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Energy efficiency parametric design tool in the framework of holistic ship design optimization

E K Boulougouris^{1*}, A D Papanikolaou², and A Pavlou²

¹Department of Naval Architecture, Faculty of Technological Applications, Technological Educational Institute of Athens, Athens, Greece

²Ship Design Laboratory, School of Naval Architecture and Marine Engineering, National Technical University of Athens, Athens, Greece

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Abstract: Recent International Maritime Organization (IMO) decisions with respect to measures to reduce the emissions from maritime greenhouse gases (GHGs) suggest that the collaboration of all major stakeholders of shipbuilding and ship operations is required to address this complex techno-economical and highly political problem efficiently. This calls eventually for the development of proper design, operational knowledge, and assessment tools for the energy-efficient design and operation of ships, as suggested by the Second IMO GHG Study (2009). This type of coordination of the efforts of many maritime stakeholders, with often conflicting professional interests but ultimately commonly aiming at optimal ship design and operation solutions, has been addressed within a methodology developed in the EU-funded Logistics-Based (LOGBASED) Design Project (2004–2007). Based on the knowledge base developed within this project, a new parametric design software tool (PDT) has been developed by the National Technical University of Athens, Ship Design Laboratory (NTUA-SDL), for implementing an energy efficiency design and management procedure. The PDT is an integral part of an earlier developed holistic ship design optimization approach by NTUA-SDL that addresses the multi-objective ship design optimization problem. It provides Pareto-optimum solutions and a complete mapping of the design space in a comprehensive way for the final assessment and decision by all the involved stakeholders. The application of the tool to the design of a large oil tanker and alternatively to container ships is elaborated in the presented paper.

Keywords: greenhouse gases, holistic design approach, LOGBASED Project, ship systems optimization, parametric design tool

1 INTRODUCTION

It is today a well-established fact that human activities have a significant impact upon the levels of greenhouse gases (GHGs) in the atmosphere, i.e. those gases that absorb and emit radiation within

the thermal infrared range. The gases with the most important release to the atmosphere are, in descending order, water vapour, carbon dioxide (CO₂), methane, and ozone. The Intergovernmental Panel on Climate Change released in 2007 a report stating that ‘most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations’ [1].

One of the main contributors of the emissions of GHGs due to human activity is the burning of fossil fuels. The total CO₂ emissions from shipping

*Corresponding author: Department of Naval Architecture, Faculty of Technological Applications, Technological Educational Institute of Athens, St. Spyridonos Street, Athens 12210, Greece.
email: vboulg@teiath.gr

(domestic and international) amounted to about 3.3 per cent of the global emissions from fuel consumption during 2007, according to Buhaug *et al.* [2]. The central estimates in the Second International Maritime Organization (IMO) GHG Study (2009) is that, if no policy for the reduction in the GHG emissions is implemented, the growth of shipping will result in an increase by 150–250 per cent of the ship emissions relevant to their 2007 levels.

Climate stabilization by 2100 at no more than 2°C warming over the pre-industrial levels will require significant reductions in the CO₂ emissions by 2050, and the international shipping industry needs to participate in this process. Although maritime transport is the most efficient mode of transport and least pollutant in terms of GHG emissions, present discussions and expected regulatory measures suggest that the collaboration of all major stakeholders is required to address this complex techno-economical and highly political problem efficiently (see, for example, Document MEPC 57/4/5 [3]). The list of stakeholders embraces both shipbuilders and ship operators. The actions to be taken include the development of proper design, operational knowledge, and assessment tools for the energy-efficient design and operation of ships. More recently, an IMO study team emphasized that (see reference [2], p. 61)

‘...Ships’ lifetimes may exceed thirty years, and the operating and business environment may change significantly in the course of this time. Flexibility to allow upgrades and efficient operation in different scenarios should be considered at the design stage. It is thus critical to build the right ship for the job, which provides sufficient flexibility in operation. Specifying a ship and subsequently designing to that specification is a highly complex task. Estimating the potential for saving energy at this stage is equally complex; however, the influence of choices that are made at this stage of the design process is very significant and should not be under-estimated.’

This is exactly the field of application of the approach elaborated in this paper which is based on the EU-funded Logistics-Based (LOGBASED) Design Project.

2 BACKGROUND

The type of effort coordination required by many maritime stakeholders with often conflicting interests and ultimately aiming at optimal ship design and operation solutions has been addressed within the LOGBASED methodology, developed in the

recently completed LOGBASED Project [4, 5]. The approach has a modular structure where the various modules can be utilized to various extents pertaining to the specific case in question (Fig. 1). The various modules guide the business developer and/or designer through a systemic process. This provides decision-making support to the development of a transport system and the pertinent integrated ship design solution within the specific business development context in question. Thus, the LOGBASED method can be used not only for the design of a single ship but also for the management of a whole fleet of ships. The project focused on roll-on-roll-off (ro-ro) ships, but the methodology developed can be easily extended to other ship types, such as oil tankers, bulk carriers, and container ships.

3 THE PROBLEM

In most cases the development of a transport system has many stakeholders: commercial, operational, economical, technical, and social. In this business environment, the optimization of the design of the tailor-made ship for the particular trade is the ideal situation that reduces the risk and maximizes the returns of the investment. This is well known among ship operators. The problem is how to define the ‘perfect ship’ given the following:

- (a) the fluctuations in the market (i.e. the cargo demand);
- (b) the flexibility of the competitors (i.e. the cargo capacity);
- (c) the uncertainty in the behaviour of the rest of the stakeholders (cargo owners, port authorities, international regulatory bodies, financial investors, etc.);
- (d) the uncertainty in the environmental factors.

The above uncertainties lead many shipping companies to be conservative [6] and sometimes result in the loss of good opportunities due to the lack of proper decision support tools. These companies prefer to use ships in a similar way to their competitors under the assumption that in this way they minimize their risk. Therefore, when they decide to build a new ship, they usually suggest a set of owner’s requirements that resemble those of existing ships. These requirements are mandatory for ship designers, who rarely have the capability or the opportunity to question their rationality. This has been addressed within the LOGBASED Project which attempts to provide designers, shipbuilders, and ship operators with better guidance to develop

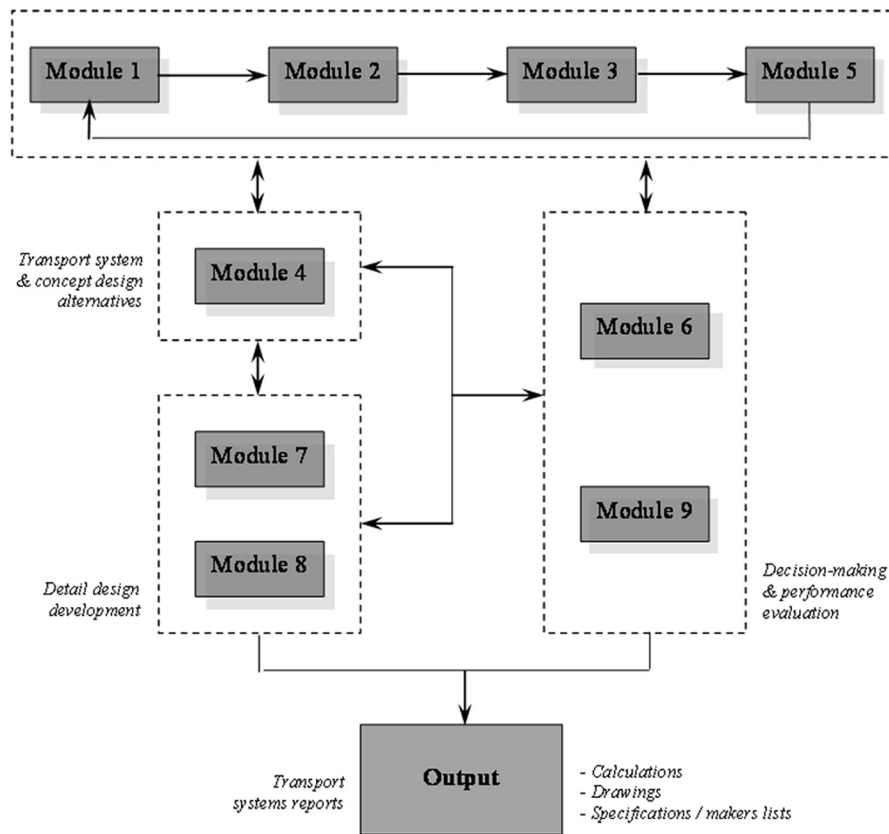


Fig. 1 The LOGBASED methodology (from reference [5] with permission): module 1, business concept definition; module 2, performance expectations; module 3, competitive position; module 5, risk assessment; module 4, transport system and design solution development; module 6, decision-making support; module 7, ship functions; module 8, ship systems; module 9, performance evaluation

effective ship designs for business opportunities. The difference between the old approach and the new approach is shown in Fig. 2. In the new approach the designer and the owner are working side by side, using the available market mapping in order to rationalize the ship requirements. The market is captured using advanced forecasting tools such as artificial neural networks (ANNs), trained according to the existing historical data. The designer creates a parametric ship model that is optimized using state-of-the-art tools such as genetic algorithms (GAs) and the owner's preference is captured using multi-attribute decision-making (MADM) methods, such as the analytical hierarchy process (AHP) and utility functions (utilité additive (UTA)). It is obvious that the impact of this approach is maximized when it is used early in the business case development phase.

As part of the knowledge base developed within LOGBASED, a parametric design tool (PDT) has been developed by the National Technical University of Athens, Ship Design Laboratory (NTUA-SDL). The PDT facilitates the interaction of

the novel LOGBASED approach with the traditional ship design methods accommodated in modules 7 and 8. The PDT is an integral part of module 4 (i.e. transport system and design solution development (see Fig. 1)). Its aim is to provide the user with the capability to develop different design solutions and to exploit the feasible design space very rapidly. Furthermore, the PDT tool is also used to benchmark or calibrate heuristically selected system design parameters for extreme values or outliers.

Traditionally the environmental impact of a ship (except in the cases of the oil spills of tankers) or a fleet is taken into account in a qualitative way, i.e. through compliance with a set of rules requiring some sort of system to exist (i.e. scrubber) or a procedure to be followed (i.e. water ballast management). Thus, even if for the decision maker the maximization of the environmental friendliness is of top performance expectation (module 2), this would be achievable only through the proper selection of the systems in module 8. The introduction of the CO₂ index or energy efficiency design index (EEDI) of the attained new ship design has permitted the

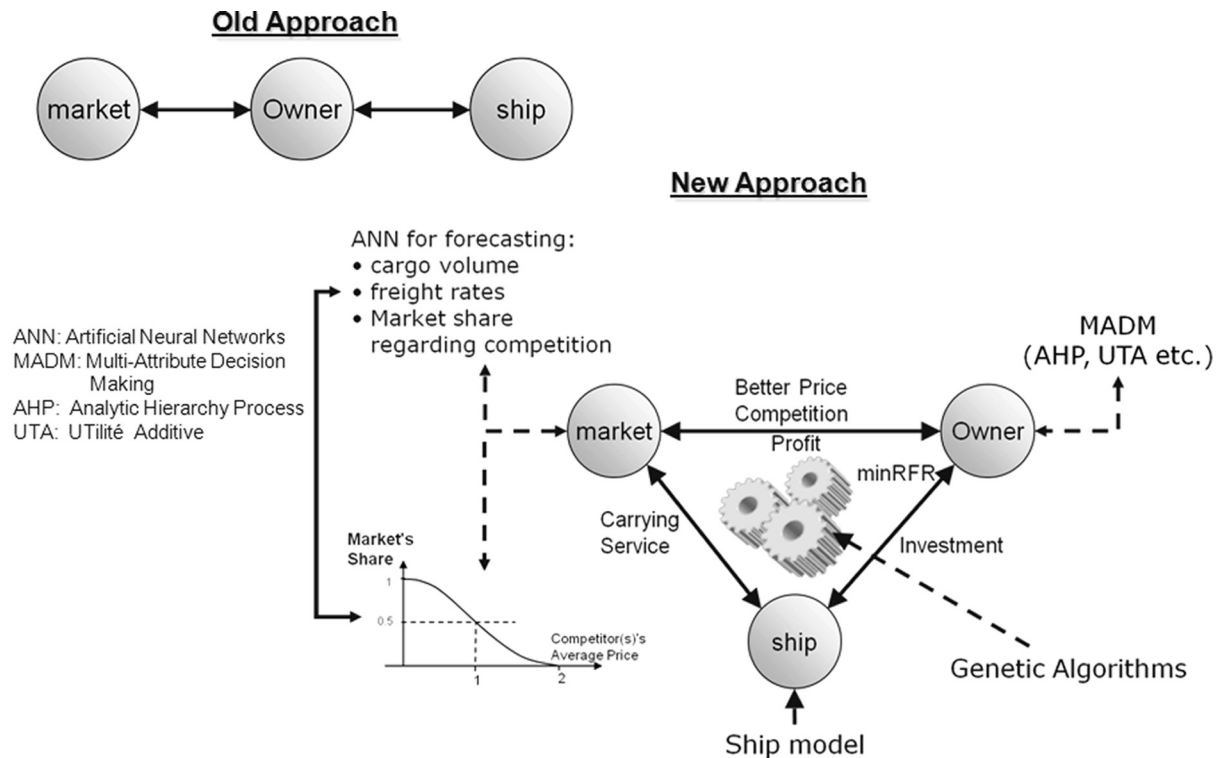


Fig. 2 Comparison of the old approach and the new approach (from reference [7] with permission)

evaluation of the environmental friendliness from a quantitative perspective. Thus, the minimization of the EEDI has been introduced as an objective into a multi-criteria design-making (MCDM) problem.

4 HOLISTIC DESIGN OPTIMIZATION

Most design problems are formulated on the basis of the determination of a set of design variables (e.g. the number of ships and the individual ship size and speed in fleet optimization) that provide a design solution that satisfy certain relations between, and restrictions of, these variables (e.g. physical, technical, legal, and economical). In case there are a number of combinations of design variables that satisfy all these conditions, a measure of merit is selected (e.g. the weight, cost, or yield) which creates a ranking, resulting in the selection of the optimal combination [8]. The number of design variables is always constrained by efficiency considerations [9].

Since the mid-1960s with the advance of computer hardware and software more and more parts of the design process have been taken over by computers, particularly the heavy calculatory and draughting elements of ship design. Simultaneously, the first computer-aided preliminary design software systems

were introduced, dealing with the mathematical parametric exploration of design space on the basis of empirical and simplified ship models for specific ship types or the optimization of design variables for specific economic criteria by gradient-based search techniques [10, 11]. Also, computer-aided studies on optimization of the ship's hull form for least resistance and best seakeeping behaviour (hydrodynamic design optimization) or of the ship's midship section and structural design for least steel weight (structural design optimization) started to be introduced to the naval architectural scientific community until they led to mature results in more recent years [12, 13].

With the further and faster advance of computer hardware and software tools, together with their integration into powerful hardware 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 the ship's life (or all elements of the entire ship's life cycle system), and at least the stages of design, construction and operation; within a *holistic ship design* optimization, herein this means exhaustive multi-objective and multi-constrained ship design optimization procedures even for the individual stages of the ship's life (e.g. conceptual design) with least reduction in the entire real problem [14]. Recently, the scientific

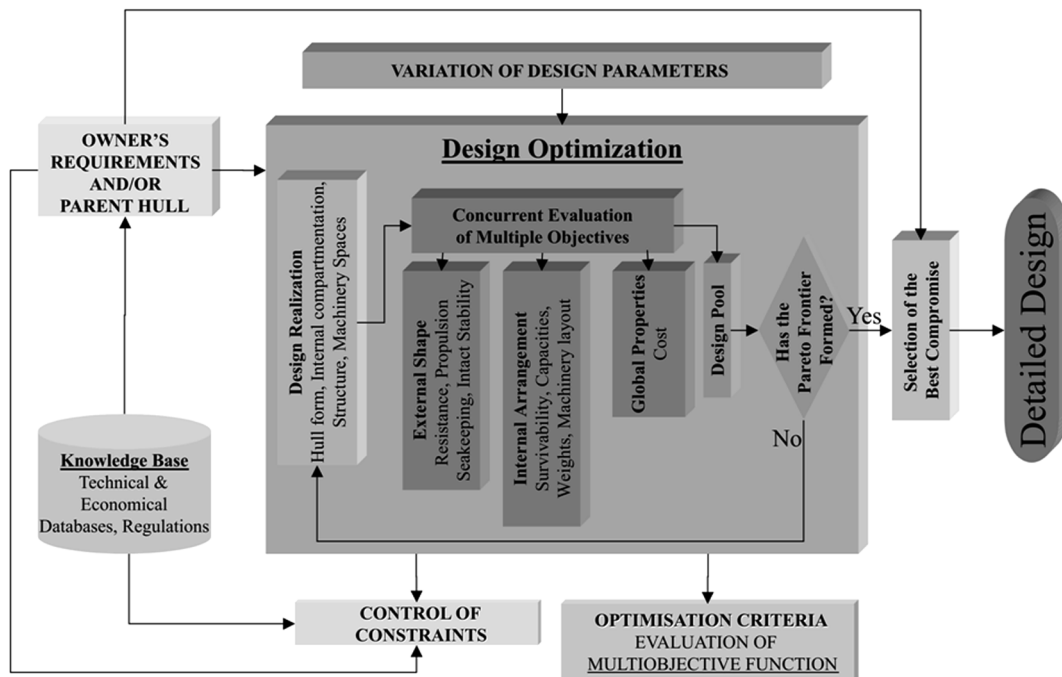


Fig. 3 Ship design optimization procedure (from reference [13] with permission)

disciplines introduced in the general framework of ‘design for XXX’, namely ‘design for safety’ [15, 16], ‘design for efficiency’, ‘design for production’, ‘design for operation’, etc., indicate the need for approaches and the availability of mature methods and computational tools to address holistically the ship design optimization problem.

The use of GAs, combined with gradient-based search techniques in microscale exploration and with a utility functions technique for MADM, provides the means for a generic type of optimization technique, producing and identifying optimized designs through effective exploration of the large-scale non-linear design space and a multitude of evaluation criteria. 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 [17], the optimization software modeFRONTIER [18], the PDT, and various other application software tools, as necessary for the conceptual design, the evaluation of the stability, the resistance, the seakeeping, etc., may be found in the listed references. A sketch of the approach to generic ship design optimization is shown in Fig. 3.

In this paper, the holistic ship design approach will be implemented for the classical design problem of large tankers for a given deadweight (DWT) with the following objectives:

- (a) minimization of the EEDI;
- (b) minimization of the ideal ship price (ISP);

- (c) minimization of the displacement of the ship;
- (d) maximization of the ship’s speed.

Additionally, the holistic ship design approach will be implemented for the investigation of the benefits of designing slow-speed container ships in order to minimize their environmental footprint.

5 THE TOOLS

It is true that in the context of the holistic design approach there are more advanced methods and tools for treating the above problem. For example, hull optimization can be performed by the integration of NAPA, SHIPFLOW, and modeFrontier [13]. Nevertheless, they require the skills of a well-trained naval architect and also they are time consuming for the conceptual design phase. In that respect, the PDT is the ideal tool that can be easily used by all stakeholders (i.e. designers, builders, owners, and operators).

The PDT has been developed in MS EXCEL 2003 and recently upgraded to MS EXCEL 2007. It consists of four main functional elements:

- (a) element I, a database of existing ship designs and their main particulars including the ship’s type, size, and other special features;
- (b) element II, a query tool for the analysis of the database and the extraction of useful relationships between the various design parameters;

- (c) element III, a tool for the design and the trade-off analysis around a design point;
- (d) element IV, the ISP calculator.

The database of element I was recently extended to include the following:

- (a) ro-ro cargo ships [19] and other ship data from partners of the LOGBASED Project;
- (b) container ships [19];
- (c) oil tankers built after 1995 with a DWT larger than 70 000 ton;
- (d) bulk carriers with a DWT capacity from 500 ton up to 33 000 ton;
- (e) bulk carriers built after 1995 with a DWT from 55 000 ton up to 322 000 ton;
- (f) general cargo ships with a DWT from 500 ton up to 52 000 ton.

Element II is a query tool for filtering the design database. Three-stage filtering has been introduced on the basis of feedback from end users. In the first stage the user selects the subset of ships according to their date of build. In the second stage this subset is refined according to the speed range. The last filtering of the data set (i.e. the third stage) is achieved according to the cargo-carrying capacity, i.e. the DWTs for tankers, bulk carriers, and general cargo ships or the lane metres for ro-ro ships. Thus, at the end a subset of 'similar designs' according to the designer's requirements is created. The statistical values of the main particulars and regression analysis formulae resulting from the selected subset are used for initiating the feasible alternative designs.

Element III is a simplified model of the traditional design spiral in the preliminary design stage. Starting from the basic requirements for the cargo-carrying capacity (DWT or lane metres), the speed, and the endurance and utilizing the information extracted from the database subset, an iterative process is used to balance the resulting main dimensions, the weights, and the installed horsepower of each design.

Element IV is a tool that calculates the ISP. The need for the development of such a tool was triggered by the large fluctuations occurring in the ship's price market and the confidentiality of actual ship price data. Instead of estimating the actual building cost plus profit (a function of both the shipyard location and country and the time of building), the following methodology has been developed. Given the market's freight rate (FR), the ISP is calculated by reversing the procedure method for the required FR calculation, namely on the basis of the zero net present value (NPV) of the

investment; in other words, the 'ideal' ship price that will zero the NPV for the given required FR is found. The feasibility of a project is evaluated by comparison of the resulting 'ideal price' designs with current market prices. The viability of an investment in purchasing a new building or an existing ship can also be assessed according to the preferred difference from the ISP.

The tool can also calculate the required FR if the ship price is given as the input from existing market data. The ISP is practically a special case of the zero NPV of Buxton's [20] 'permissible price' concept. The ISP proves to be a very handy indicator for estimating very rapidly the feasibility of a business case according to the magnitude of the required investment and its profitability given the actual market prices.

The core of the PDT is element III. Standard naval architecture methodologies are used in order to calculate the various lightship weight groups (structure, machinery, and outfitting). For ro-ro ships, Watson's [21] methodology and adjusting relevant semiempirical coefficients based on a verification of up-to-date designs recorded in databases of the LOGBASED design team are utilized. The machinery weight is estimated on the basis of the installed main engine's horsepower while the outfit weight is based on the main deck's area [8].

The resistance is estimated according to the method described by Holtrop and Mennen [22] and Holtrop [23] using appropriate margins for appendages, design, and sea conditions according to the usual contract specifications. The method is considered very accurate for the types of hull forms of interest herein, and it is quite sensitive in capturing hull design alternatives. Transom sterns and bulbous bows are taken into account. Thus, the employed method allows the definition of hull form variables in the form of a number of parameters which are used for minimization of the resistance and powering. It is worth noting that engine manufacturers are using this method to estimate the required engine type for similar ship types [24].

The cargo-carrying capacity for ro-ro ships is estimated in lane metres based on approximate empirical formulae taking into account the lane width, the utilized deck length, the margins from the side walls, and the number of decks. For bulk carriers and tankers the cargo capacity in cubic metres is calculated on the basis of empirical coefficients resulting from the analysis of real designs. Finally, the approach for container ships is based on an assumption for the number of 20 ft equivalent container units (TEUs) on and under deck, depending on the vessel size or class, and the calculation of the

number of carried TEUs by approximate empirical formulae accounting for the vessel's main dimensions.

5.1 Energy efficiency design index

The EEDI is calculated herein on the basis of the IMO's interim guidelines on the method of calculation of the EEDI for new ships [25].

Using the procedure and the assumptions described in the interim guidelines an initial estimation of the EEDI for the ships in the PDT database was performed. The specific fuel consumption (SFC) was assumed to be 170 g/kW h for the main engine(s) and 190 g/kW h for the auxiliary engine(s). The results for bulk carriers are shown in Fig. 4 while the relevant graph for the tankers is shown in Fig. 5. In Fig. 6 the EEDI for container ships, using 65 per cent of their DWT as a measure for their utilization, is shown.

What is interesting to observe in Fig. 4 is that almost the entire existing fleet of bulk carriers (except for a few outliers) is above the baseline formula proposed in Document GHG-WG 2/2/7 [26], even though a reduced SFC has been used in comparison with the values of 190 g/kW h and 210 g/kW h proposed in Document GHG-WG 2/2/7 [26]. This provides additional verification of the comments made by several delegations at the 60th session of the Marine Environment Protection Committee (MEPC) of the IMO [27].

In generating data for Fig. 5 (tankers), the same assumptions as in Document GHG-WG 2/2/7 [26] were used, i.e. an SFC for the main engine of 190 g/kW h, an SFC for the auxiliary engine of 210 g/kW h, and $C_F = 3.13 \text{ g CO}_2/\text{g fuel}$, where C_F is a conversion factor between fuel consumption and CO_2 based on the fuel's carbon content. The sample set within the PDT database fits the proposed baseline very well.

In Fig. 6, using the same assumptions as above, the sample set of container ships within the PDT database verifies the baseline for the container ships proposed in reference [28].

From the graphs in Figs 4 to 6 it is obvious that, for a given DWT requirement, the EEDI may vary significantly, in terms of both the ship size and the ship type, emphasizing the fact that there is room for improvement in the efficiency of many representatives of these types of ship.

The optimization procedure adopted herein employs the commercial software modeFRONTIER® [18] as the optimization scheduler and NAPA® for the naval architectural calculations and ship design. The important features of modeFRONTIER are as follows.

1. It is written 100 per cent in Java, making it completely portable.
2. It offers a menu of several optimization algorithms: GAs, conjugate gradient method, quasi-Newton method, sequential quadratic programming, and simplex. Algorithms can be combined, e.g. GAs for a global search and another algorithm for a local search (refinement).
3. It can handle both real and integer variables.
4. It can integrate software on different platforms in networks, e.g. a hull description in NAPA under MS Windows XP and a computational fluid dynamics code under UNIX on another computer.
5. It allows the boundary conditions to be checked first before an objective function is evaluated. This is important if the objective function requires far more central processing unit time than the (violated) boundary condition.
6. It runs on parallel architectures.

The data flow between the applications is shown in Fig. 7.

6 CASE STUDIES

6.1 AFRAMAX tanker

The application of the above optimization procedure to the conceptual design of an AFRAMAX tanker with a DWT capacity of around 112 000 ton was selected for the first case study. This work is complementary to previously published research work [14, 29], where the internal subdivision of a fixed-hull AFRAMAX tanker was optimized with respect to the carrying capacity and the oil outflow. In the present study, the internal subdivision was kept fixed, whereas the ship's hull form was varied. Thus, the main dimensions of the hull form (i.e. the length, the breadth, the depth, and the draught) and the buoyancy distribution (i.e. the longitudinal centre of buoyancy and the areas of the bulbous bow and transom) were varied herein, as they were considered as the design variables. The speed and the range were kept constant.

The PDT output variables include a large number of different design features such as the displacement, the lightship, the installed horsepower, the initial intact stability, the daily bunker consumption, the consumables, the payload, and the cargo capacity. Four of these output values were used as objectives for minimization in the present case study as follows:

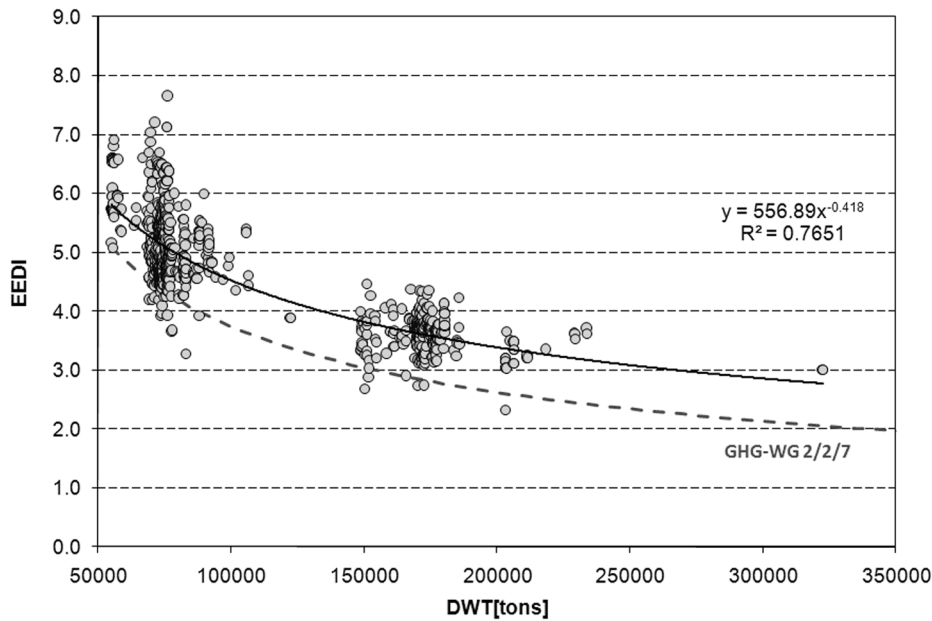


Fig. 4 The EEDI versus the DWT for bulk carriers with a DWT greater than 55 000 ton built after 1995

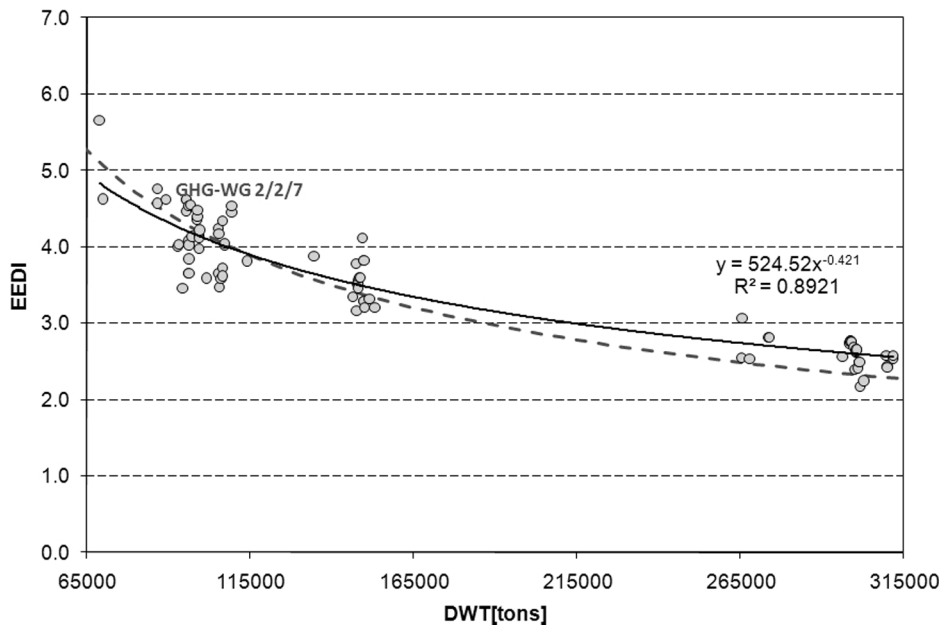


Fig. 5 The EEDI versus the DWT for crude oil tankers with a DWT greater than 65 000 ton built after 1995

- the total transportation cost per unit of cargo (in US dollars per ton);
- the EEDI;
- the lightship;
- the specific gravity of the cargo at the homogeneous full-load condition as a measure to maximize the carrying capacity for the same required DWT.

The total transportation cost per unit of cargo is calculated by subdividing the annually delivered cargo (millions of tons) by the total costs (millions of US dollars). The total costs include the annual voyage costs, the non-voyage operating costs, and the capital costs.

A number of constraints were used in this optimization as follows:

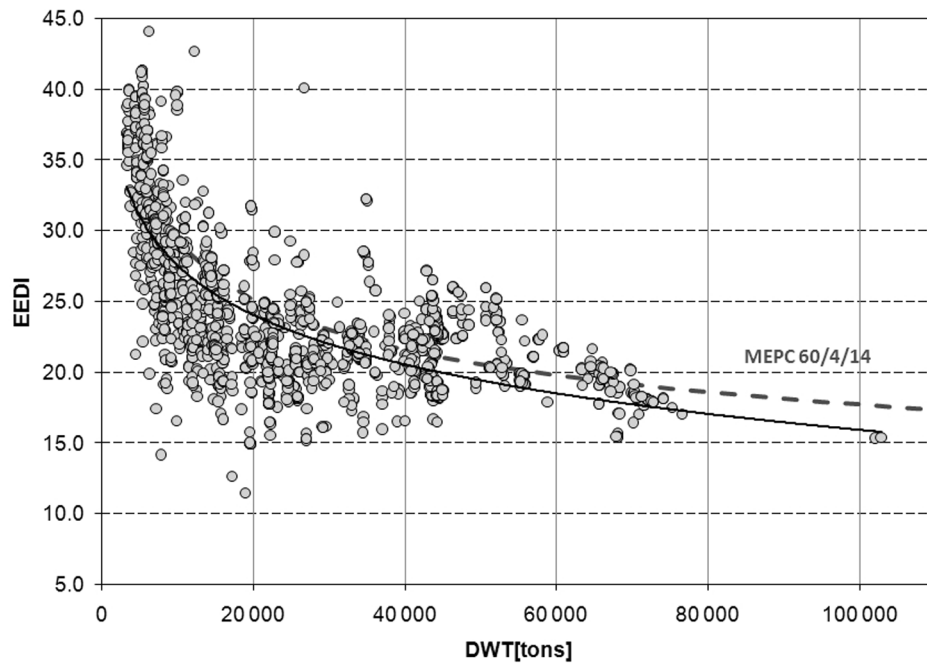


Fig. 6 The EEDI based on the DWT versus the DWT for container ships according to Circular MEPC.1/Circ.681 (from reference [25] with permission)

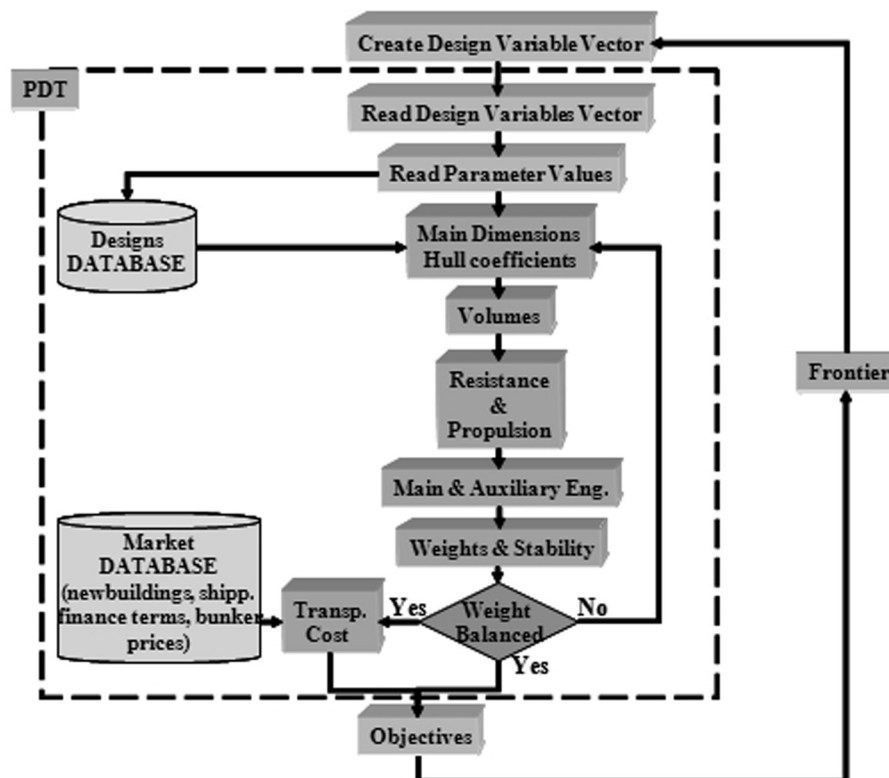


Fig. 7 Optimization data flow chart

- (a) the metacentric height uncorrected for the free-surface effect;
- (b) the maximum value of the cargo's specific gravity;

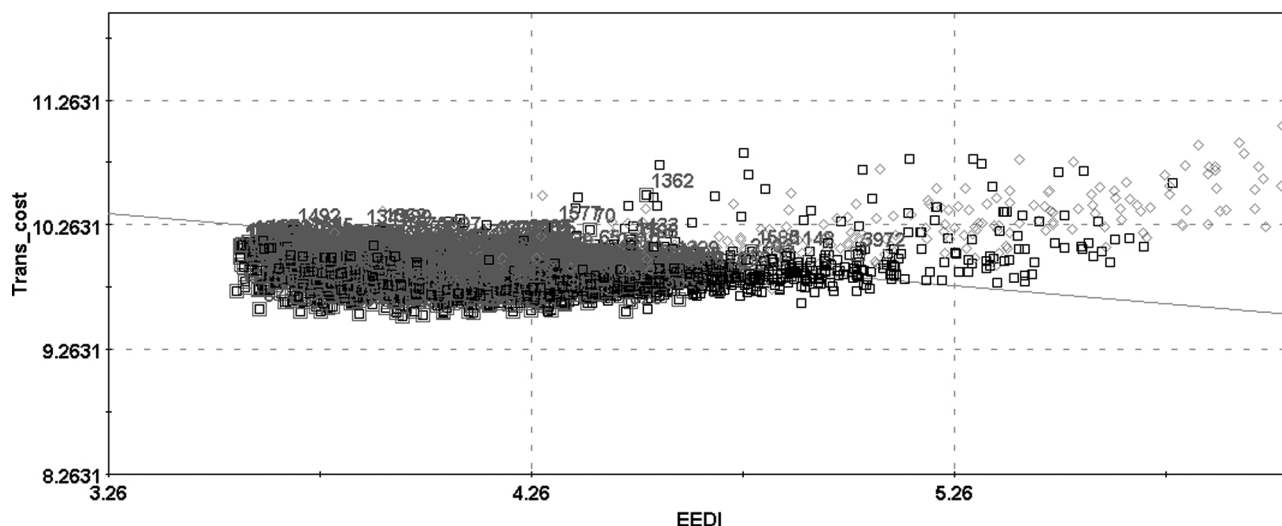


Fig. 8 The transportation cost per ton versus the EEDI

- (c) the minimum and maximum block coefficients in order to create valid tanker designs;
- (d) the adequacy of the capacity of the segregated ballast tanks to meet the relevant MARPOL requirements;
- (e) the maximum draught according to the Load Line Convention (LLC) which should not be exceeded.

The range of variance of the design variables was selected on the basis of the available PDT database (element II) for a DWT range ± 5 per cent around the required DWT. The data for the engines were taken from an engine database.

In the optimization procedure, 4000 different designs were generated. The scatter diagram of the total transportation cost in US dollars per ton versus the EEDI is shown in Fig. 8. In Fig. 9 the estimated lightship versus the cargo's specific gravity for the homogeneous full-load condition is shown.

Based on the above results, the Pareto (non-dominated) designs could be identified. In order to select the optimum design, the preference of the decision maker should be taken into account. Using modeFrontier's MCDM GA and requesting that the objectives should be ranked in descending order of importance, namely (herein as a demonstration example), first, the EEDI, second, the transportation cost, third, the lightship, and, finally, the maximum specific gravity of the cargo, a ranking of the Pareto designs was produced. The algorithm assists the decision maker in finding the best solution for a set of Pareto alternatives. It verifies the coherence of the expressed preferences and, if all pairwise comparisons are valid, it generates a valid utility function and ranking [18]. In the present case it resulted in the utility functions shown in Fig. 10.

Using these functions the Pareto designs can be ranked and the optimum can be identified.

The optimum design identified herein was design number 917 with the main dimensions and characteristics shown in Table 1.

Given the outcome of the conducted optimization, the decision maker has a comprehensive understanding of the physical and economic constraints of the design problem in hand; the range of the variance of the objectives and the compromises that have to be made may be systematically explored in order to obtain the best design solution fulfilling the initial expectations.

The results of the present PDT tool can be easily fed into modules 7 and 8 of the LOGBASED methodology, where the traditional design process takes place. For instance, a design software platform, such as NAPA, can be used in order to produce the ship's hull form and the arrangement with the required characteristics as shown in Fig. 11. Optimization of the internal subdivision is a feature of the holistic design concept that has already been demonstrated [14]. Verification of the weight estimations and especially of the weight of the steel structure is a more tedious task, requiring the integration of structural design software tools in the optimization, e.g. of classification-scanning software tools. This has also been addressed recently by NTUA-SDL in the framework of multi-objective tanker design optimization, in which, together with the structural weight, the oil outflow and the internal subdivision were optimized [30].

6.2 Slow-steaming container ship

The growing practice of slow-steaming container shipping services coincided with an unexpected

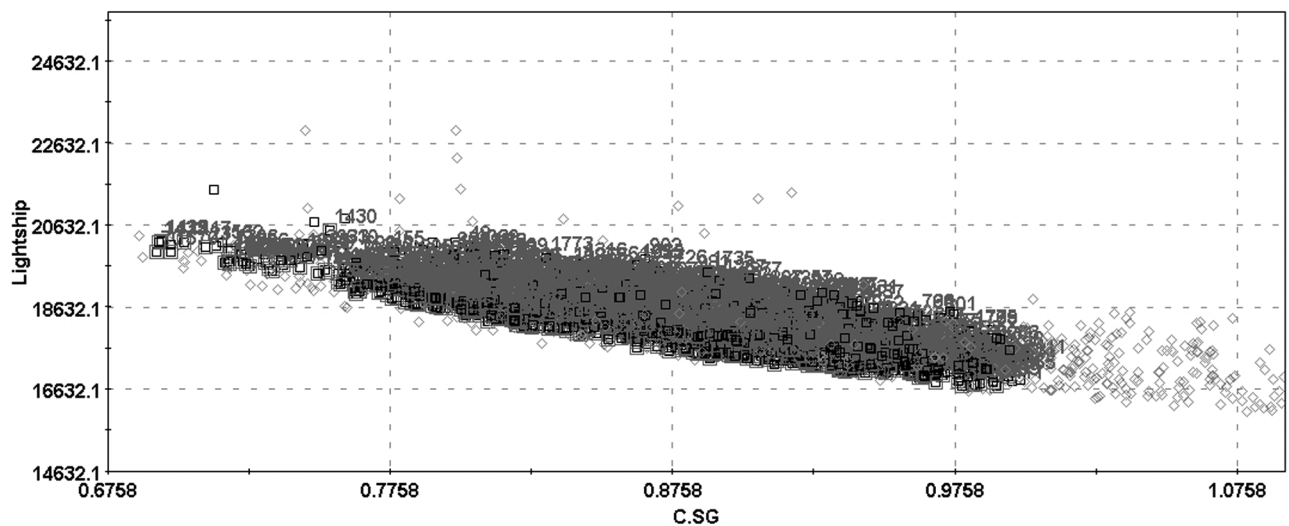


Fig. 9 The lightship versus the specific gravity of the cargo for the homogeneous full-load condition

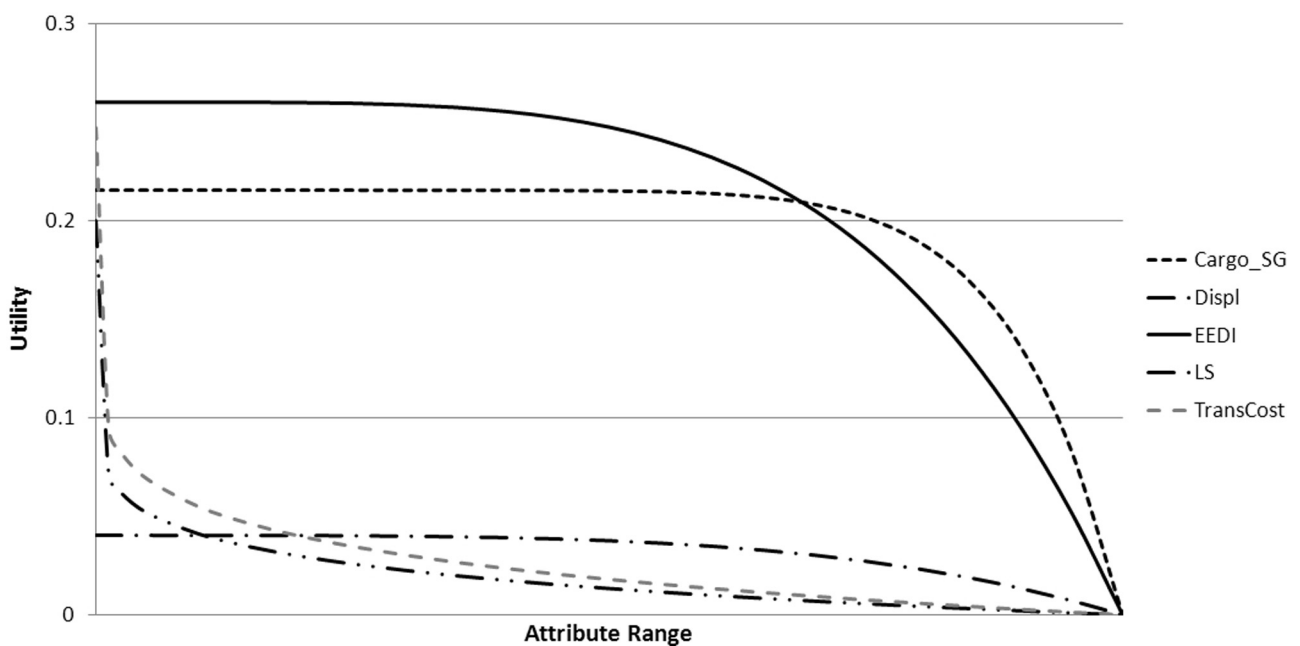


Fig. 10 Utility functions for ranking the Pareto AFRAMAX designs (SG, specific gravity; LS, lightship)

Table 1 Main dimensions of the optimum design

Length	241.00 m
Breadth	45.05 m
Depth	19.50 m
Draught	14.67 m
Block coefficient	0.827
Deadweight	116 000 ton
Lightship	18 877 ton
Main engine power	13 407 kW
EEDI	3.95
Payload	112 550 ton
Transportation cost	9.54 US\$/ton
Maximum specific gravity	0.935 t/m ³

deterioration in the on-time arrivals of vessels (see the latest Container Shipper Insight report by Drewry Shipping Consultants). Of nearly 1600 ships tracked in the 3 months between 1 October 2009 and 31 December 2009, Drewry's report found that only 53 percent arrived either on the scheduled day of arrival or a day prior to the scheduled day of arrival [31].

In order to investigate the impact of resetting the design point of future container ships with respect to the speed of service, a case study for the design

of two container ships with a carrying capacity of about 5000 TEU, but with different reductions in the speed, was launched. The first reduced the speed by 4 kn, namely from 25 kn to 21 kn, while the second corresponds to an even more radical speed reduction by 9 kn, i.e. to 16 kn. Valuable relevant information was retrieved from the Quantum project of Det Norske Veritas (DNV) [32]. A container ship database with ships built after 1995 up to 2007 was used, including 2535 different ships of various capacities. Relationships and charts in the NTUA-SDL ship database were updated to account for the influence of the TEU cargo capacity on the main particulars of the vessels. Energy efficiency indices, such as the Heickel coefficient and the specific resistance (SR) [33] or the specific tractive force (STF) were introduced, when comparing different modes of transportation [34]. The SR or the STF is defined as the fraction of the installed power divided by the product of the weight multiplied by the speed. The formulation given by Akagi and Morishita [35] was used with the power expressed in kilowatts, the weight in tons-force, and the speed in kilometres per hour. Finally, the semi-empirical weight estimation formulae were updated to account for the container ship calculations.

In order to examine the impact of the design changes, module 4 (i.e. the transport system and design solution development) was updated with an economic model for the container liner service. The data used were deduced from the work of Stopford [36]. The trans-Pacific route was selected for the case study. The model includes the following:

- (a) the service schedule based on a weekly schedule with seven port calls on the round voyage (e.g. Shanghai, Kobe, Nagoya, Tokyo, Sendai, Oakland, and Los Angeles);

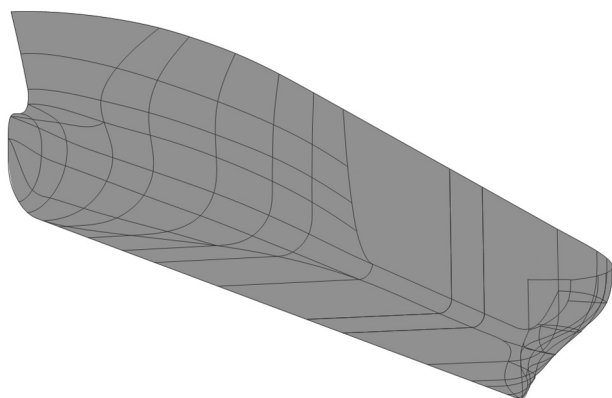


Fig. 11 Optimum AFRAMAX tanker hull form

- (b) capacity utilization, 90 per cent for the eastbound leg and 40 per cent for the westbound leg, recognizing the fact that there is much more cargo moving east in the selected route;
- (c) ship costs per day including operating expenses (OPEX), capital costs, and bunker costs;
- (d) port charges;
- (e) the cost of containers and their handling including transshipment, inland transport, inter-zone repositioning, and cargo claims;
- (f) the administration cost of running a global container service.

Thus, the updated module 4 includes all eight building blocks of liner costs [36] as follows:

- (a) the ship and its characteristics;
- (b) the service;
- (c) the capacity utilization;
- (d) the daily ship costs (OPEX, capital costs, and bunker costs);
- (e) the port charges;
- (f) the deployment of the containers;
- (g) the cost of containers and container handling;
- (h) the administration cost.

Given that the liner pricing is based on the cost per TEU, comparison of the economic efficiency of the designs in the following case studies was based on the average cost per TEU, i.e. the cost that the company should charge on both the eastbound leg and the westbound leg in order to cover all voyage costs.

6.3 The 21 kn container ship design

In this case, the implementation of the PDT as a fast decision support tool was investigated. Instead of performing a full optimization, the goal was to improve an existing design, producing radical changes in a short timeframe. In real life this could be accomplished during one or two executive meetings in a shipping company, with or without a major cargo owner.

The analysis of the database revealed that most of the existing designs are located around the $(C_b, Fn) = (0.65, 0.25)$ operation point, where C_b is the block coefficient and Fn is the Froude number (Fig. 12). Additionally, using the reciprocal transport efficiency as a metric of the transport efficiency of the design [33], it is obvious that, in the 4000–6000 TEU range, a larger capacity is not directly linked to a higher efficiency (Fig. 13). The resemblance of the plot of the reciprocal transport efficiency versus the TEU capacity to the plot of the EEDI versus the DWT capacity

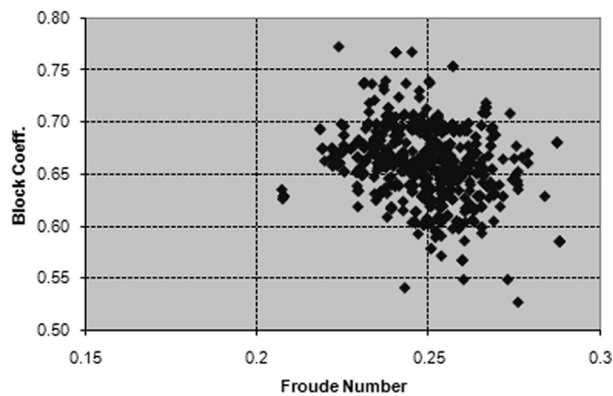


Fig. 12 The block coefficient C_b versus the Froude number Fn of existing container ships

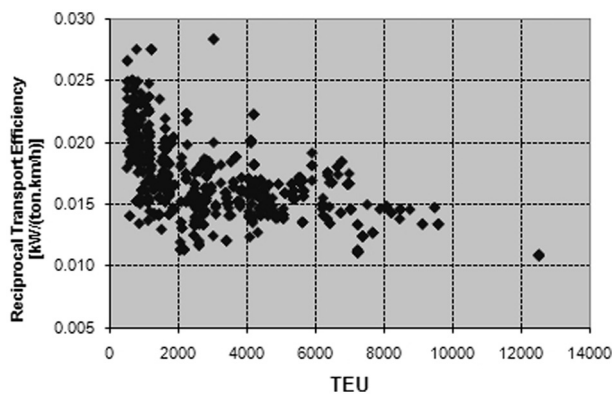


Fig. 13 The reciprocal transport efficiency versus the TEU capacity

(Fig. 6) is remarkable. The reciprocal transport efficiency is defined as

$$\text{Reciprocal transport efficiency} = \frac{\text{BHP(kW)}}{\Delta(\text{ton}) V_s(\text{km/h})} \quad (1)$$

where BHP is the brake horsepower, Δ is the displacement, and V_s is the service speed.

A subset of the database was used with designs having a TEU capacity of between 5000 and 6000 boxes. A reference ship was selected for verification of the PDT weight formulae. The general arrangement of the ship is shown in Fig. 14 and her main particulars are given in Table 2.

Based on only the TEU capacity, the PDT will normally design a typical post-Panamax ship, similar to the reference ship. Hence, the design goal herein will be to design a slower and wider ship with the required capacity. The TEU capacity of a cellular box-type ship, such as a container ship, is a function of the cross-section capacity and of the cargo hold length (Fig. 15).

Table 2 Main dimensions of the reference container ship

Length	263.00 m
Breadth	40.00 m
Draught	14.00 m
Block coefficient	0.61
TEU	5500
Speed	25 kn
BHP	≈ 55 000 kW
EEDI	24.05
Average cost per TEU	US\$1124
Number of ships for the schedule	4.9
Capital value	US\$89 × 10 ⁶

The design goal herein is to increase the capacity per section in order to reduce the length of the ship, noting that this may eventually reduce the structural weight and increase the payload capacity. The reference design DWT is a function of the weight of the TEUs plus the weight (8670 tonf) of the bunkers. If the number of TEUs remains the same, then the number of bunkers is expected to be significantly reduced. It is assumed that the payload remains the same and the breadth of the ship is increased from 40 m to 45.6 m. This creates two additional rows both in the hold and on deck and will increase the capacity per hold by 72 TEUs. Therefore, one hold can be omitted, reducing the required length by 29.68 m to 233.32 m. This may be expected to lead to a reduced structural weight, in view of the reduced longitudinal bending and torsional moments.

Using the data from the reference design, its voyage cost was calculated and its breakdown is shown in Fig. 16.

Using the PDT a systematic evaluation of different designs was performed. Given the constraints in the main dimensions, only a small subset of the design variables was altered. This quick investigation resulted in an improved design with the following particulars. The resulting design is very close to DNV's Quantum project design, with a reduced block coefficient. From Table 3 it is obvious that a significant reduction in the installed power was achieved (−48 per cent). This resulted in a reduction of 33 per cent in the EEDI, although the utilization was reduced. The capital value was also reduced owing to the smaller required main engine. A factor of 250 €/kW was assumed for the machinery costs. All the above resulted in a reduction of 5 per cent in the average cost per TEU for the given ship. The problem, however, is that by operating this ship the company will have to put one more ship into service in order to maintain a weekly liner service. In Fig. 17 the reason for the small overall cost reduction is obvious; the total ship costs were reduced for

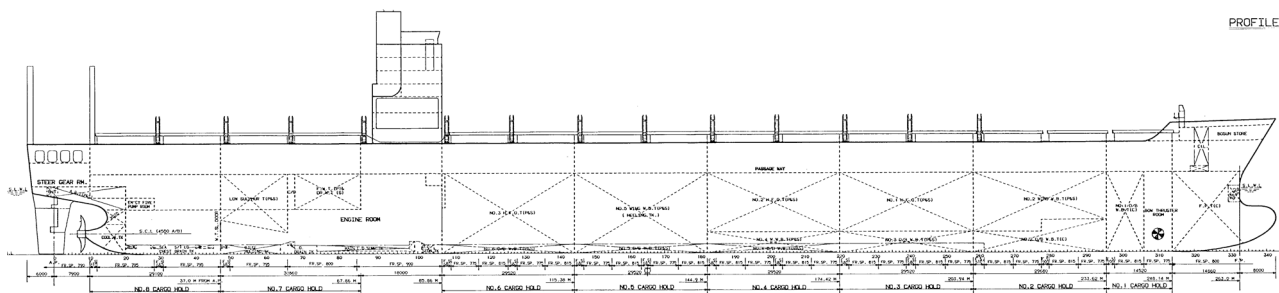


Fig. 14 GA of the reference container ship

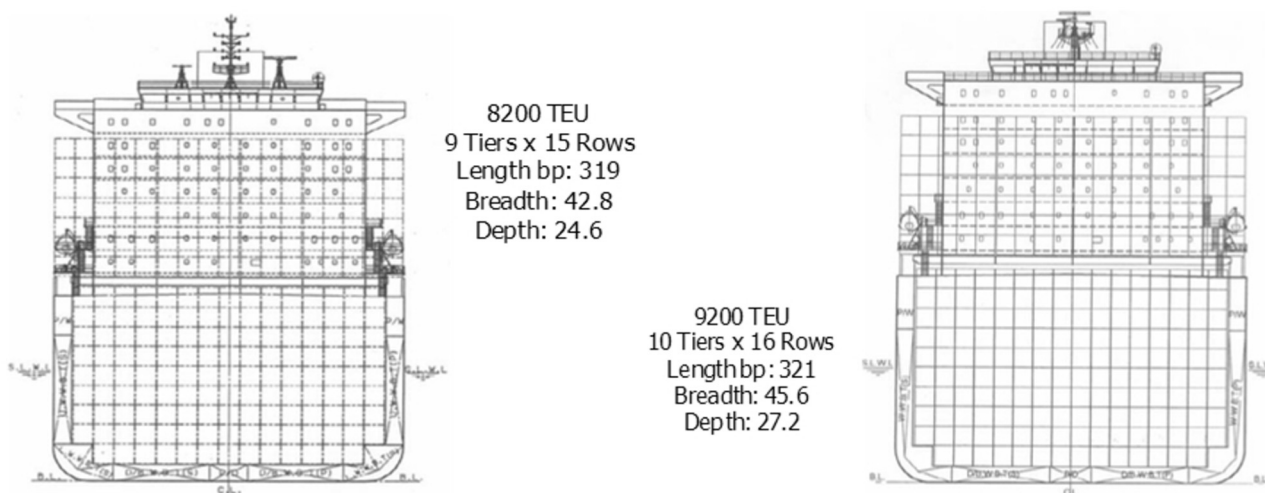


Fig. 15 The total TEU capacity as a function of the cross-section capacity

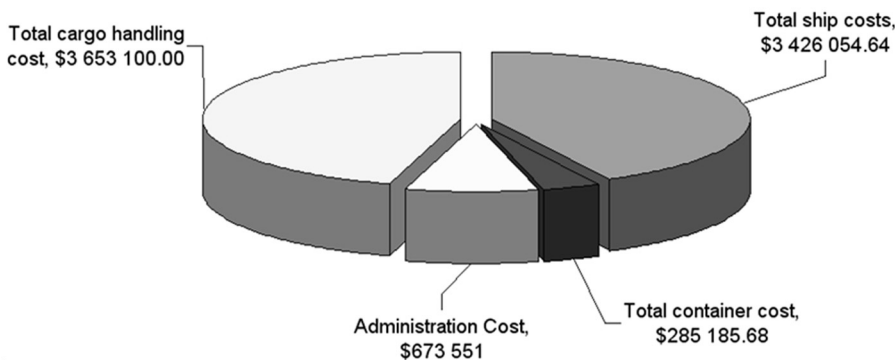


Fig. 16 Reference ship voyage cost breakdown

the improved design, but the rest of the cost items are more or less inflexible.

6.4 The 16 kn container ship design

An even slower design travelling at 16kn with a capacity of about 5000 TEUs was also investigated. This resulted in a ship with the particulars given in Table 4. It is an extreme container ship design, coming closer to slow cargo ship designs. Employing the traditional naval architecture methodology, the

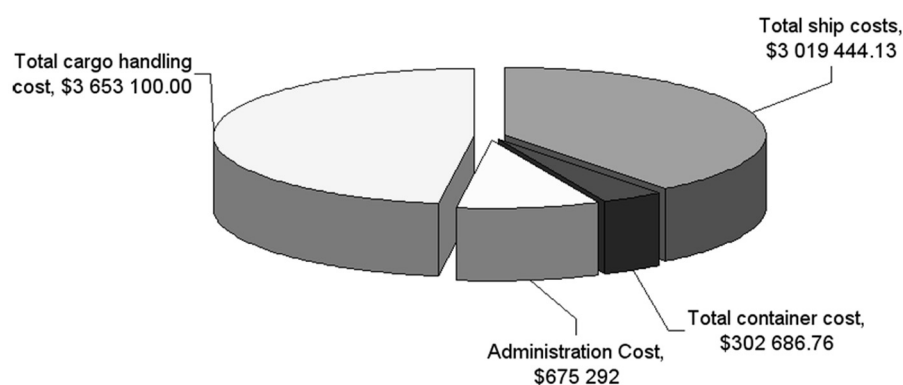
design specifications and the owner's requirements were transformed into requirements for the lines plan. The hull design was developed using data from the well-known FORMDATA Series [37, 38]. The preliminary body plan of the design is shown in Fig. 18, and the corresponding capacity plan in Fig. 19. The capital cost in this case was reduced both for the reduction in the machinery cost and for the reduction in the steel cost. The latter was assumed to be reduced by a factor of 3.5×10^3 US\$/ton, resulting in a reduction of $US\$9 \times 10^6$ on top of

Table 3 Main dimensions of the 21 kn improved design

L	233 m
B	45.6 m
T	13.5 m
TEU	5500
Speed	21 kn
Displacement	≈ 87 000 ton
C_b	0.59
Lightship	≈22 200 ton
BHP	≈29 000 kW (−48%)
EEDI	16.30 (−33%)
Average cost per TEU	US\$1056 (−6%)
Number of ships for the schedule	5.6 (instead of 4.9); thus + 1 ship
Capital value	US\$82 × 10 ⁶
Depreciation time	20 years
Interest rate	8%
OPEX	7700 US\$/day

Table 4 Main dimensions of the 16 kn improved design

L	230 m
B	44 m
T	13.0 m
TEU	4978
Speed	16 kn
Displacement	≈105 000 ton
C_b	0.78
Lightship	≈20 600 ton
BHP	≈17 200 kW (−69%)
EEDI	9.725 (−60%)
Average cost per TEU	US\$1086 (−3%)
Number of ships for the schedule	6.9 (instead of 4.9); thus + 2 ships
Capital value	US\$71 × 10 ⁶
Depreciation	20 years
Interest rate	8%
OPEX	7700 US\$/day

**Fig. 17** 21 kn improved design voyage cost breakdown

the machinery cost savings. The 16 kn improved design voyage cost breakdown is shown in Fig. 20.

The results of this case study show that the drastic reduction in the EEDI does not correspond to drastic changes in the average cost per TEU. On the contrary, the significant fixed cost of cargo handling, the reduced number of round trips per year, and the reduced TEU capacity by almost 9 per cent diminishes the gains made by a reduction in the speed (−3 per cent). In addition, two more ships are now required in order to maintain the schedule, which means a higher capital investment to provide the same liner service. However, it should be noted that herein the probable reductions in the outfitting weight and the related cost, in view of the reduced ship length and capacity, could not be exactly accounted for and were assumed conservatively with marginal impact on the ship's capital cost. The same applies to consideration of the reduction in the machinery costs, noting that the reduction in the speed by 9 kn, or 36 per cent with respect to the reference ship's speed of 25 kn, led herein to a reduction in the powering by *merely* 69 per cent,

although further reductions could be achieved with detailed hull-form optimization. Thus, the above conclusions will be conservative in general but show the techno-economic limits of slow steaming. In Table 5 the Quantum design developed by DNV, the reference ship, and the two designs developed by SDL are compared. All designs have adequate ballast tank capacities and their maximum draughts meet the LLC requirements.

7 THOUGHTS ON THE EEDI

Using the EEDI in the above studies as a merit function for design optimization, it is inevitable that a few remarks should be made on this new environmental footprint index. The proper definition of the EEDI may be disputed. One main contradiction in the definition of the EEDI is that, although the aim is fundamentally to maximize the efficiency, the index in its present form should be minimized. Although this may be easily corrected by considering the reciprocal value of the EEDI, another

Table 5 Comparison of the designs

Parameter (units)	Value for the following			
	DNV Quantum design	Reference ship	21 kn SDL PDT design	16 kn SDL traditional design
Length (m)	272.3 (overall)	263 (bp)	233 (bp)	230 (bp)
Breadth (maximum/WL) (m)	49.0/42.5	40.0/40.0	45.6/45.6	44.0/44.0
Draught (m)	12.0	14.00 m	13.5 m	13.0 m
TEU	6210	5500	5500	5000
C_b	0.57	0.61	0.59	0.78
BHP (kW)	23 000*	55 000	29 000	17 200
Speed (kn)	21	25	21	16
DWT/TEU	8.78	12.36	11.76	16.96

*Installed 33 MW.

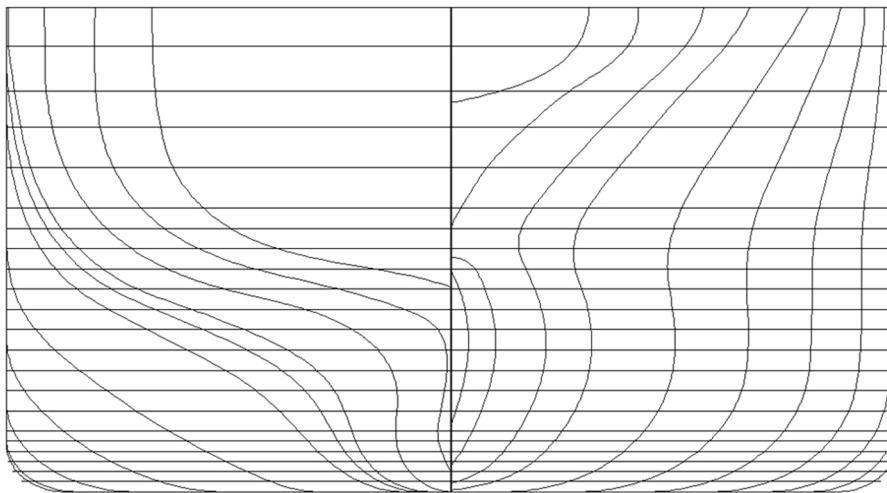


Fig. 18 Body plan of the 16 kn container ship design (from reference [39] with permission)

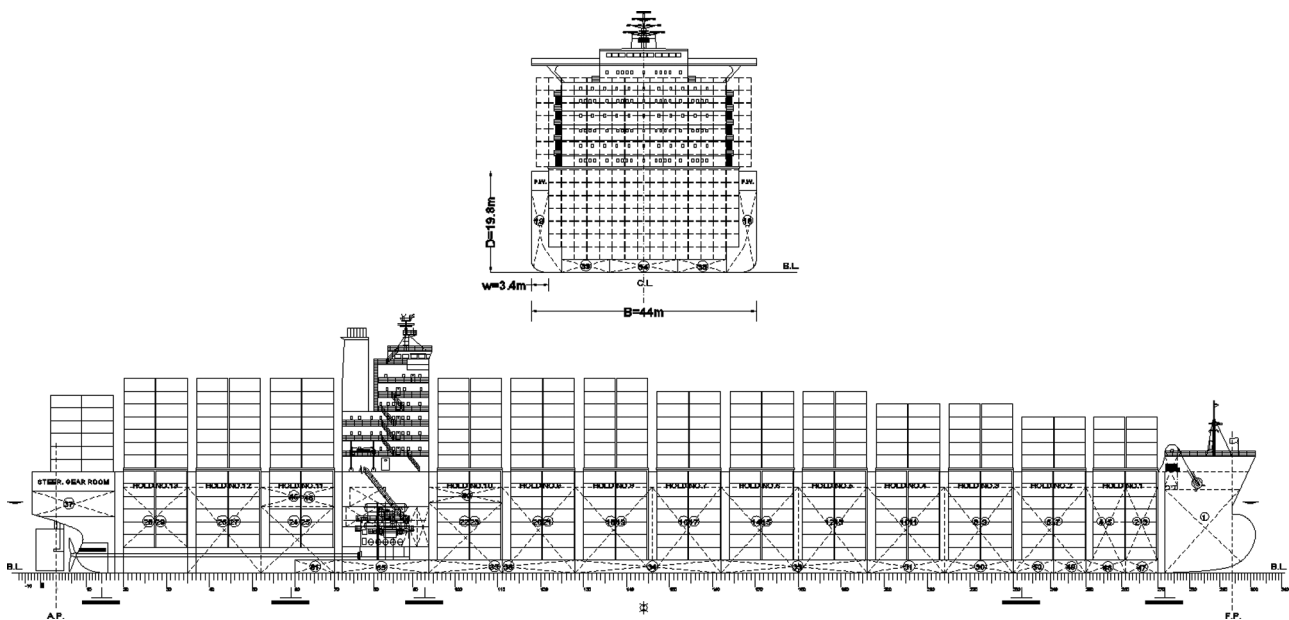


Fig. 19 Capacity plan of the 16 kn container ship design (from reference [39] with permission)

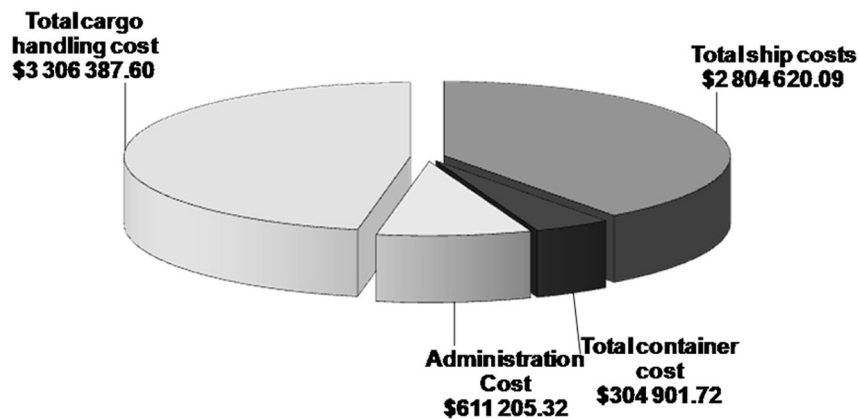


Fig. 20 16 kn improved design voyage cost breakdown

drawback cannot be remedied, namely that the physics of the ship's powering are not properly reflected in the EEDI; thus, the impact of the size of the vessel and the installed power are not taken into account in the existing formulation. It could be argued that for the naval architect there are some very traditional and reliable measures for the assessment of the hull and propulsion efficiency, such as the well-known *British Admiralty constant* or the related *Heickel coefficient* defined as

$$K = \left(\frac{\sqrt{\Delta}}{P_B} \right)^{1/3} U \quad (2)$$

where Δ is the displacement, P_B is the engine power, and U is the ship's trial speed. Either the Admiralty constant or the Heickel coefficient could be modified accordingly to take into account any improvements regarding the fuel consumption savings or the use of fuels that emit less CO_2 (i.e. have a lower C_F). In this case an alternative EEDI* definition could be in the form

$$\text{EEDI}^* = \text{hull efficiency index} \times \text{energy efficiency index} \times \text{fuel CO}_2 \text{ efficiency index} \quad (3)$$

Another effective way to assess the efficiency of transport vehicles (of any type, i.e. land-borne, airborne, and waterborne vehicles) is the well-known Gabrielli-von Kármán (GK) [33] diagram. The diagram shows the required power per tonne of weight at a given speed of transport. The lower this ratio is for a given speed, the higher the efficiency. The GK diagram depicts the physical and technological limitations of the various means of transportation. In Fig. 21 the design points of the reference container ship and of the 21 kn improved design are plotted. It is obvious that, from the GK transport efficiency point of view, the improved design proves to be not better than the

initial design, although it demonstrates an improved EEDI, which is not considered herein.

8 CONCLUSIONS

The work presented herein demonstrated the applicability of a holistic ship design approach using a PDT to optimization at the conceptual design stage. The PDT developed initially for the implementation of the LOGBASED methodology in ro-ro ship design has been further enhanced to facilitate the design of other ship types, such as bulk carriers, tankers, and container ships. The tool can help the decision maker to assess the ship design space of the transportation system rationally in its business concept and to estimate the environmental impact and the economic incentives. Case studies of an AFRAMAX oil tanker, two 5500 TEU container ships, and one 5000 TEU container ship were presented herein to demonstrate the developed concept. The tool can also be used to assess the operating CO_2 index of a ship in a given trading scheme, using the existing methods in the LOGBASED module 4. This is a further step in the initial LOGBASED methodology, thereby improving the interaction between yards, operators, and other market stakeholders when searching for optimal ship design solutions.

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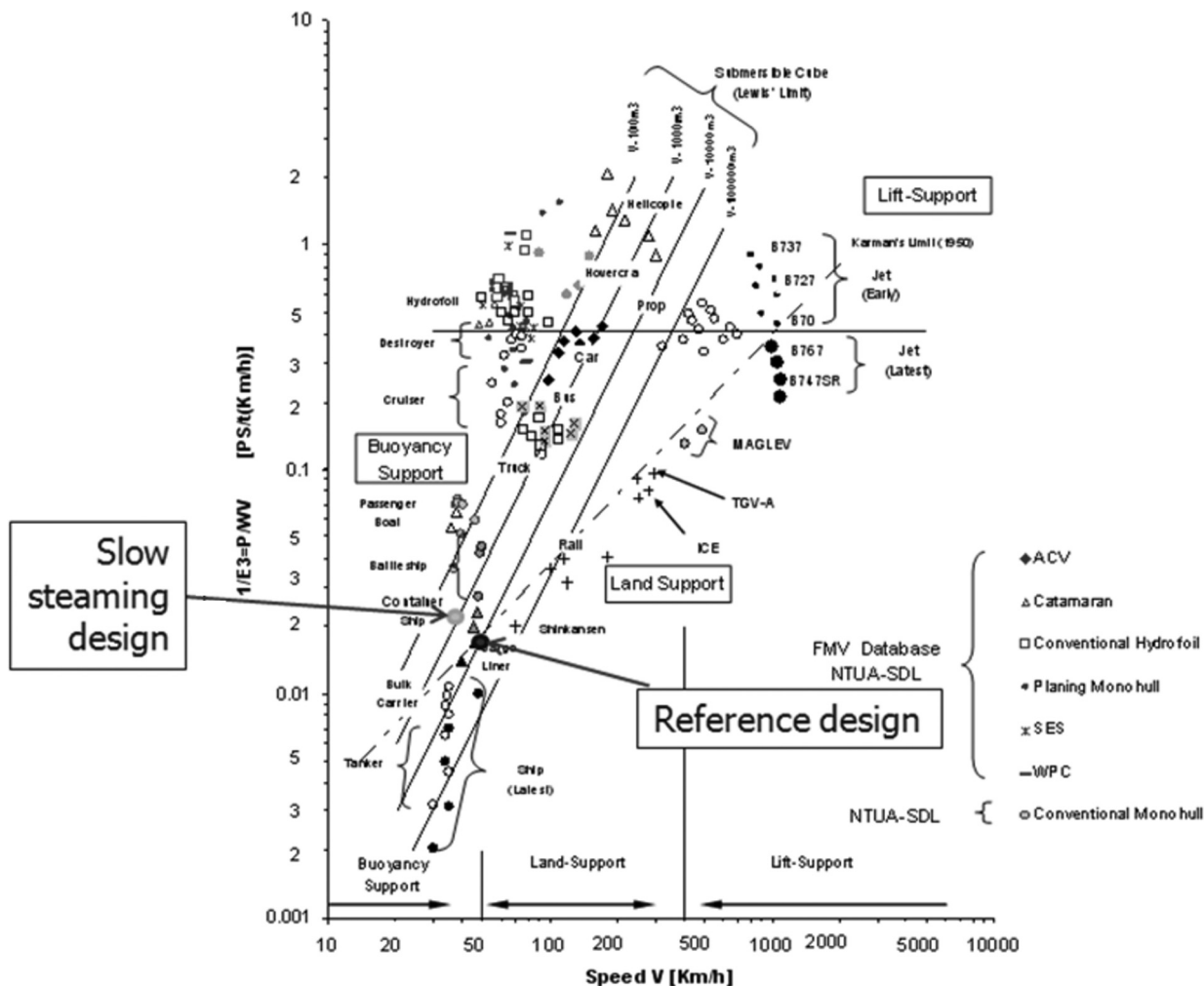


Fig. 21 Design points of the reference and the 21 kn improved designs on the GK diagram (from reference [40] with permission): (ACV, air cushion vehicles; TGV-A, Train à Grande Vitesse-Atlantique; SES, surface effect ships; WPC, wave-piercing catamarans)

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