objective optimisation software facilitates the design space exploration in a rational and efficient way, enabling the identification of favourable and unfavourable areas of the design variables and ultimately for the determination of the optimal designs located on the Pareto Frontier (in case of multicriteria optimisation). Furthermore, once the optimum design has been selected, its detailed NAPA model including (but not limited to) the hullform and the watertight subdivision is readily available for further elaboration and detailed design work, reducing considerably related effort.

A final comment on the way ahead: though the generic solution approach to the holistic ship design problem appears well established, it remains for researchers to develop and integrate a long list of application algorithms and related software, addressing the great variety of ship design for life-cycle. This is a long term task of decades, requiring profound skills and understanding of the physics and design of ships, a domain requiring properly trained naval architects and scientists of related disciplines.

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REFERENCES


Figure 12: Scatter Diagram of Net Present Value vs. the Installed Propulsion Power
Figure 13: Scatter Diagram of Net Present Value vs. Building Cost

Figure 14: Scatter Diagram of Net Present Value vs. DWT
Figure 15: Parallel Diagram of the Free Variables with corresponding NPV: All Feasible Designs Included

Figure 16: Parallel Diagram of Free Variables with corresponding NPV: Feasible Designs with NPV > 9m€ Included