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Original Article

Fuel efficiency optimization of tanker with focus on hull parameters

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Abstract

Fuel efficiency optimization is of crucial importance in industries. Marine transportation industry is no exception. Multi-disciplinary optimization is a branch of engineering which uses optimization methods for solving problems in which the objective function is simultaneously affected by several different factors. As one of the tools for this type of optimization, genetic algorithm has a high quality and validity. The objective of the present study is to optimize fuel efficiency in tankers. All presented equations and conditions are valid for tankers. Fuel consumption efficiency of tankers is a function of various influential factors. Given the lack of equations for describing and modeling these factors and unavailability of valid performance database for inferring the equations as well as the lack of literature in this field, the preset study includes five optimizing factors affecting the fuel consumption efficiency of a tanker in genetic algorithm by using the genetic algorithm toolbox of MATLAB software package.
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Keywords: Fuel consumption efficiency; Tanker; Multi-disciplinary optimization; Genetic algorithm; Hull parameters.

1. Introduction

With increasing fuel oil prices, fuel performance has become vital for financial reasons. It had led fuel to be one of most important factors in the shipping industries so the attention of designers has been recently attracted to optimize fuel performance in any possible ways. The objective of the fuel performance optimization is to increase the ability of fuel and to establish conditions to produce more output power out of a ship's propulsion system. The fuel performance of a ship is related to many factors. In this study, these factors are considered as physical and chemical properties of fuel, design and features of propeller in an engine, hydrodynamic, dimensional design of ship and the average speed of ship. The quality of fuel is a function of physical and chemical properties such as calorific value, viscosity, ash content, water content, sulfur content, flash point, specific gravity, etc. [1,2]. These properties are usually specified with very high precision by international organizations so the optimization of fuel properties for increasing fuel performance is not practical especially from marine engineer point of view. For this reason, in this study the effects of the properties of fuel on its performance are neglected. Also given the inaccessibility and lack of some performance databases for different statuses of engine and propeller and their attachments, they are neglected in the process of optimization, too. So, the goal of this study will be the multi-disciplinary optimization of the fuel performance of a tanker with genetic algorithm under the disciplines related to hydrodynamic, dimensional design and average speed of the tanker.

The genetic algorithm is an artificial intelligence methodology that is inspired by the evolution theory of Darwin. This was first mathematically formulated by Holland in his paper, "Adaptation in Natural and Artificial Systems". Many researchers and scientists have worked on the genetic algorithm after Holland until now. Mitchel published a great book, *An Introduction to Genetic Algorithm* [3]. It is one of most popular references to genetic algorithm learning. Homaifar et al. presented an application of genetic algorithms to the system optimization of turbofan engines that was similar to the way have been chosen in the present project [4]. Chipperfield et al. provided a user's guide for genetic algorithm toolbox

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Nomenclature

B	ship width, *m*
T	ship draught, *m*
D	ship height, *m*
C_B	hull bulk coefficient
C_∇	volume–length coefficient
C_p	prism coefficient
A_M	intermediate intersection area, m^2
C_f	friction resistance coefficient
C_{pv}	viscous–pressure resistance efficient
t	trust reducing factor
S	wetted area
L	ship length, *m*
V	ship speed, *knot*
W_{st}	mass of steel used in ship hull, *tone*
R_n	Reynolds number
F_n	Froude number
w	Wake coefficient
∇	ship volume, m^3
Δ	ship mass, *tone*
η_H	hull efficiency
η_o	propeller efficiency in free waters
η_R	propeller relative rotating efficiency

for use with MATLAB in Sheffeild University [5]. Seif and Tavakoli presented new technologies for reducing fuel consumption in marine vehicles. This paper reviewed different methods used for reducing the fuel consumption of marine vehicles in recent years. Methods for optimizing hull forms, use of micro bubbles and new coating, weight saving and improvement of propulsion system efficiency are discussed. Moreover, different components of resistance and methods of drag reduction are investigated and new hull forms are presented [6]. Weck and Willcox presented multidisciplinary system design optimization as a training course in 23 lectures in Massachusetts Institute of Technology [7]. The role and significance of MDO in engineering, various methods, techniques of MDO, etc. have been explained in this course. They also stated that the genetic algorithm is a reliable and efficient method for MDO. Shuaian Wang et al. stated three Bunker consumption optimization methods in shipping [8]. Nelson et al. stated simultaneous optimization of propeller–hull systems to minimize lifetime fuel consumption. This work presented a method (not Multi-disciplinary by genetic algorithm) to optimize the propeller–hull system simultaneously in order to design a vessel to have minimal fuel consumption. The optimization uses a probabilistic mission profile, propeller–hull interaction, and engine information to determine the coupled system with minimum fuel cost over its operational life [9].

2. Multi-disciplinary optimization and genetic algorithm

Multi-disciplinary optimization is a branch of engineering in which optimization methods are used for solving problems in which the optimizing parameter is simultaneously influenced by several disciplines. In this method, the optimization is so carried out that each factor plays a role in proportion with its impact on optimization result.

Four main foundations of multi-disciplinary optimization include (i) design variables, (ii) parameters, (iii) objective function, and (iv) conditions. In multi-disciplinary optimization, design variables can vary in their definition domain to reach to the optimum answer of the problem. But parameters are components that are considered as to be constant in problem space. The design variables in the present study are C_B, T, B, L, D, and V. As these variables change, each discipline of the optimization is so changed that results in the optimization of objective function depending on their impact on fuel consumption efficiency (FCE). Since the density and viscosity of the sea water through which tankers sail cannot be designed or changed, these two properties are considered as design parameters. In the present study, the density and viscosity of seawater was assumed as to be 1025 kg/m^3 and 1.8×10^{-3} Pa.s, respectively.

Objective function is the function whose optimization (maximization or minimization) is the intention of an optimization function. For the FCE of a tanker, there is no precise, thorough mathematical equation that is not impacted by designable variables. Furthermore, a precise or empirical equation can be hardly developed on the basis of valid statistical data for each factor that influences FCE of a tanker. Few numbers of successful researches in this sense proves this claim. Therefore, it is necessary to develop a function for this specific case, i.e., FCE optimization, that although its value does not equal the FCE of a tanker, its behavior shows the enhancement of the FCE. For instance, lower resistance of the ship hull would certainly result in higher FCE. So, the developed objective function should be so that its optimum value corresponding the minimum possible case for the resistance of a ship hull.

Given the fact that the variation domain of the design variables as well as the disciplines of the problem should be in the acceptable domain, then some constraints (conditions) are required for the validity of the problem. These constraints are usually of the type of mathematical equations or non-equations and/or of numerical interval. For example, in the present case, if the variation domain of block coefficient of the hull is as $0.48 \le C_B \le 0.85$ in accordance with standards, then after optimizing it is impossible to have a tanker whose $C_B = 0.9$; therefore, a constraint (condition) should be defined for each component of the problem during its optimization, if required.

2.1. Genetic algorithm

Genetic algorithm is a biological evolution-based calculation method of optimality. It generates a method for effective search in huge and extensive spaces which finally leads towards finding the optimum answer. Genetic algorithm is a heuristic optimization algorithm which takes natural evolution and selection as its paradigm. Although genetic algorithm does not always provide the optimum solution, it has its own advantages and is a powerful tool for solving complicated problems which are composed of some components.

The present study uses genetic algorithm toolbox of MATLAB software package. This toolbox is set of functions with the capability of optimization by using numerical calculations space. To optimize by this toolbox, it is necessary to prepare objective function and all conditions of the problem as M file for MATLAB software [3,5].

3. Optimization disciplines

As mentioned, the objective of the present study is to simultaneously optimize multi-disciplinarily by genetic algorithm. Therefore, it is necessary to list the factors affecting FCE of a ship as a function of them. Noteworthy, given the intended optimization method it is necessary for disciplines to have a precise mathematical equation or valid empirical relations for the tanker. At the final conclusion, five following criteria were considered out of all factors affecting FCE which not only effectively influence FCE but also are appropriate for multi-disciplinary optimization by genetic algorithm:

1. Wetted surface of the ship.
2. Friction resistance.
3. Viscous-pressure resistance.
4. Weight of steel of the ship hull.
5. Hull efficiency.

3.1. Wetted surface of the ship, s

Increasing in ship wetted surface results in higher resistance. On the other hand, it is directly proportional to ship load. Consequently, for higher wetted area, a ship's propulsion force needs to move heavier mass. So, it is concluded that wetted surface of a ship has an inverse relation with FCE; i.e., the higher the wetted surface of a ship, the lower its FCE. Wetted surface of a tanker is calculated by empirical Eq. (1) [10]:

$$S = \frac{\nabla}{B} \cdot \frac{1.7}{C_B - 0.2(C_B - 0.65)} + \frac{B}{T} \tag{1}$$

3.2. Hull resistance

As shown in Fig. 1, total hull resistance is divided into (1) wave resistance and (2) viscous resistance. The present study ignores the effect of wave resistance on optimization process.

Viscous resistance is a component of resistance expressing the energy lost by fluid viscosity for the object floating in it. Viscous resistance is divided into two general components of friction resistance and viscous-pressure resistance. The important parameter of these resistance is their relevant resistance coefficient, i.e., C_f and C_{PV}. It is necessary to reduce these coefficients in order to improve FCE.

Coefficient of friction resistance is calculated by Eq. (2) [11]:

$$C_f = \left(C_{f,ITTC-57}\right)G_1, \tag{2}$$

where

$$C_{f,ITTC-57} = \frac{0.075}{\left(\log_{10}(R_n) - 2\right)^2} \tag{3}$$

and

$$G_1 = \begin{Bmatrix} 0.09335 + 0.147x^2 - 0.071x^3 \\ if\ 1.5\times10^6 \le R_n \le 2\times10^7 \\ 1.0096 + 0.0465x - 0.013944x^2 + 0.0019444x^3 \\ if\ 2\times10^7 \le R_n \le 6\times10^9 \end{Bmatrix}, \tag{4}$$

where

$$x = \begin{Bmatrix} \log_{10}(R_n) - 6.3 & if\ 1.5\times10^6 \le R_n \le 2\times10^7 \\ \log_{10}(R_n) - 7.3 & if\ 2\times10^7 \le R_n \le 6\times10^9 \end{Bmatrix} \tag{5}$$

Coefficient of viscous-pressure resistance is calculated by empirical Eq. (6) [12]:

$$C_{pv} = \left[(26.C_\nabla + 0.16) + \frac{B}{T} - \frac{13 - 10^3.C_\nabla}{6} \times \left(C_p + 58.C_\nabla - 0.408\right).(0.503 - 35C_\nabla)\right] \times 10^{-3} \tag{6}$$

$$C_\nabla = \nabla / L^3 \tag{7}$$

$$C_p = \nabla / A_M L \tag{8}$$

The variation range of C_p for a tanker is $0.78 \le C_p \le 0.87$. In this paper, the mean of 0.825 was considered for C_p for simplicity which is reasonable for optimization [13].

3.3. Ratio of hull steel weight to total ship weight (W_{st}/Δ)

Steel is most heavy element in ship construction whose minimization has always been focused by designer because of its high price and great effect on ship weight. The empirical Eq. (9) shows the ratio of the required mass of steel for a tanker to total ship mass. It should be noted that this equation is merely valid for tankers [14].

$$W_{st}/\Delta = [\alpha_L + \alpha_T(1.009 - 0.004 \cdot (L/B)) \cdot 0.06 \cdot (28.7 - (L/D))] \tag{9}$$

$$\alpha_L = [(0.054 + 0.004L/B) \cdot 0.97] \div \left[0.189 \cdot (100L/D)^{0.78}\right] \tag{10}$$

$$\alpha_T = \begin{Bmatrix} 0.029 + 0.00235 \cdot \Delta/100000 & \Delta < 600000t \\ 0.0252 \cdot (\Delta/100000)^{0.3} & \Delta > 600000t \end{Bmatrix} \tag{11}$$

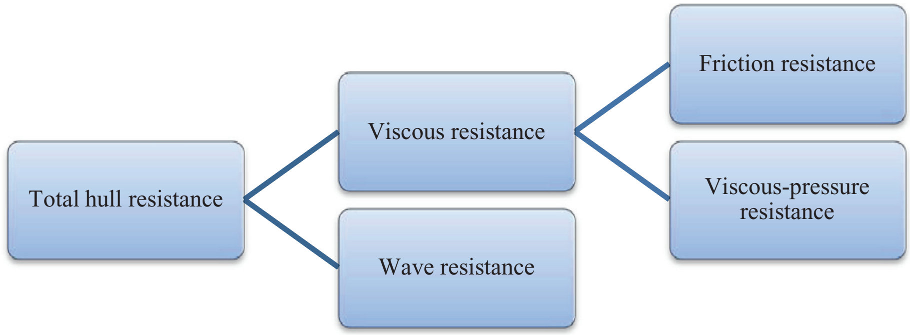

Fig. 1. The components of total hull resistance.

3.4. Hull efficiency (η_H)

Propulsive efficiency of a ship is influenced by three components as shown in Eq. (12) [15]:

$$\eta_D = \eta_H \cdot \eta_O \cdot \eta_R \tag{12}$$

Component η_O mainly depends on the selection of the type and properties of ship propeller which is ignored here in the optimization process of FCE because of the complexities of its equations. The component η_R was also considered as 1 which is very close to its real value [9]. Therefore, η_H or hull efficiency is included according to Eq. (13) as another discipline required for optimizing FCE [16].

$$\eta_H = \frac{1-t}{1-w} \tag{13}$$

$$t = 0.25w + 0.14 \tag{14}$$

Table 1
Maximum value of optimization criteria.

Optimization criteria	Maximum value of criteria
S	25,773 [m]
C_f	0.00262 [ ]
C_{pv}	0.00233 [ ]
W_{st}/Δ	0.04509 [ ]
$1/\eta_H$	1.18531 [ ]

Table 2
Weight coefficients and related value.

Weight coefficient	Value
n_1	0.1
n_2	0.25
n_3	0.20
n_4	0.30
n_5	0.15

4. Objective functions and restrains

To generate objective function, it is first necessary to examine the effect of the foregoing criteria on optimizing FCE. Afterwards, it can be found that maximizing FCE needs ship wetted area, coefficients of friction resistance and viscous-pressure resistance; and ratio of hull steel weight to ship displacement to be minimized and hull efficiency to be maximized. Then, the inverse of hull efficiency equation is used in which all equations of the criteria result in the maximization of FCE when are minimized. Now, we will have five equations that show similar behavior with respect to the maximization of FCE. Thus, in order for simultaneous optimization, the objective function is obtained as a linear combination of these five equations given the coefficient related to the effect of each factor as weight coefficients.

It should be noted that these five equations have their own range and unit which can create an error in optimization process. For example, if the numerical value of a ship area is 100,000 SI units and the numerical value of friction resistance is 0.003 SI units, the effect of friction resistance their sum will be practically neutral in optimization process. So, they need to become dimensionless to sum up them in one equation as the objective function. Therefore, entire equation needs to be divided by its maximum value according to values presented in Table 1 in order to put their numerical value in the interval (0,1). Given the fact that the genetic algorithm toolbox of MATLAB software package is only able to minimize, to calculate the maximum of the equations of optimization criteria, first their inverse minimum is calculated. Then, after obtaining the numerical values of the variables and their substitution in the main equation, their maximum is calculated. It should be mentioned that the optimization conditions for finding the maximum of these criteria are included in genetic algorithm.

Since the criteria have different effect on FCE varies, e.g., ship hull weight may affect FCE more than the coefficient of friction resistance, and then the extent of the effect needs to be recognized by a weight coefficient which is the effect of their equations on the main objective function. Thus, the weight coefficients n_i are so defined according to Table 2 that $\sum_{i=1}^{5} n_i = 1$.

As is evident in Eqs. (15)–(19), all variables will not be directly participated in all equations which cause an essential error in the results of optimization. It is because of the dependencies among the geometric variables and the operational variables of a specific ship on the basis of the statistical data for the ships.

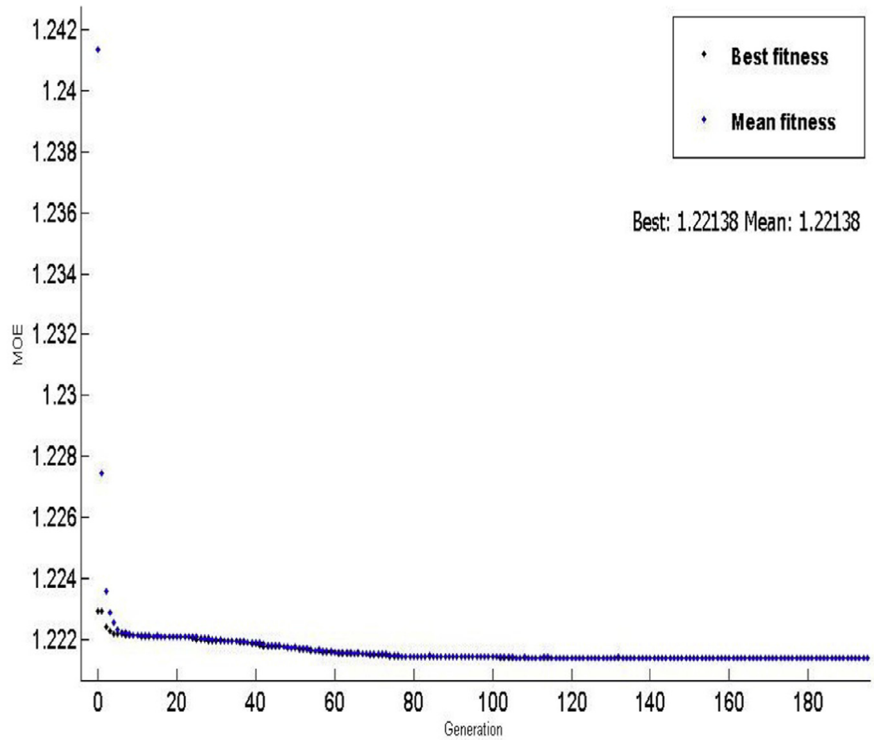

Fig. 2. The diagram of the output of genetic algorithm and its convergence.

$$S = f(B, T, C_B, \nabla) \quad (15)$$

$$C_f = f(R_n) \quad (16)$$

$$C_{pv} = f(B, T, C_\nabla, C_P) \quad (17)$$

$$W_{st}/\Delta = f(L, B, D, \Delta) \quad (18)$$

$$\eta_H = f(w) \quad (19)$$

To solve this error, it is necessary to substitute the equations of the criteria, based on empirical equations, in the design variable in terms of specific variables. In the present paper, all equations were represented in terms of ship length, L (m), and ship speed, V (knot). This was done by auxiliary Eqs. (14) and (20)–(29) [10–17].

$$\nabla = L \cdot B \cdot T \cdot C_B \quad (20)$$

$$B = 0.125L + 2.45 \quad (21)$$

$$T = \frac{0.78L}{13.5} \quad (22)$$

$$D = \frac{L}{13.5} \quad (23)$$

$$C_B = 0.70 + 0.125\tan^{-1}((23 - 100F_n)/4) \quad (24)$$

Table 3
Converted version of optimization criteria.

Optimization criteria	Function
MOP_1	$S = f(L, V)$
MOP_2	$C_f = f(L, V)$
MOP_3	$C_{pv} = f(L, V)$
MOP_4	$W_{st}/\Delta = f(L, V)$
MOP_5	$1/\eta_H = f(L, V)$

$$F_n = \frac{0.507V}{\sqrt{9.8L}} \quad (25)$$

$$C_\nabla = \frac{\nabla}{L^3} = \frac{B \cdot T \cdot C_B}{L_2} \quad (26)$$

$$\Delta = \left(\frac{L}{\frac{10}{3} + \frac{5V}{3\sqrt{L}}} \right)^3 \quad (27)$$

$$R_n = \frac{1025 \times 0.507 \times V \times L}{1.08 \times 10^{-3}} \quad (28)$$

$$w = 1.7643C_B^2 - 1.4745C_B + 0.2574 \quad (29)$$

Wherein Eqs. (24)–(28), m/s was converted to knot by the coefficient 0.507.

All criteria of optimization which are called measure of performance MOP_i, were converted into a function of L and V according to Table 3 by the foregoing equations.

Finally, the final objective function for the optimization problem was obtained as a linear combination of Eq. (30) in terms of dimensionless optimizing criteria given the extent of

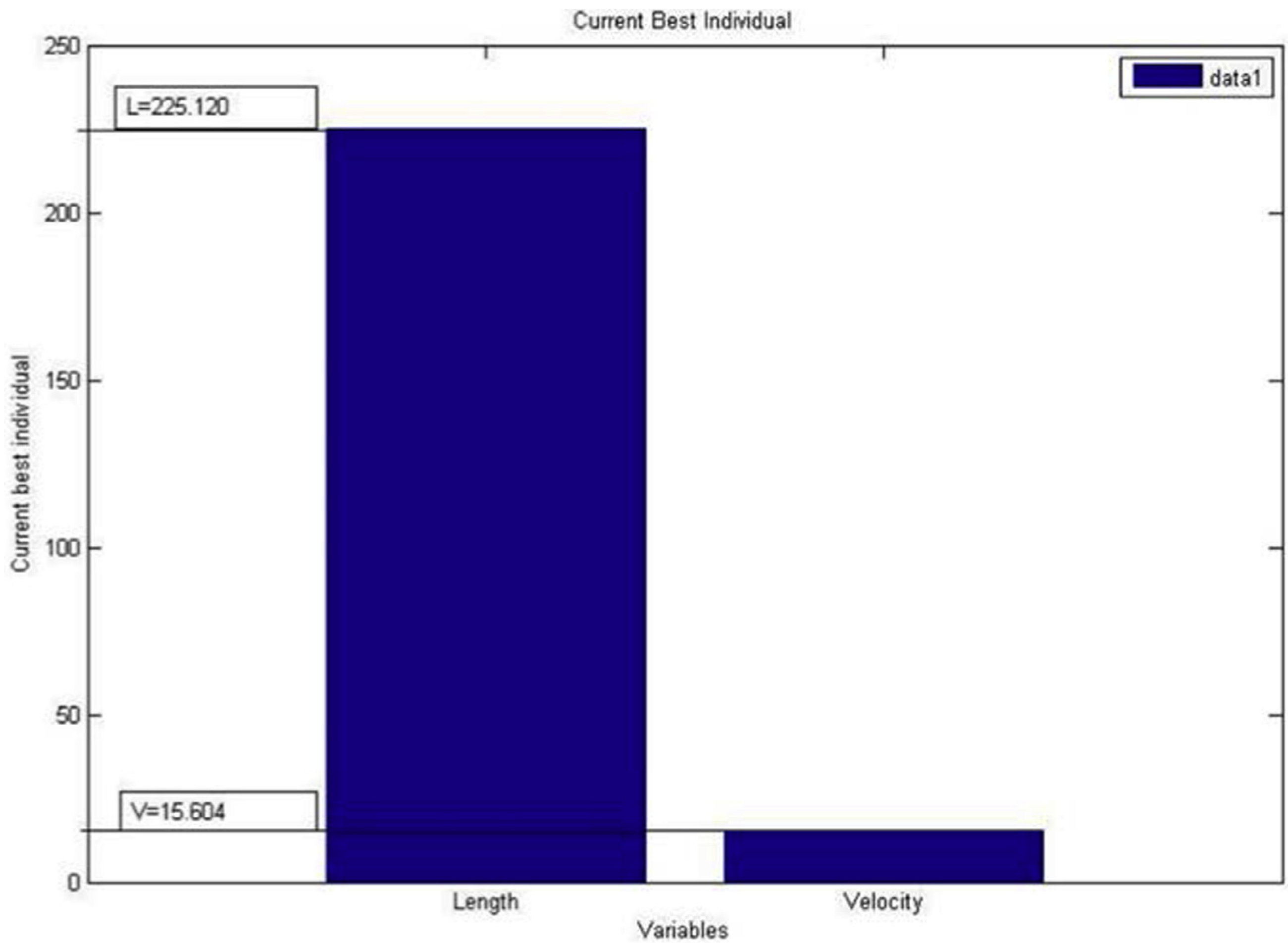

Fig. 3. Optimizing variables for the minimum of objective function.

their effect on the optimization of a tanker's FCE.

$$MOE(L, V) = \sum_{i=1}^{5} n_i \times \frac{MOP_i(L, V)}{Max(MOP_i(L, V))} \quad (30)$$

To validate the results of optimization problem under real conditions of a tanker design and construction, some conditions should be defined. The conditions were selected according to the constraints of five criteria of the studying problem from literature [10–18] as well as on the basis of the opinion of some experienced experts in the field of maritime and ship construction as Eqs. (31)–(36).

$$0.48 \le C_B \le 0.85 \quad (31)$$

$$0.001 \le C_\nabla \le 0.007 \quad (32)$$

$$\Delta \le 600,000 \text{ tonne} \quad (33)$$

$$2 \times 10^7 \le R_n \le 6 \times 10^9 \quad (34)$$

$$200 \le L \ (\text{in meter}) \le 480 \quad (35)$$

$$10 \le V (\text{in knot}) \le 30 \quad (36)$$

Table 4
Value of variables of minimized objective function.

Variable	Value
L [m]	225.12
V [knot]	15.60
MOE [ ]	0.78

5. Results

After applying objective function and the conditions in genetic algorithm toolbox of MATLAB software package, the absolute (non-local) minimum of objective function *MOE* will be obtained for 200 generations according to values given in Table 4 for the design variables of optimization problem as well as objective function.

As shown in Fig. 2, genetic algorithm converges to minimum of *MOE* after about 120 generations. Fig. 3 presents the diagram of the best individuals obtained from solving optimization problem of a tanker's fuel consumption by using genetic algorithm of MATLAB software package that expresses

Table 5
Value of design variables.

Variable	Value
B [m]	30.50
T [m]	13.00
D [m]	16.50
C_B	0.82

the numerical values of the variables of the objective function for their minimizing.

In other words, the result of optimization is that a tanker can be optimized in terms of FCE that firstly, its length is 225.12 (m) and secondly, sails at the speed of 15.60 knots.

After obtaining the optimum amount of the variables of the objective function by Eqs. (14) and (20)–(29), the numerical values of other variables required for designing a tanker with optimum fuel consumption can be obtained according to Table 5.

6. Conclusion

The present paper examines the application of multi-disciplinary optimization by genetic algorithm for maximizing a tanker's FCE which resulting in the following findings:

1. Numerous factors affect a ship's FCE, the most important ones being physical and chemical attributes of the fuel, functional components affecting the design of ship engine, propulsion and mass system attributes, and the form and resistance of ship hull.
2. Given the lack of researches on the subject with respect to the factors affecting the design of engine as well as the mismatch of the studies on fuel properties and the field of marine engineering, the present study on optimization focused on factors of propulsion system, mass and hull resistance of a ship.
3. Five criteria were included as the main criteria of multi-discipline optimization in the present study: wetted area of a ship, friction resistance, viscous-pressure resistance, the weight of steel used in the structure of a ship and hull efficiency. The objective function was deduced by combining the equations of these five criteria in proportion to the extent of their impact on FCE as a linear combination of these criteria with proper weight coefficients.
4. Given the dependence of objective function to various variables including geometric dimensions, speed and hydrodynamic properties, it is necessary to define the functions of the dependencies among these variables by theoretical and empirical equations which are available for a tanker's properties. In this method, objective function is obtained as a function of two variables of ship length and speed. This objective function can be optimized by conventional optimization methods, genetic algorithm being one of them.

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