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2011

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JOURNAL OF OFFSHORE MECHANICS AND ARCTIC ENGINEERING-TRANSACTIONS OF THE ASME, v.133, n.4, 2011
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Multi-Objective Optimization Design of Tanker Ships via a Genetic Algorithm

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The cost of a new ship design heavily depends on the principal dimensions of the ship; however, dimensions minimization often conflicts with the minimum oil outflow (in the event of an accidental spill). This study demonstrates one rational methodology for selecting the optimal dimensions and coefficients of form of tankers via the use of a genetic algorithm. Therein, a multi-objective optimization problem was formulated by using two objective attributes in the evaluation of each design, specifically, total cost and mean oil outflow. In addition, a procedure that can be used to balance the designs in terms of weight and useful space is proposed. A genetic algorithm was implemented to search for optimal design parameters and to identify the nondominated Pareto frontier. At the end of this study, three real ships are used as case studies. [DOI: 10.1115/1.4002740]

1 Introduction

There are many currently available programs that can be used to analyze a preliminary naval project such as General HydroStatics Software (GHS), NavCad^{TM} (software tool for the prediction and analysis of vessel speed and power performance), Ship Hull Characteristics Program (SHCP), and Systems, Applications and Products in Data Processing (SAP). Unfortunately, these programs do not provide a synthesis procedure; therefore, they do not aid the designer in the initial choice of the system parameters (not even in the adjustment of an already analyzed option) to meet the design requirements or to improve the performance index.

All engineering projects can be generalized to problems of optimization. In order to obtain the best solution, it is often necessary to have a synthesis procedure that is capable of cyclically integrating the analyses of the several subsystems that compose an option.

A tool that is typically used in the naval area is the spiral of project, which provides a way to analyze the integration of different systems components of the ship in a systematic way. The logical order of the groups in the spiral is specified in accordance with both the interference and the dependence between each subsystem, yielding a final solution that satisfies the owner's requirements and the inherent constraints. Nevertheless, there is no guarantee that the final configuration obtained by this procedure is the best solution in terms of the adopted performance index. Consequently, a synthesis procedure (and its implementation in an efficient computational tool that helps the naval engineer in decision making) is vital in the process of the preliminary selection of the dimensions of a new ship.

A primary goal of the current study is to present a rational process of selecting the optimal dimensions of tanker ships to be applied in the preliminary design phase. Therein, it is presented as a simple procedure that depends on principal dimensions, which aims to balance ship design in terms of weight and useful space. In order to solve the optimization problem that is associated with balancing weight and useful space, a multi-objective genetic algorithm is developed to find the set of nondominated solutions to this problem. The following metrics are used to evaluate each ship during the optimization process.

- The total cost, which consists of the cost of the construction plus the cost of operation during the service life of the ship.
- The mean oil outflow due to accidental grounding or collision of the ship.

Parametric models have been used to assess the characteristics of each ship (principal dimensions, size of the crew, weights and centers, resistance and propulsion, capabilities, initial transverse stability, and cost and outflow) [1–6]. The quality of the results obtained therein strongly depends on the accuracy of these assessments; hence, for the applicability of the proposed procedure, these results are frequently limited by the validation range of the formulations that are used in the parametric models.

The following items explain the parametric models that are used to create each ship: the procedure developed to balance each ship, the applied cost and oil outflow model, and the implemented multi-objective genetic algorithm that facilitates the identification of the optimal Pareto frontier of the problem. Finally, the validation of the rational procedure is demonstrated by comparing its results to the dimensions of real ships.

The emphasis of this study is on the results of the proposed methodology. For more details regarding the parametric model, the reader is encouraged to consult our prior work [7,8].

2 Parametric Model

In the modeling of a ship, it is necessary to preliminarily define the following subsystems: hull geometry, arrangements and cargo volume, structure and deckhouse, propulsion system, manning, and weights.

Each subsystem should be represented by the minimal number of independent variables. The following relationships were chosen to define the hull geometry: length/beam (C_{LB}), beam/draft (C_{BT}), and block coefficient (C_B).

At present, several constraints limit the design of tankers; these constraints are focused on achieving a suitable level of security for the transportation of unsafe products. As a result, in the definition of arrangements and cargo volume, it is necessary to include the height of the double bottom (h_{db}), the width of the double side (w), and the number of transverse bulkheads (N_{cargo}) to be used in the cargo area as independent design variables because these factors are critical in the calculation of oil spilling. A trade-off between the safety of a ship and its associate cost of construction and maintenance can be made with the manipulation of these variables. Additionally, in tankers that are at least 100 m long, it is common to use a longitudinal bulkhead in the cargo area

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Contributed by the Ocean Offshore and Arctic Engineering Division of ASME for publication in the JOURNAL OF OFFSHORE MECHANICS AND ARCTIC ENGINEERING. Manuscript received January 23, 2009; final manuscript received September 15, 2010; published online April 8, 2011. Assoc. Editor: John Halkyard.

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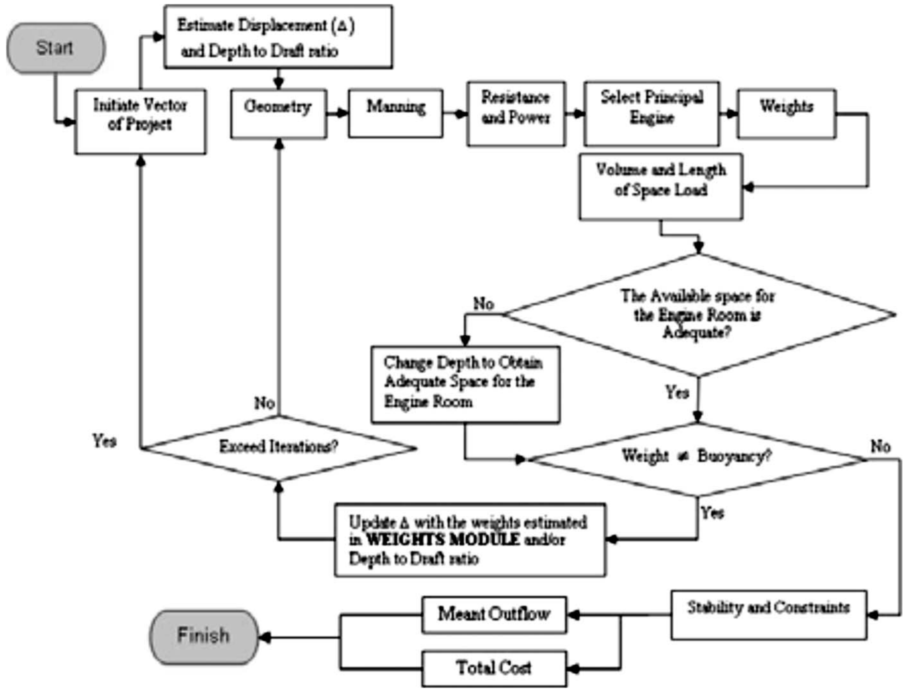

Fig. 1 Ship synthesis model

(this strategy is not practiced in tankers shorter than 100 m). Because the equations used in this study are generally valid for tankers with lengths that range from 100 m to 400 m, a longitudinal bulkhead is included in the general cargo region.

A variable that controls the height of each deck (H_{DK}) of the deckhouse was included to represent its weight and the length of the blind area of the surface of the sea that is observable from the bridge, as well as to analyze different configurations. The minimal thickness of the plates, modeling the hull as a beam, is defined by the principal dimensions of the ship, as proposed by Mish et al. [6].

The propulsion system is controlled by two variables during the optimization process. One parameter is the number of principal motors (P_{systyp}) and the other is the type of stern (N_{stern}). P_{systyp} controls the possibility of redundant propulsion systems and N_{stern} affects the fuel efficiency as determined by the stern, wherein one is assumed to be highly efficient and the other less efficient.

Finally, in the manning subsystems, the estimation of the number of crew that are necessary to guarantee the safe operation of a tanker strongly depends on the level ship automation. A highly automated ship is very expensive but has a low risk of oil spill, whereas a ship with a lower cost level of automation (i.e., not very automated) has a higher risk of spill. For this reason, a variable (manning factor (ManFac)) that controls the number of crew in the ship is included, which indicates the automation level of the ship.

The hull geometry defines the buoyancy force, whereas the other defined subsystems specify the weight of the ship. A balance between weights and buoyancy must be achieved and is obtained through the iterative procedure proposed in the next item.

The limits used in the analyzed cases of each variable are shown in the following table, wherein these variables are considered to be sufficient in the preliminary definition of each ship. Therein, the first three coefficients define the geometry of the hull vessel, the next three define the cargo space, the seventh and eighth parameters are related to the propulsion system, the ninth parameter defines the level of ship automation, and the tenth parameter defines the height of the decks in the deckhouse.

A parametric model was constructed for each of the mentioned subsystems by using previous variables and equations that were taken from Refs. [1–3,6]. The principal ideas of the parametric models are presented in the following item during the explanation of the proposed ship design synthesis model. For a more detailed description of the parametric models used in this study, the reader should refer to previous work [7,8].

3 Ship Design Synthesis Model

An iterative process must be implemented to guarantee the balance of the ship's weight and usable space. Using the aforementioned parametric models, a rational procedure was developed to obtain feasible values for ship weight and volume, in other words, a synthesis model for a determined set of parameters. The proposed procedure is sketched in Fig. 1. This proposed procedure is accomplished for each ship that forms the search space of the design problem.

The process starts by randomly assigning ten initial values to the project variables, obeying the ranges presented in Table 1. Initially, the value for the depth to draft ratio is assumed to be equal to 1.2, and the initial displacement is set to be equal to the deadweight times the typical deadweight coefficient (displacement/deadweight), which were taken from Ref. [1]. After that, it is possible to completely define a ship in an iterative way using the parametric models.

The *geometry* module uses the parametric model for the hull

Table 1 Design parameter range

Description	Min. value	Max. value
Beam/draft (C_{BT})	2.0	4.0
Length/beam (C_{LB})	5.0	7.0
Block coefficient (C_B)	0.7	0.9
Double bottom height (m) (h_{db})	0.76	4.00
Double side width (m) (w)	1.0	4.0
Transverse subdivision (N_{cargo})	4	8
Stern type (N_{stern})	1	2
No. of engines (P_{systyp})	1	2
Manning factor (ManFac)	0.5	1.0
Deck height (m) (H_{DK})	2.5	3.0

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geometry, structure, and deckhouse and defines the principal dimensions, the coefficients of form, and the structure of the ship and of the deck house, including its minimum height. The first variable to be calculated is the length of the vessel in the design draft. Departing from the Archimedes Principle, Watson and Gilfillan [9], with some algebraic manipulation, obtained the following expression to calculate the length of a vessel:

$$\mathrm{LWL} = \left(\frac{\Delta \times \left(\frac{\mathrm{LWL}}{B} \right)^2 \times \left(\frac{B}{T} \right)}{\gamma \times (1+s) \times C_B} \right)^{1/3} \quad (1)$$

where Δ is the design displacement, γ is the specific weight of salt water, s is an appendix coefficient, C_B is the block coefficient, B is the beam of the vessel, and T is the draft. Thus, knowing the values of the independent variables (C_{LB}), (C_{BT}), and (C_B) and the displacement, it is possible to calculate the length of the vessel. After that, the other dimensions (beam, draft, and depth) are calculated using the independent variables and the length of the vessel.

In order to calculate the water plane coefficient (C_{wl}), the relationship for tankers between C_{wl} and C_B was taken from Ref. [1], whereas the maximum section coefficient C_x was estimated based on the bilge radius. Assuming that the vessel has a full midship section with no deadrise, is flat of side, and has a given bilge radius, the maximum section coefficient C_x can be easily related to the beam, the draft, and the bilge radius r as follows:

$$C_x = 1 - \left(\frac{0.429 r^2}{BT} \right) \quad (2)$$

Producibility considerations will often make the bilge radius r equal to or slightly below the inner bottom height h_{db} so as to facilitate hull construction. Here, r was considered to be $0.9h_{db}$.

The parametric model for the ship structure (via the estimation of an equivalent thickness of plate using the theory of beam flexions, as proposed by Mish et al. [6]) leads to a ship that can be represented by a hull girder that consists of the inertial contributions of bottom, side, double bottom and side, deck, and longitudinal bulkhead plates.

Finally, the minimum height of the deckhouse is defined using the International Maritime Organization (IMO) and International Convention for the Prevention of Pollution From Ships, 1973 as modified by the Protocol of 1978 (MARPOL 73/78) requirements. They, respectively, define the maximum length of the blind area of the sea surface that is observable from the bridge and the minimum draft of the vessel in the ballast condition. It is assumed that the superstructure is longitudinally located to $0.85 \times \mathrm{LWL}$ behind the bow. With the necessary space in the deckhouse and its minimum height, it is specified that the value for the deck height (H_{DK}) must satisfy the range defined in Table 1.

The *manning* module uses the parametric model for manning and defines the number of crew needed to operate the vessel by considering the design variable ManFac that is associated with the level of automation of the vessel. A value of 0.5 indicates that the vessel has a high level of automation (and consequently, a greater cost for construction and maintenance) but a lower risk of spilling the transported oil due to grounding or accidental collision. The other limit value of ManFac (that is, 1) indicates the opposite, that the vessel has a low level of automation, which implies a lower cost of construction but a higher risk of spilling due to grounding or collision. The crew number (N_{crew}) is estimated using a regression that was obtained using data that were originally presented by Watson [3] in terms of the deadweight. The value of the regression is multiplied by the ManFac variable.

The following module, *resistance and power*, uses the parametric model of the propulsion system and calculates the ship resistance and the necessary power to attain the specified velocity of operation. The estimation of ship resistance will be accomplished using the method presented by Holtrop and Mennem [2]. The calculations are made for a range of velocities, from the required velocity imposed as a constraint to this value plus 5 kn. An increment due to the resistance of air for the dead area of the vessel is also considered. Finally, the curve of effective horsepower (EHP) versus velocity is calculated with an allowance (5%) for severe ocean conditions. The curve of shaft horsepower (SHP) versus velocity is calculated by dividing the EHP by the propulsive coefficient (PC), wherein the PC is defined by the type of stern. Two types of stern are analyzed; one is efficient (PC=0.75) in terms of fuel consumption but has a high cost of production (associated to an N_{stern} value of 2) and the other is less efficient (PC=0.7) but has a lower cost of production (associated to an N_{stern} value of 1). After that, the principal engine is randomly chosen from the constructed database to guarantee (at least) that it can provide the required velocity, with the possibility of one or two engines. The database (68 engines) contains the following characteristics for low and medium speed diesel engines: total power, fuel rate consumption, length, width, height, weight, and revolutions per minute.

The module *weights* uses the parametric model of weights to estimate the weight of the components that belong to the light weight (hull, deckhouse, principal engine, and outfit) parts of the ship, as well as the elements that compose the deadweight (the weight of the load, the fresh water for all purposes, the fuels and lubricants, the crew, the crew's effects, and the supplies).

In the last module, *volume and length of cargo space*, the required volume for the load to be transported and the necessary length to carry it are calculated using the parametric model for arrangements and cargo space. The lengths of the fore and aft peaks are estimated using the suggested values proposed by the Lloyd's Register, and a constant value of 3 m is used for the cofferdam. In addition, the length of the slop tanks is determined by considering their capability to be equal to 2% of the cargo volume to be transported. By subtracting these lengths from the length of the vessel, the available space to locate the engine room is obtained. The required length and height of the engine room (specified in the *select principal engine* module, which was chosen when the motor was selected) is compared with the available space.

If the available length for the engine room is not sufficient, the value of the cargo length is reduced and the depth is increased enough so that there is enough space for the load to be transported. Another possibility is that the length of the engine room is much bigger than is needed, which is why the depth should be decreased and the length available for the load increased. For either of the two previous cases, the depth was modified, introducing the need to update the relationship of depth to draft. In the same way, the depth can be increased to guarantee the minimum engine room depth that is required to support the height of the engine room, as specified in select principal engine module.

In a sequence of the synthesis model developed herein (see Fig. 1), if the total weight of the vessel is different from its buoyancy, then the module updates the displacement by considering the aggregated weight, as estimated in the weight module, and (if the previously established limit of iterations has not been exceeded) the procedure returns to the geometry module and continues with the process of balancing the ship. If the number of allowed iterations to balance the ship has been violated, a new set of initial values for the design parameters are randomly generated and the process restarts.

Finally, if the number of iterations is not exceeded, the available space for the engine room is sufficient (not longer than an initially pre-established value) and the buoyancy is equal to the displacement within some level of tolerance, then the ship is considered balanced in weight and volume. After calculating the initial stability, the cost, and the mean oil outflow, the synthesis procedure is finished.

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Table 2 Estimation of construction costs [4]

Description	Labor force ($)	Materials ($)
Structure	$CF \times 177 \times (W_{\text{hull}})^{0.862}$	$800 \times W_{\text{hull}}$
Propulsion	$CF \times 365(W_{\text{maq}})^{0.704}$	$10^3(15+20(W_{\text{maq}}))$
Outfit	$310 \times (W_{\text{outfit}})^{0.949}$	$10^3(5+10(W_{\text{outfit}}))$

4 Cost Model

The costs of the construction and operation must be considered in a preliminary design phase, being each one influenced by several factors such as the characteristics of the market or of the ship (type of ship, size, and automation) and the legal and environmental standards. In light of the available information, the following items were considered to represent the construction costs: steel structure, propulsion system, outfit, and margin, as well as independent costs such as consultancy, model trials, and tank test. The operational costs that were included in this study were fuel, maintenance, crew salary, daily running, insurance, taxes, and towage in ports.

Assuming that the accurate calculation of the total cost of a new tanker was not an objective of this study, preliminary estimations were made to consider the impact of the costs in the optimal values of the principal dimensions of the designed tankers. The PODAC model, which was presented by Miroyannis [4], was used to estimate the construction costs, whereas the models proposed by Watson [3] and Mish et al. [6] were used to estimate operational costs.

The construction cost is based on the costs of the labor force and the materials used in the hull, machinery, and outfit. Table 2 depicts some of the relations Miroyannis [4] proposed to estimate, at the level of preliminary design, the labor force costs, and the costs of materials for each one of the systems that constitute the light weight of the ship.

The parameter CF is defined as a complexity factor and is equal to

$$CF = \text{STF} \times 32.47 \times \Delta^{-0.3792} \tag{3}$$

where STF is a constant that depends on the type of ship and has a value of 0.9 for ships with a double hull, Δ is the displacement in the total load condition, and each weight is expressed in tons.

To take into account the real effect of costs in the determination of optimal principal dimensions, it is also necessary to consider the costs of operation and ship maintenance. All of the expenses in the service life of the ship were aggregated via a present worth factor (PWF) and under the assumption of an annual rate of interest of 7%, a service life of 30 yrs, and 312 days per year of operation. Table 3 presents the expressions used herein to estimate the costs of food and supplies, annual salary, price of fuel per ton, and maintenance expenses.

In Table 3, W_{fuel} is the weight of the fuel oil consumed per operational day, in tons. Salary, fuel cost, and maintenance are expenses that might vary widely from country to country, between crew members, and as a function of company politics. Thus, the values used in this study are casual estimates of the effect of operational costs in new designs. Finally, the cost of the construction is added to the cost of operation and maintenance so as to obtain the total cost of the ship.

Table 3 Estimation of operational costs [3,6]

Description	Value ($)
Food and supplies	$\text{PWF} \times 7 \times N_{\text{crew}} \times 312$
Salary	$\text{PWF} \times 36{,}000 \times N_{\text{crew}}$
Fuel	$\text{PWF} \times 100 \times W_{\text{fuel}} \times 312$
Maintenance	$\text{PWF} \times 100{,}000 \times (N_{\text{cargo}} + P_{\text{systyp}})$

5 Oil Outflow Model

The International Association of Independent Tanker Owners (INTERTANKO) has proposed a method to be used in the evaluation of accidental oil spills from tanks, which allows for the assessment of the relative risk of spills through the analysis of historical data from accidents. This analysis takes into account the relative position of the damage and the penetration depth into the hull of the vessel. This allows the evaluation of the influence of alternative tank configurations in the cargo space during the designing phase, the assessment of the associated capital costs with each configuration, and their impact on safety and ship operations. Actually, this methodology was initially proposed to analyze the mean oil outflow from bunker tanks; however, because the probability density function (PDF) proved to be independent from the type of liquid inside the tanks, it has been conservatively applied to the cargo tanks of newly designed tankers. The methodology of calculation that was proposed by the INTERTANKO [5] to the IMO is based on the following suppositions: An event of grounding or collision occurs and the external hull is broken.

Therein, the proposed procedure assesses the consequences (in terms of oil spill) of grounding or collision with an external hull opening, without discussing the probability that such an accident might occur. The specification of the damage and the corresponding occurrence probabilities are obtained via a set of PDFs for the location and extent of hull damage.

These PDFs are based on historic Lloyd's Register data of 52 collisions and 63 groundings of tankers with deadweights of at least 30,000 tons. All variables that describe the situations of damage are assumed to be independent due to the lack of adequate data to define their dependence. The parameters of spilling are separately calculated for collision and grounding and then combined in a ratio of 40% for collision and 60% for grounding. The ship is assumed to be loaded to the design draft, without heel or trim. In addition, the cargo tanks are assumed to be at 98% capacity.

In the case of collision, it is assumed that the total content of the tank is spilled, and in the case of grounding, two conditions of tide, 2.5 m and 0.0 m, are combined with a contribution of 70% spilling of the load for the case with no tidal variation and 30% spilling of the tank for a negative variation of a 2.5 m tide. The mean outflow (OM) for each tank in the case of grounding is calculated based on the hydrostatic principles of balance between columns of liquids. The cargo level after the damage is calculated as follows:

$$h_F = \frac{(T + t_C - Z_l) \times \gamma_S - p_{\text{sig}}}{\gamma_N} \tag{4}$$

where h_F is the height of the surface of the load above Z_l (m), T is the draft at the project load line (m), and t_C is the variation of the tide (m). Reductions in the tide should be expressed by negative values. Z_l is the height of the lowest point of the cargo tank above the base line (m), γ_S is the specific weight of sea water (N/m^3), γ_N is the specific weight of the load (N/m^3), and p_{sig} is the pressure of inert gas in the tank (N/m^2).

The assessment of the mean outflow from a collision O_{MS} is calculated by

$$O_{MS} = \sum_{i=1}^{N} P_{S(i)} \times O_{S(i)} (\text{m}^3) \tag{5}$$

where i represents each cargo tank, N is the total number of cargo tanks, $O_{S(i)}$ is the outflow m^3 from side damage, which is assumed equal to the total volume in a tank that is filled to 98% capacity, and $P_{S(i)}$ is the probability of tank i penetration due to side damage.

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In a similar way, the mean outflow from bottom damage O_{MB} is calculated for each tidal condition as follows:

$$O_{MB(K)} = \sum_{i=1}^{N} P_{B(i)} \times O_{B(i)} (\mathrm{m}^3) \tag{6}$$

where K represents the condition of the examined tide (0.0 m or −2.5 m), i represents each cargo tank, N is the total number of cargo tanks, $P_{B(i)}$ is the probability of tank penetration due to bottom damage, and $O_{B(i)}$ is the outflow from damage at the bottom of tank i in m^3.

The probability of damage in any tank on the bottom or the side is the product of three other probabilities. INTERTANKO [5] presented the PDF for each of these in a tabular form as a function of the longitudinal, transverse, and vertical positions of the tank.

6 Multi-Objective Genetic Algorithm

Genetic algorithms (GAs) are defined as models that are based on a population that use operators of selection, crossover, and mutation to generate a new set of solutions within the search space. These models were introduced by Holland in 1975. The selection of the best options is achieved by using the concept of dominance, which can be introduced as follows: If X_1 and X_2 are two feasible solutions to a problem of multidimensional optimization with N objectives, a solution X_1 is strongly nondominated if, and only if, the following conditions are satisfied in a minimization problem:

1. $\forall i \in (1, \ldots, N): f_i(X_1) \leq f_i(X_2)$
2. $\exists i \in (1, \ldots, N): f_i(X_1) < f_i(X_2)$

A solution x is Pareto optimal if, and only if, a solution y that dominates x does not exist. In other words, a solution is Pareto optimal if another feasible solution that simultaneously improves all of the objectives does not exist, that is, the solution is Pareto optimal if any improvement of one objective causes a simultaneous degradation of at least one other objective.

The basic idea of a genetic algorithm is the evolution of an initial population of solutions, called chromosomes or individuals. The principle of survival of the fittest is used to choose better solutions and to improve their characteristics with the application of the genetic operations of crossover and mutation. The basic operations associated with GAs and their logical sequences are shown Fig. 2.

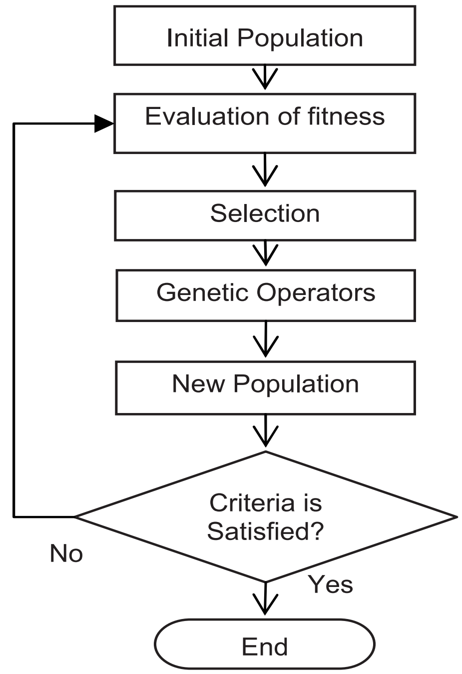

Fig. 2 Basic operations performed in GAs

The process begins with a population of solutions of finite size (N_{pop}). Next, each solution (chromosome) is evaluated through a mathematical model to assess its respective performance. The aforementioned parametric model is the mathematical model used in this study, wherein the assessment of the cost and mean oil outflow serve as the means of evaluating the performance of every chromosome. These two measures will determine whether a chromosome is good or bad. A procedure to select the individuals that will compose the new population is applied after having evaluated the population.

The selection scheme is probabilistic, i.e., it does not select the best but gives chromosomes with good performance better chances to survive. Individuals with better fitness have a greater chance to survive to a later stage of the optimization process, whereas individuals with poor fitness possibly die. This selection scheme keeps some important information in the next generation that may be present in a relatively bad chromosome, and furthermore, this selection scheme can choose the same chromosome more than once. Thus, the next generation should be better, on average, according to the selection scheme.

With the goal of exploring the search space, the genetic operators of crossover and mutation are used in the individuals that were selected to compose the new population. These operators are an artificial imitation of evolution. Crossover is the process of creating new individuals, known as children, by mixing genes of two different chromosomes, known as parents, whereas mutation is the occasionally random change in any gene value of the chromosome. The children are placed in the population and evaluated.

A balance between exploration and exploitation should be obtained in genetic algorithms. This exploration refers to looking for new points in the feasible space, whereas exploitation refers to using information from previous solutions to find better solutions. In other words, the algorithm should use the best individuals to evolve the optimal solutions. GAs simultaneously combine exploitation and exploration with the operations of "selection" and "crossover and mutation," respectively.

An important feature that defines the behavior of GAs is the selection pressure that is implicit in each method of selection. The term selection pressure indicates the strength with which individuals are selected to form the next population in the process of optimization. For an extensive exploration of the search space, the selection pressure must be increased; however, by concentrating the selection to a few individuals, the pressure is reduced. This means that with a selection pressure of 0, the better individual will always be selected and with a selection pressure of 1, the selection tends to be random. The formal definition of selection pressure that is used in genetics is the change in the average fitness of the population as a function of the method of selection. The selection pressure can be regulated with the methodology used herein to select individuals for the next generation.

In addition, there are other fundamental operators in multi-objective GAs: Pareto filter and Niche operators. The Pareto filter pools nondominated solutions at each generation and makes the GAs more robust, as described by Cheng and Li [10]. Niche forces individuals to share resources and maintain appropriate diversity in a population along the Pareto frontier.

7 PATANGA

The implemented algorithm uses a floating number representation for design variables instead of the typical binary depiction. Some advantages in doing this are the closer representation of the problem space, the shorter length of the chromosome, and an increased accuracy. The Pareto tanker genetic algorithm (PATANGA) uses the typical operators of selection, crossover, and mutation, in addition to Filter and Niche operators.

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The tournament selection scheme is used, wherein it conducts a tournament between groups that have been randomly selected from the population so as to choose one winning individual. The chromosome with the best performance in the group is selected, and in the case of a possible tie, a random process is used to choose the winner. The process is repeated until the new population has reached a full size. With this process, each chromosome can be selected more than once.

For the calculation of each individual's performance, a progressive sorting is done using the values of cost and mean oil outflow for each ship. The sorting of the population is a continuous process of identifying the nondominated members of the population. In each generation, the nondominated chromosomes are selected for rank 1 (the best performance). From the remaining population, nondominated chromosomes are identified and selected for rank 2. This process continues for ranks 3, 4, and so on until every individual of the population has been ranked. The chromosomes with better rankings are those that have better performance; consequently, they have a greater chance of being selected to compose the next generation.

The one point crossover operator crosses two chromosomes, called parents, at one point of their length, which is chosen at random. The group of selected chromosomes is randomly organized into pairs. The decision of whether each pair is going to experience crossover depends on the probability of crossover (P_C), which is a predefined value that specifies the expected number of chromosomes that will be matched for crossover. The crossover occurs if a random number that is uniformly distributed in [0,1] is less than or equal to P_C and then the created offspring go on to the next generation. On the other hand, if the random number is greater than P_C, the parents remain unchanged and they go on to the next generation.

The mutation operator can change the genes of the population that survived the selection scheme and also the chromosomes that have experienced crossover. Mutation is conducted via the use of a parameter called mutation probability (P_m). For each of the chromosomes of a new generation, a random number that is uniformly distributed in [0, 1] is generated. If it is less than or equal to P_m, a randomly selected gene in the chromosome will be replaced by a random value within the domain of that gene.

The filter consists of storing the best solutions of the evolution process to be included in the next generation, which increases the pressure of selection on the process. In each generation, the nondominated points (rank 1) are placed in the filter and a new test of dominance between the present individuals on the filter is conducted, eliminating dominated individuals. The size of the filter is a default parameter and is equal to some percentage (10–30%) of the size of the population. When the size of the filter is exceeded, the individuals with a minimal relative distance to the other individuals are removed to hold individuals that tend toward a uniform distribution along the Pareto front within the filter.

A premature convergence of the evolutionary process can occur due to the artificial finite population size and the genetic operators. The phenomenon known as genetic drift causes the disappearance of genes in the population by chance. Also, the excessive numbers of some child solutions cause a premature convergence of the process. In order to prevent this, the Niche operator helps to retain genetic diversity in the population.

The Niche methodology used in this study is the same as that used by Cheng and Li [10]. This methodology replaces one individual (father) with his child if the child performs more successfully. Therein, diversity is maintained because chromosomes tend to be replaced by those that are similar to or better than them.

8 Imposed Constraints

To identify whether a ship (chromosome) is feasible or not, the following constraints were considered.

Table 4 Design requirements that have been imposed on the Ataulfo Alves

Description	Value
Total deadweight	153,000 tons
Velocity	14 kn
Endurance range	20,000 miles
Load density	0.8674 tons/m^3
Service life	30 yrs

- The requirement of MARPOL 73/78 for the minimum draft in the ballast condition.
- The initial stability (GM/B) in the fully loaded and ballast conditions must be greater than 0.08, where GM is the metacenter height of the ship and B is the beam.
- The velocity achieved by the chosen propulsion system must be equal to or greater than the required value.
- The minimal freeboard must satisfy the load line regulation of 1966.

The external penalty strategy was used to address the aforementioned constraints. With this strategy, it is not necessary to know an initial feasible solution. This penalty strategy uses an additional function to transform the original problem into an equivalent problem without any constraints.

The developed algorithm was tested with the four test functions proposed by Zitzler [11]; these functions are intended to form a complete group of test functions, which can be used to validate and compare algorithms that aim to identify a Pareto set of solutions. The selected test functions include convex, nonconvex, and discontinuous functions, in addition to one real problem (a beam welded to another one) with five constraints. This implementation satisfactorily obtains results that are similar to those obtained by Zitzler [11].

9 Application

In order to analyze the obtained results with the proposed rational process of selecting the optimal dimensions of tankers, three real vessels of different types were used as case studies: a Suezmax, an Aframax, and a Panamax.

The following subsections present and analyze the results for each vessel type. The characteristics of the real vessels are compared with the results of the proposed procedure, and the minimum cost (MC) and minimum mean oil outflow configurations are also examined.

9.1 Ataulfo Alves: A Suezmax Vessel Type. The first ship that was compared with the results of the proposed rational process of optimization in terms of principal dimensions was the *Ataulfo Alves*. This ship is Suezmax-type vessel of Transpetro-Petrobras Transportes. The design requirements that have been imposed on this ship are presented in Table 4.

The PATANGA was run 3 times to verify the convergence of the optimization process, which was started from different initial populations. Figure 3 depicts the convergence of the initial population to the Pareto frontier and employs an initial population of 1200 ships, with crossover and mutation probabilities of 0.85 and 0.025, respectively. Tournaments were conducted among ten ships, using 50 solutions in the filter and 50 total generations.

It can be noted that all of the runs converged to the same optimal frontier, which verifies that the GA solutions do not depend on the initial population. In each extreme of the Pareto frontier depicted in Fig. 3, two points have distinctive markings. In the vertical section of the frontier, one marked point represents the minimum cost, whereas the other represents another vessel with almost the same cost of the first but with a significant reduction of the mean oil outflow. In the horizontal section, one marked point represents the minimum mean oil outflow, whereas the other rep-

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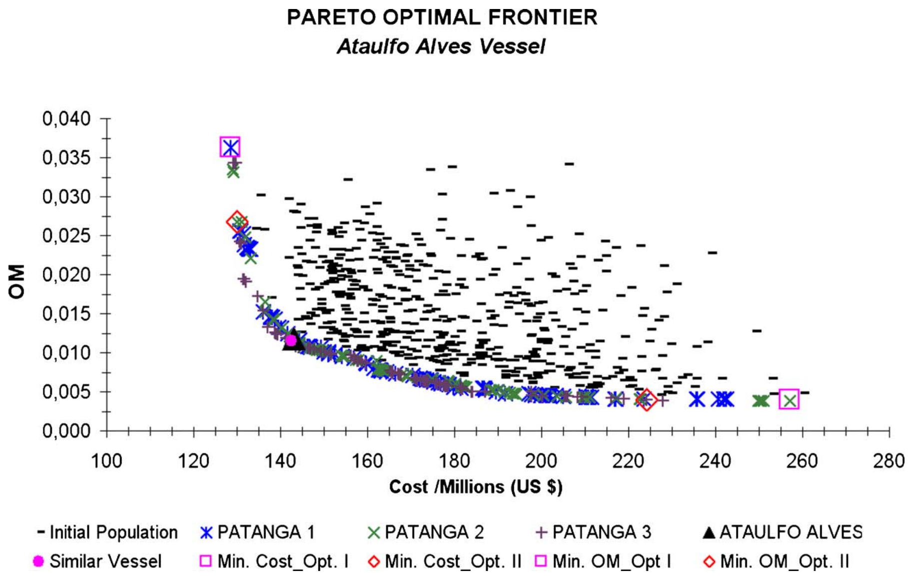

Fig. 3 Optimized results using the PATANGA for the Suezmax-type ship case

resents another vessel with almost the same mean oil outflow of the first but with a significant reduction in the cost. The other two points with distinctive markings refer to the Ataulfo Alves and the nearest point on the Pareto frontier, which is the equivalent ship that has been obtained by the PATANGA.

Table 5 shows, for the six points outlined above, the ten parameters of the project: the main dimensions, components of displacement, required power, initial stability criteria, and values of the objective functions, that is, the cost and the mean oil outflow. The weight of the propulsion systems, the weight of the outfit, the midship coefficient, the cost, and the mean outflow for the Ataulfo Alves were calculated using the previous parametric model.

The performance, similarities, and differences of each vessel can be assessed by considering the ten variables that were used as design parameters and their influence on the characteristics of structural strength, resistance, initial stability, freeboard, total cost (construction plus operation), and mean oil outflow.

The first three parameters of Table 5, which define the geometry

Table 5 The main dimensions and characteristics of the Ataulfo Alves and the vessels that were obtained using the PATANGA

Parameter	PATANGA project	Suezmax Ataulfo Alves	Minimum cost		Minimum OM	
			Option 1	Option 2	Option 1	Option 2
C_{LB}	5.60	5.61	5.13	5.16	5.99	7.0
C_{BT}	2.85	2.84	2.56	2.61	3.30	2.7
C_B	0.880	0.889	0.832	0.818	0.701	0.701
h_{db}	2.81	2.40	1.36	1.18	3.91	3.8
w	2.49	3.75	1.69	2.67	3.73	2.8
N_{cargo}	7	6	4	4	8	8
P_{systyp}	2	1	1	1	1	2
N_{stern}	2	2	2	2	2	2
ManFac	0.55	1.00	0.52	0.51	0.55	0.50
H_{DK}	2.8	2.7	2.9	2.8	2.6	3.0
Length LWL (m)	260.0	258.0	238.9	243.2	351.6	354.9
Beam B (m)	46.4	46.0	46.6	47.1	58.7	50.9
Depth D (m)	25.5	24.4	28.0	28.6	21.3	23.3
Draft T (m)	16.3	16.2	18.2	18.1	17.8	18.9
C_x	0.996	0.997	0.999	0.999	0.995	0.995
N_{crew}	16	30	16	15	16	15
Δ (ton)	177,372	175,201	172,632	173,592	263,872	245,681
Cargo (ton)	147,936	147,694	148,409	148,412	147,071	147,407
Weight hull (ton)	19,163	18,317	15,587	16,414	101,130	84,561
Weight outfit (ton)	2762	2673	2633	2683	3489	3019
Weight prop. system (ton)	1028	1211	1100	1100	1377	1124
MCR (hp)	22,880	20,900	20,950	20,950	26,740	25,740
Speed Vs (kn)	14.4	14.0	14.1	14.1	14.1	14.3
$(GM/B)_{\mathrm{ballast}}$	0.314	0.313	0.378	0.304	0.319	0.271
$(GM/B)_{\mathrm{full\ load}}$	0.082	0.080	0.080	0.82	0.232	0.167
Cost of construction (million U.S. $)	91.3	93.9	80.3	81.9	192.7	161.5
Total cost (million U.S. $)	142.0	143.1	128.6	130.0	257.1	224.1
Mean outflow (OM)	0.0115	0.0111	0.0363	0.0268	0.0039	0.0040

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of the ship and the respective values of length, beam, depth, and draft show that the PATANGA project and the Ataulfo Alves are similar ships.

The designed propulsion system of the PATANGA project is composed of two low speed engines, each with eight cylinders, a fuel consumption rate of 0.127 kg(BHP × h), and a weight of 187 tons. This configuration results in a total power increase of 9.5% in comparison to the power system of the Ataulfo Alves, which has a single main low speed engine with a fuel consumption rate of 0.124 kg(BHP × h) and a weight of 597 tons. Both vessels satisfactorily reached the design speed requirements.

The minimum freeboard is generally established by the IMO, by the transverse stability or the structural strength of the ship. The IMO recommendation primarily depends on the length, the block coefficient, and the L/D ratio. The freeboard of the PATANGA project was 1.0 m greater than that presented by the Ataulfo Alves (8.2 m). This difference is justified by the difference in the principal dimensions (length, beam, and draft) and the useful space for cargo load.

The initial transverse stability, in the proposed rational process, is one constraint that evaluates each vessel during optimization. An acceptable and quick criterion that can be evaluated to assess the stability is the B/D ratio. According to Watson [3], a value of 1.5 is associated with ships that have "poor" stability and 1.8 with ships that have "good" stability. The values of 1.89 and 1.82 for the Ataulfo Alves and the PATANGA project, respectively, indicate that both of these vessels have good stabilities. Because the beam on both projects is very close, the difference in the transverse stability is caused by the difference in depth.

Table 5 assesses structural strength via the L/D ratio and demonstrates that both ships are within the limits recommended by ship classification societies; $L/D=10.6$ for the Ataulfo Alves and $L/D=10.2$ for the PATANGA project.

The midship coefficient C_X was estimated using Eq. (2) under the assumption of a bilge radius equal to 90% of the double bottom height. There is no significant difference in the C_X for both the Ataulfo Alves and the PATANGA project.

The components of weight of the PATANGA project and the Ataulfo Alves also show no significant difference. The difference between the displacement and the sum of light weight and cargo capacity is 6483 tons for the PATANGA project and 5306 tons for the Ataulfo Alves, indicating that the need for higher capacity fuel tanks due to the greater fuel consumption rate of the PATANGA project overshoots the need for a higher capacity for water and provisions in the Ataulfo Alves due to the greater number of crew members.

The configuration of the cargo area of both vessels is similar but with certain differences in the width of the double side and of the double bottom. Moreover, the Ataulfo Alves has 12 cargo tanks (six on each side), whereas the PATANGA project has 14 tanks (seven on each side), both offering a high level of safety against a possible risk of spill. The configurations of cargo space are apparently equivalent because the OM values are similar. The height of the double bottom of the PATANGA design is 0.41 m greater, whereas the Ataulfo Alves has a double side width that is 1.26 m greater in comparison to the PATANGA project. In contrast, the PATANGA project has one additional cargo subdivision in comparison to the Ataulfo Alves; this creates a balance among these three features, resulting in the generation of ships with similar levels of security.

The operational cost of the PATANGA project is \$50.7 million, whereas the Ataulfo Alves is 3% cheaper. Table 3 depicts the expressions that were used to estimate the operational costs. The food, supplies, and salary are proportional to the number of crew, the fuel is proportional to the engine power and fuel rate consumption, and the maintenance is proportional to number of transverse bulkheads and main engines of the ship. With this in mind, the greater operational cost of the PATANGA project is due to maintenance (one more transverse bulkhead) and fuel (higher fuel consumption), which is almost compensated for by the lower cost associated with the fewer crew members in comparison to the Ataulfo Alves; hence, the operational costs of both vessels are similar.

The proposed methodology indicates that by using the Pareto frontier of the problem, the engineer/planner can choose the configuration that best fits their purpose by taking into consideration the cost and mean oil outflow of each individual on the presented frontier. It will not be possible to obtain simultaneous improvements in cost and outflow via changes to projects that have been identified in the Pareto frontier. Finally, it is believed that the Ataulfo Alves is an optimized project when considering the two criteria of total cost and mean oil outflow. There is a great deal of similarity between the Ataulfo Alves and the PATANGA design, which demonstrates the applicability of the proposed methodology.

A brief description of the characteristics of the vessels with minimum cost, now referred to as the MC, and minimum oil outflow, now referred to as the MO, will be presented below. Two options were chosen to represent the solutions with minimal cost and minimal OM, which are the beginning and ending of the vertical and horizontal portions of the Pareto frontier, respectively. Table 5 depicts the information of each solution.

The first minimum cost option (MC1) corresponds to the solution at the end of the vertical portion of the Pareto frontier, whereas the second minimum cost option (MC2) corresponds to the first point, where the Pareto frontier deviates from the vertical. Both solutions have almost the same cost, with only a 1% difference, whereas the MC2 has a 26% reduction in the mean oil outflow. This is the principal advantage for choosing the MC2 solution as a feasible option.

A similar phenomenon happens on the other extreme of the frontier. The first minimum OM option (OM1) corresponds to the end of the horizontal portion of the Pareto frontier, whereas the second minimum OM option (OM2) corresponds to the first point, where the Pareto frontier deviates from the horizontal. Both solutions (OM1 and OM2) basically present the same value of OM but the OM2 solution has a total cost reduction of 12.8% in comparison to the OM1 solution.

In general terms, MC solutions correspond more to vessels with shorter lengths (length being the most expensive dimension) and greater depths (the most economic dimension) in comparison to MO solutions. Thus, full ships produce the minimum cost options and slender ships with more subdivisions produce the least oil outflow.

Both the MO and MC solutions have good initial transverse stabilities, with B/D ratios that range from 1.65 to 2.75.

Regarding the characteristics of the cargo space, MO vessels have more tanks and a much larger double bottom height and double side width in comparison to MC solutions, which result in a lower average rate of oil outflow. Both MO and MC vessels have high levels of automation.

Neither of the options has an advantage in the ability to load; however, the MC ship requires less power to achieve the design speed and (due to the shorter length) also benefits from a lower light weight, which directly reduces the cost of construction. Furthermore, the MC option presents lower operating costs, which are primarily due to the higher consumption of fuel by the MO ships as a result of their higher power requirements.

9.2 Tatina: An Aframax Vessel Type. The Hellespont website[2] contains technical information of its 15 ships and their various load capacities. One of these ships, the *Tatina*, is an Aframax-type vessel and was chosen for the comparative analysis. The design requirements that were imposed on the PATANGA are shown in Table 6.

Similar to the previous case, the PATANGA was run 3 times to

[2]http://www.hellespont.com.

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Table 6 The design requirements imposed on the Tatina

Description	Value
Total deadweight	105,535 tons
Velocity	14 kn
Endurance range	22,036 miles
Load density	0.8674 tons/m^3
Service life	30 yrs

verify the convergence of the process using different initial populations. Figure 4 depicts the convergence from the initial population to the Pareto frontier. The parameters of the GA were the same as those used in the earlier case.

Again, six points can be identified on the Pareto frontier (two points on the vertical section, two on the horizontal section, the Tatina, and the "similar" PATANGA-formulated ship). For these points, Table 7 presents the ten parameters of the project, the primary dimensions, the components of displacement, the required power, the initial stability criteria, and the values of the objective functions. The propulsion system weight, outfit weight,

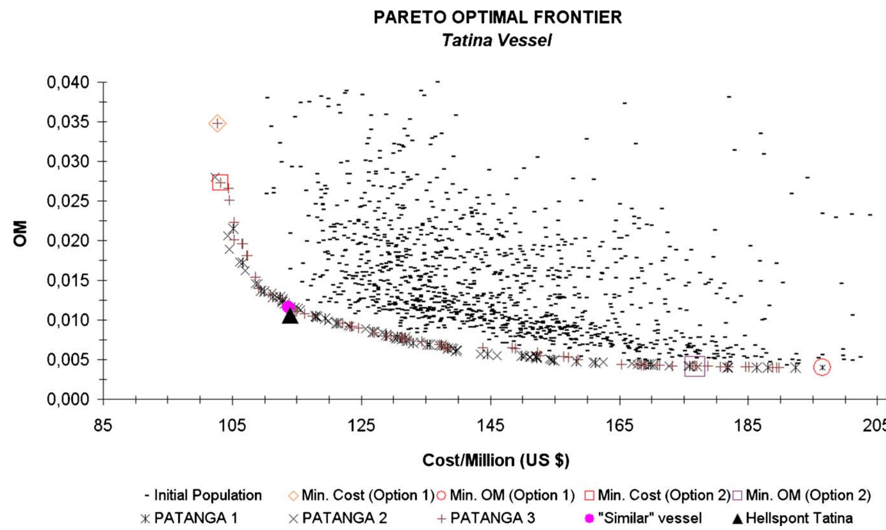

Fig. 4 Optimized results using the PATANGA for the Aframax case

Table 7 The primary dimensions of the Tatina and the characteristics of the vessels that were obtained using the PATANGA

Parameter	PATANGA project	Tatina	Minimum cost		Minimum OM	
			Option 1	Option 2	Option 1	Option 2
C_{LB}	5.15	5.55	5.12	5.12	6.85	6.99
C_{BT}	2.93	2.82	2.67	2.71	2.92	2.86
C_B	0.790	0.814	0.855	0.855	0.710	0.740
h_{db}	3.97	2.09	1.13	1.13	3.65	3.90
w	2.26	2.23	1.92	2.26	3.10	2.34
N_{cargo}	6	6	4	4	8	8
P_{systyp}	1	1	2	2	1	2
N_{stern}	2	2	2	2	2	2
ManFac	0.50	1.00	0.50	0.50	0.79	0.50
H_{DK}	2.5	2.7	2.6	2.6	2.5	2.6
Length LWL (m)	228.8	232.9	211.8	213.0	323.1	315.3
Beam B (m)	44.4	42.0	41.4	41.6	47.2	45.1
Depth D (m)	25.5	21.3	25.1	25.2	19.6	19.9
Draft T (m)	15.2	14.9	15.5	15.4	16.2	15.8
C_x	0.992	0.997	0.999	0.999	0.994	0.993
N_{crew}	13	28	13	13	21	13
Δ (ton)	124,755	121,500	119,039	119,294	179,228	170,089
Cargo (ton)	101,335	100,247	101,176	101,176	100,413	100,770
Weight hull (ton)	15,363	12,845	10,365	10,584	66,549	58,187
Weight outfit (ton)	2467	2350	2217	2236	2837	2714
Weight propulsion (ton)	808	770	691	691	1100	933
MCR (hp)	17,160	18,320	17,740	17,740	20,950	19,800
Speed Vs (kn)	14.2	14.0	14.2	14.2	14.2	14.1
$(GM/B)_{\text{ballast}}$	0.300	0.420	0.350	0.33	0.28	0.3
$(GM/B)_{\text{loaded}}$	0.084	0.133	0.083	0.084	0.190	0.171
Cost of construction (million U.S. $)	71.3	65.2	58.6	59.1	139.5	124.2
Total cost (million U.S. $)	113.0	114.0	102.7	103.1	195.5	176.7
Mean outflow (OM)	0.0116	0.0104	0.0348	0.0273	0.0040	0.0041

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midship coefficient, GM/B for both load conditions, cost, and mean oil outflow for the Tatina were calculated using the previously described parametric model, and the other parameters were reproduced from information at the Hellespont site.

The first three parameters of Table 7 define the geometry and depict the similarities between the Tatina and the PATANGA project.

The propulsion system that was designed for the PATANGA presents a weight and total power increase of approximately 5% in comparison to the Tatina power system. Both systems are composed of a single low speed main engine, and they both satisfy the required speed of the design.

Concerning structural strength, the Tatina has an L/D ratio of 10.9 and the PATANGA project a ratio of 9.0, which shows that both vessels have adequate primary strengths and that the primary bending stress is lower for the Tatina.

The freeboard of the PATANGA project is 4.0 m greater than that of the Tatina (6.4 m). The PATANGA depth is 20% greater than that of the Tatina, which is the primary cause of this difference. The depth of the PATANGA project was set depending on the weight of cargo to be transported and according to the proposed ship synthesis model.

The components of displacement show that the PATANGA project has almost the same cargo capacity in comparison to the Tatina. The weight of the outfit differs by 5.0%, the weight of the hull by 19.6%, and there is a 4.9% difference in the propulsion system. Although the Tatina is 1.8% longer than the PATANGA project, which suggests that it might have a greater hull weight, the increased depth (20%) and greater beam (5.8%) generate a greater hull weight for the PATANGA project.

The light weight (18,638 tons) of the PATANGA project is 16.7% greater in comparison to the Tatina. The aggregations of the light weight and cargo weight of the designed ship and the Tatina result in 119,973 tons and 116,212 tons, respectively. The difference between the displacement and the previous sum is the weight of the variable items of deadweight (consumables, food, crew, etc.), which show that the Tatina has a greater capacity for provisions, which is consistent with the number of crew that is required for each vessel.

It can be said that there is a good likeness between the PATANGA project and the Tatina when the parameters of the project and primary dimensions are considered; however, it must be mentioned that the parametric models suggest the Tatina does not satisfy the requirements of MARPOL 73/78 for minimum draft ($T=6.58$ m required versus 6.07 m actual draft) in the ballast condition that was imposed as a constraint on the PATANGA project. This is why the Tatina has a lower cost and mean outflow in comparison to the solutions in the optimal Pareto frontier depicted in Fig. 4.

A brief description of the characteristics of vessels with minimum total cost and minimum oil outflow will be made below. Again, two options were selected to represent the solutions with minimal cost and minimal OM, wherein these are in the beginning and ending of the vertical and horizontal portions of the Pareto frontier, respectively. The definition of these solutions is the same as that employed in the previous case study.

The two solutions for the minimum cost have almost the same geometries (see Table 7). The internal arrangement for the MC2 option is the primary difference between these two solutions. The MC2 solution has a double side width of 2.26 m, which is 18% greater than that of MC1. Technically, both solutions have the same cost (with a difference of only 0.5%), whereas the MC2 solution has a 21% reduction in the OM. This is the principal advantage in choosing the MC2 solution as a feasible option.

Similarities also occur in the other extreme of the frontier. The first minimum OM option (OM1) corresponds to the end of the horizontal portion of the Pareto frontier, whereas the second minimum OM option (OM2) corresponds to the first point, where the Pareto frontier deviates from the horizontal. Both solutions, OM1 and OM2, basically have the same value of mean oil outflow (OM) and differ by only 2%; however, the OM2 solution has a total cost reduction of 10% in comparison to the OM1 solution.

Table 8 The design requirements that were imposed on the Pride ship

Description	Value
Total deadweight	73,727 tons
Velocity	15 kn
Endurance range	16,801.8 miles
Load density	0.8674 tons/m^3
Service life	30 yrs

In general terms, the MC solutions correspond to vessels with shorter lengths (the most expensive dimension) and greater depths (the most economic dimension) in comparison to the MO solutions. Thus, full ships yield minimum cost options and slender ships with more subdivisions yield minimum oil outflows.

9.3 Pride: A Panamax Vessel Type. The last case of comparison involves a Panamax-type vessel. The *Pride* was chosen from the Hellespont group, and the design requirements used to run the PATANGA are shown in Table 8.

For this particular case, it was necessary to make some small changes in the source code of the PATANGA. The first change increased the constraint on two variables. More specifically, the length and beam were restricted to values of less than or equal to 290 m and 32.3 m, respectively, due to the constraints of the Panama Canal. Exploratory tests were conducted and their results suggest that the Pride, in a loaded condition, did not meet the imposed constraint for the GM/B (a value greater than or equal to 8%). The GM of the Pride was estimated to have an approximate value of $0.06B$. As a result, the constraint on the GM/B was reduced to a minimum of 4%. The L/B ratio limit was also increased to 7.5 to guarantee a better definition of the horizontal region of the Pareto frontier.

As in the previous cases, the PATANGA was run 3 times using different random starting populations. Figure 5 shows the convergence of the optimization process to the Pareto optimal frontier. The parameters of the GA were the same as those used in the earlier cases.

In this case, only four points with distinctive markings can be identified on the Pareto frontier (minimum cost, minimum OM, the Pride, and its similar vessel on the Pareto frontier, which is referred to here as the PATANGA project). For these points, Table 9 presents the ten parameters of the project, the primary dimensions, the components of displacement, the required power, the initial stability criteria, and the values of the objective functions, that is, the cost and the mean oil outflow. The weight of the propulsion system, the weight of the outfit, the midship coefficient, the cost, and the mean oil outflow for the Pride were calculated using the previously described parametric model.

Regarding the size of the crew, Table 9 shows that the Pride has a much larger number of crew members than was suggested by Watson [3]. The regression obtained from the data presented by Watson [3] suggests that the Pride's crew should be composed of 25 members, whereas it actually has 36 members.

The first three parameters of Table 9, which define the geometry of the ship and the respective values of length, beam, depth, and draft show that the PATANGA project and the Pride are similar ships.

The propulsion system designed for the PATANGA project is composed of two engines of medium speed, resulting in a total power increase of 17% in comparison to the Pride's propulsion system, which has a single low speed main engine. Both vessels achieve the required speed.

Concerning displacement, the Pride and the PATANGA project have almost the same capacity to transport cargo. The weights of

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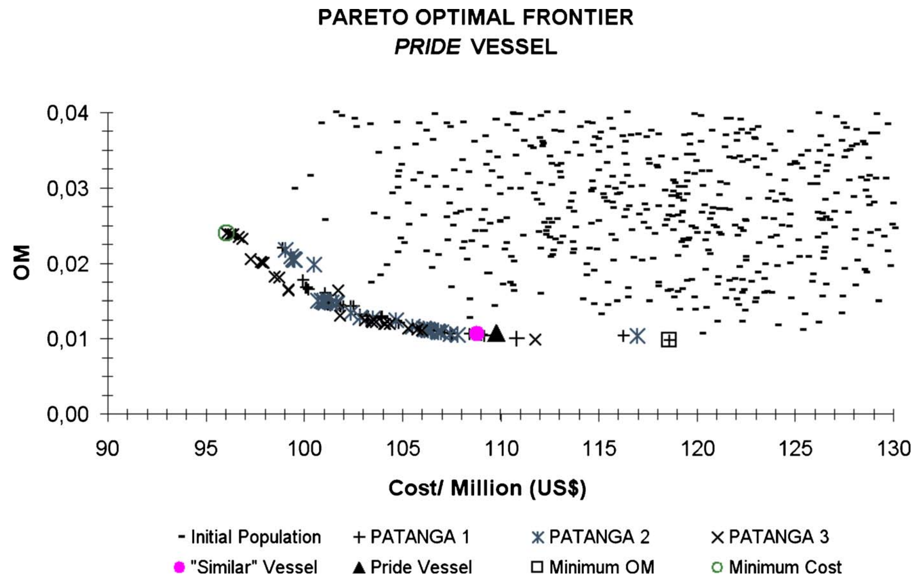

Fig. 5 The optimized results using the PATANGA for the Panamax-type vessel

the propulsion system components between the two ships differ by 6.5%, which is due to the medium speed engines of the PATANGA project. The outfit is very similar between the two vessels; however, the weight of the hull differs by 9.6%, which is primarily due to a 3.1% difference in length and a difference in the number of tanks.

The configuration of the cargo space of the PATANGA project and that of the Pride is different; however, the effect of the greater number of tanks of the PATANGA project (16 versus 12 in the Pride vessel) is balanced by the lower width of its double side (0.30 m, which is 15% lower than that of the Pride). As a result, both vessels present the same mean oil outflow.

Both vessels have very similar construction and operational costs. The small increase in the operational cost of the PATANGA project is due to maintenance (it has two more bulkheads), and the increased rate of fuel consumption is compensated for by the lower number of the crew members.

The same OM value for both vessels and the small decrease in

Table 9 Primary dimensions of the Pride and the characteristics of the vessels that were obtained using the PATANGA

Parameter	PATANGA project	Pride	Minimum cost	Minimum OM
C_{LB}	7.41	7.09	8.84	7.50
C_{BT}	2.22	2.22	2.30	2.30
C_B	0.827	0.814	0.862	0.837
h_{db}	2.03	2.00	1.09	1.93
w	1.70	2.00	1.73	1.79
N_{cargo}	8	6	4	8
P_{systyp}	2	1	2	2
N_{stern}	2	2	2	1
ManFac	0.77	1.44	0.50	0.51
H_{DK}	3.0	2.8	2.6	2.9
Length LWL (m)	235.8	228.6	219.5	241.6
Beam B (m)	31.8	32.3	32.1	32.2
Depth D (m)	21.5	20.8	22.1	20.6
Draft T (m)	14.3	14.5	14.0	14.0
C_x	0.997	0.997	0.999	0.997
N_{crew}	19	36	12	13
Δ (ton)	91,158	89,344	86,884	93,477
Cargo (ton)	70,623	70,554	70,627	70,336
Weight hull (ton)	14,339	13,087	10,322	16,280
Weight outfit (ton)	1790	1791	1749	1829
Weight prop. system (ton)	691	739	691	933
MCR (hp)	17,740	15,156	17,740	19,800
Speed Vs (kn)	15.3	15.0	15.10	15.25
$(GM/B)_{\text{ballast}}$	0.200	0.228	0.213	0.209
$(GM/B)_{\text{load}}$	0.042	0.057	0.041	0.060
Cost of construction (million U.S. $)	57.5	57.4	52.5	66.5
Total cost (million U.S. $)	108.8	109.8	96.0	118.6
Mean outflow (OM)	0.0106	0.0106	0.0240	0.0098

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the total cost for the PATANGA project suggests that the Pride is not an optimized vessel; however, they are similar, which demonstrates the applicability of the optimization methodology used herein to this kind of ship. By definition, it is not possible to obtain a simultaneous improvement in cost and mean outflow in comparison to the projects in the Pareto optimal frontier.

10 Conclusions

It is known that the majority of a ship's design budget is locked in during the initial phase of the project, which is governed by principal dimensions. If the right trade-offs are performed between several options during this stage, money can be saved. The creation and implementation of a rational procedure that allows trade-offs is crucial during the early stages of design. This study demonstrates that genetic algorithms can be successfully implemented as preliminary design tools and can provide the Pareto frontier for multi-objective problems. Once the Pareto frontier has been identified, an educated selection between different solutions can be made.

The evolutionary algorithm solutions found at the Pareto optimal frontier consists of short, full, and deep vessels for the vertical region and long, fine, and beamy vessels for the horizontal region. These dimensions produce the optimal solutions for minimal cost and minimal mean oil spill, respectively.

It is necessary to implement an iterative procedure to determine the principal dimensions and coefficients of form of an optimized vessel. In order to do this, a simple and effective methodology that balances the different vessel solutions in terms of weight and volume has been proposed. It was shown that if a vessel requires more space, then the simplest and most economic solution involves an enlargement of depth.

The results discussed herein are highly sensitive to the definition of the metric functions, as well as to the developed parametric model; hence, the identification of correct definitions and dependencies should be emphasized. For example, as a result of applying the proposed optimization procedure, twin engine designs using either two low speed diesels or two medium speed diesels were selected; this choice is uncommon, except for very recent designs, wherein the choice was primarily made for redundancy considerations that were not considered in the present study. These results are directly influenced by the cost model of the propulsion system (acquisition plus operation), which is based on experience with existing ships that primarily consist of single low speed engine designs. Because of this, those designs should be viewed with caution. If the designer prefers to limit the results of the optimization procedure to a single low speed design (rather than also evaluating twin engine designs), it is possible to limit the parameter P_{systyp} to 1.

For the case studies employed herein, the results were shown to be logical and acceptable. Therefore, the synthesis procedure presented in this study is recommended for initial ship design.

Acknowledgment

This study was partially supported by the Brazilian Council for Scientific and Technological Development (CNPq), whose support the authors gratefully wish to acknowledge.

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