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PARAMETRIC MODEL OF SHIP DESIGN OPTIMIZATION

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Abstract. *This work presents a design technique of ships based on optimization that use an empirical model solved using Excel. This model is multi-objective and seeks to minimize engine power (BHP) and maximize cargo transported (deadweight) from the variation of the main dimensions and the block coefficient. The contribution of the present paper is to include the propeller selection in the conceptual design phase. The model will be employed in the project conceptual phase of the bulk carrier, tank and container's ship. As result of the optimization process, an empiric parametric model of design is proposed. The proposed equations can be employed to determine the ship's dimensions and block's coefficient as a function of the type of vessel, the service speed and deadweight (cargo capacity). As an application example, a design is done with equations proposed, whose analysis allowed present a discussion about the model and the comparison with the real-world ships.*

Keywords: *Conceptual project; Merchant ships; Optimization.*

1. INTRODUCTION

The modern engineering paradigm always seeks designs more efficient, with lower costs, higher reliability, higher speed, better performance; to maximize profits or other attributes of interest. The marine engineering accompanies this trend. In recent years, merchant ships have shown an increasing trend of the main dimensions seeking to maximize cargo capacity. As a result, the structural design, propulsion plant and other design characteristics should be reevaluated to adapt to this trend.

The advances of the computers processing capacity induced a great development of mathematical techniques of representation of hull surface, of the methods to performance evaluation of the ships and of the optimization techniques. Such advances have led the important changes in the design techniques, mainly in the preliminary phases of design, as seen in (Keanet, Price and Schachter, 1990) and (Tancredi, 2013).

The disadvantage of the conventional design approach is that, in general, does not allow exploit all the space of feasible solutions and, in most cases, it cannot guarantee that can obtain an optimal solution to the established design criteria. To try to minimize these disadvantages, some researchers propose solve design problem as a problem of multi-objective optimization, as shown in (Papanikolaou, 2010) and (Parsons and Scott 2004).

The optimization model proposed in this paper aims to increase the agility of the conceptual phase of development of a new vessel, seeking the project improvement. Besides being used for the ship design, the model developed is also an efficient tool to compare different solutions for the conceptual design of a vessel described through the main dimensions and block coefficient.

As result of the optimization process, a parametric model is proposed. The equations are empirics and can be used to determine the ship's dimensions and block's coefficient as a function of the vessel type, the service speed and the deadweight.

The efficiency of a merchant ship can be measured considering the cargo capacity (DWT) in relation to the cost of construction (associated with the ship size) and operating costs (associated with the power required to the speed of service). So the object of this work is to develop a model multi objective, that minimize the engine power and maximize the cargo transported, whose the main difference from similar works is the inclusion of the propeller's attributes in the optimization process.

2. OPTIMIZATION MODEL

Using Det Norske Veritas (2014), Gross Tonnage (2014) and Royal Institution of Naval Architects (2003 - 2007), were collected data of three types of merchant ships: bulk carrier, tank and container carrier. Such information provides the database of similar ships used in this work, that consider by similar ships, ships with the same function.

In Table 1 are shown the statistic resume of the ship characteristics collected: displacement (DIS), deadweight (DWT), length overall (LOA), breadth (B), depth (D), draught (T), length between perpendiculars (LBP), length of waterline (LWL), service speed (VEL), block coefficient (CB) and deadweight coefficient (CD). The statistic parameters calculated are: minimum (min), maximum (max), median (med), standard variation (σ) and number of data (qtd).

Table 1. Statistic summary of similar ships' database.

		YEAR	DIS [10^3 t]	DWT [10^3 t]	LOA [m]	LBP [m]	LWL [m]	B [m]	D [m]	T [m]	VEL [knots]	CB (*)	CD (*)
Bulk carrier	min	2003	34.90	26.74	169.90	170.00	152.91	23.70	13.60	9.70	13.60	0.77	0.66
	max	2014	109.84	206.00	299.92	294.00	269.93	50.00	24.90	18.50	17.40	0.88	0.94
	med	2010	56.50	69.63	207.52	195.52	186.77	33.02	18.18	12.64	14.42	0.84	0.81
	σ	-	17.87	47.04	36.42	29.98	32.78	5.66	3.02	2.04	0.53	0.03	0.07
	qtd	53	38	75	75	67	75	75	74	67	72	35	37
Tank	min	2003	46.00	18.00	156.20	144.20	140.58	25.60	16.50	9.00	14.00	0.79	0.65
	max	2013	364.45	318.33	333.00	320.00	299.70	60.00	31.00	22.63	25.20	0.96	0.88
	med	2008	165.95	136.06	250.71	238.20	225.64	43.16	22.72	15.04	15.50	0.84	0.83
	σ	-	113.51	98.71	55.52	54.35	49.97	11.13	4.52	4.04	1.75	0.05	0.06
	qtd	42	38	42	42	39	42	42	41	38	42	35	38
Container carrier	min	2000	24.39	11.50	144.10	136.10	129.69	22.00	11.20	7.30	18.70	0.66	0.57
	max	2014	142.80	115.32	339.62	331.54	305.66	48.30	27.50	15.20	27.00	0.79	0.77
	med	2008	71.75	48.80	235.13	232.44	211.62	32.62	18.56	12.16	22.65	0.70	0.72
	σ	-	31.41	25.70	55.29	52.87	49.76	6.03	4.07	1.81	2.23	0.05	0.07
	qtd	59	11	59	53	47	53	59	52	46	55	8	9

* Calculated from original database collected.

Usually are used data of similar ships to define the dimensions of a new design. But the data analysis shows that there are numerous possibilities of parameters combinations that result in a ship with the same DWT value. In a new design, the engineers also must consider the limitations imposed by the route and the ports that limit the values of draught, breadth and length. These limitations can limit the cargo capacity or affect the hydrodynamic performance.

This work uses another design approach and in this section will be described a conceptual design optimization model that aims to facilitate design decisions seeking viable solutions that improve the ship performance.

2.1 Model attributes: Design variables

This model uses 7 design variables to describe the ship design solution that are shown in Table 2.

Table 2. Design variables of the optimization model.

Design variable	Unit	Symbol
Length between perpendiculars	[m]	Lbp
Breadth	[m]	B
Draught	[m]	T
Block coefficient		Cb
Number of blades		Z
Propeller diameter	[m]	Dh
Pitch /propeller diameter		P/D

2.2 Model attributes: Dimensions and geometric coefficients

The molded depth (D) is determined using the design variable draught (T) and the freeboard (BL), using equation 1.

$$D = T + BL \tag{1}$$

The freeboard (BL) value will be determined according to the International Convention on Load Lines (1966) that are shown in Figure 1a. The type A is used in tank design while the type B is used in the design of other merchant ships.

To estimate LOA in function of the LBP are used linear equations obtained from the data of similar ships that are shown in Figure 1b. The length of the waterline (LWL) is determined as 90% of LOA.

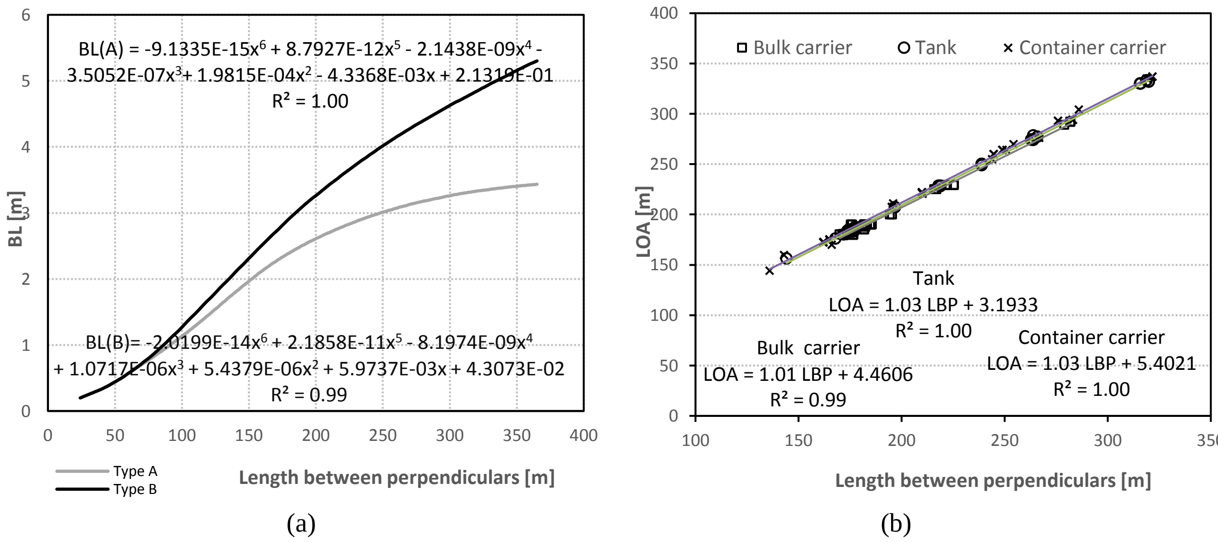


Figure 1. (a) Interpolation equations of the BL from International Convention on Load Lines (1966), (b) interpolation equations of the LOA in function of the LBP.

The midship section coefficient (CM) used the formulation proposed by Schneekluth and Bertram seen in (Parsons, 2003):

$$CM = 1.006 - (0.0056 * CB^{-3.56}) \quad (2)$$

The waterplane coefficient (Cwp) used the formulation proposed in (Parsons, 2003), that is valid for bulk carriers, tanks and container carriers:

$$Cwp = CB / (0.471 + 0.551 * CB) \quad (3)$$

2.3 Model attributes: Displacement, deadweight and lightweight

To determine the deadweight (DWT) the model uses the full load condition that usually occurs at port. In this situation, the vessel is with larger capacities of cargo and fuel. For the load capacity, a simplification was done, and the DWT is expressed in function of the model parameters and variables:

$$DWT = \Delta - LWT; \quad DWT\,[\Delta, LWT] \quad (4)$$

$$LWT\,[\,LBP, B, D, \Delta] \quad (5)$$

$$\Delta\,[\,LBP, B, T, VEL] \quad (6)$$

$$DWT\,[\,LBP, B, T, VEL, D]) \quad (7)$$

The method used for estimation of the weight of steel (Wst) is proposed by Watson and Gilfillan cited by Parsons (2003), that is showed in equation 8. This formulation considers that the Wst consists of three parts, weight of the hull, superstructure and deckhouse. For this work, the last parcel will be disregarded.

$$Wst = K * E^{1.36} * [1 + 0.5 * (CB' – 0.7)] \quad [t] \quad (8)$$

$$E = LBP * (B + T) + 0.85 * LBP * (D – T) \quad (9)$$

Another component of the ship lightweight (LWT) is the weight of the machinery (Wm) that includes engine, auxiliary machines, propellers, and shafts. Barrass (2004) proposes an empirical formula to estimate Wm in function of engine power, SHP [kN], shown in equation 10.

$$Wm = 0.075 * SHP + 300 \quad [t] \tag{10}$$

Finally, the last LWT component is the weight of equipment and outfits, which can be estimated from the formulation proposed by Schneekluth and Bertram (1998):

$$Weo = Keo * LBP * B \quad [t] \tag{11}$$

In Table 3 are shown the values of K and Keo coefficients of formulation used in weight estimation.

Table 3. Value of K and Keo

Ship type	***K***	***E min***	***E max***	***Keo***	***LBP***
Bulk carrier	0.029	3000	15000	0.25	<140
				0.18	>140
Tank	0.032	1500	40000	0.28	<150
				0.17	>150
Container carrier	0.031	6000	13000	0.38	

Adapted from Parsons (2003) and Schneekluth e Bertram (1998).

2.4 Model attributes: Resistance and propulsion

The resistance of ship (drag) is directly related to fuel consumption and depends of the hull shape. The correct determination of this resistance in the conceptual design phases is important for determining the weight of the machinery, the required thrust and the engine power. Traditionally (Molland, 2011), the total resistance (R_t) can be defined as a function of Reynolds number (Rn) and Froude number (Fn), as shown in equations:

$$R_t = \frac{1}{2}\ C_t * \rho * S * VEL^2 \tag{12}$$

$$C_t = f\,(R_n, F_n) \tag{13}$$

The most significant component of the total resistance in low-speed ships is the frictional resistance (Rf), which can be estimated in the conceptual design phase.

$$R_f = \frac{1}{2}\ C_f * \rho * S * VEL^2 \tag{14}$$

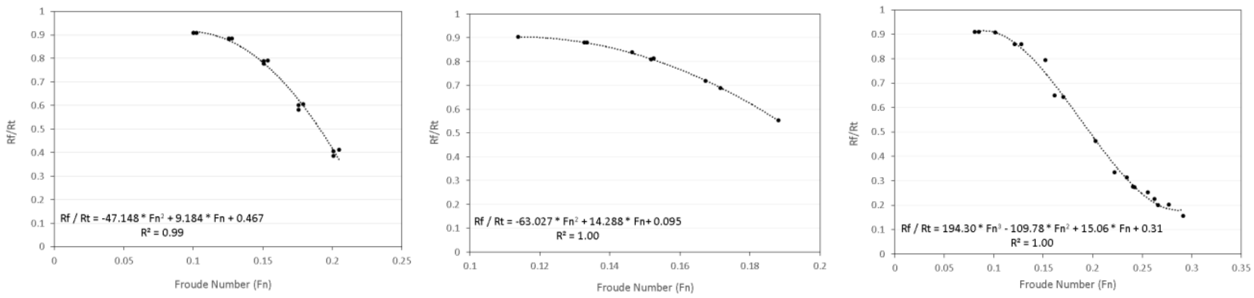
Estimating the frictional resistance coefficient (Cf) is determined according to the number of Rn by the classic method proposed by the ITTC (1957) cited by Watson (1998). The wetted area can be estimated by method proposed by Holtrop and Mennen cited by Watson (1998) that is seen in equation 15.

$$S_{holtrop} = L\,(2 * T + B)\,\sqrt{Cm}\,\left(0.45 + 0.44\,Cb - 0.28\,Cm\ - 0.003\frac{B}{T} + 0.37\,Cwp\right) + 2.38 * \frac{Abt}{Cb} \tag{15}$$

For this work, the objective is to determine the total resistance (Rt), which will be estimated from the relation Rf / Rt that is expressed as a function of Fn, as seen in (Molland, 2011). A 10% correction factor was used to consider other resistance portions such as the resistance of appendices:

$$R_t = 1.1 * R_f / (R_f / R_t) \tag{16}$$

To find the ratio Rf / Rt based on the number of Fn, the ships of the database were used. For each type of ship studied were selected three vessels, each one analyzed for different speeds, using the method proposed by Holtrop (Holtrop, 1998) with the Maxsurf software. Using the simulations' results, regressions were found as a polynomial function that describes the relation between Rf and Rt. The equations determined are shown in Figure 2.



(a) (b) (c)

Figure 2. Interpolation equations of Rf / Rt in function of Fn: a) Bulk carrier b) Tank c) Container carrier.

From the total resistance it is possible to determine the effective power (Pe), which is the power required to reach the desired speed. The equation 17 shows the definition of the Pe.

$$P_e = R_t * VEL \tag{17}$$

2.5 Model attributes: Hull-propeller integration / Determination of SHP

The main attributes used in the propeller selection process are: the propeller diameter (Dh) the number of blades (Z), the area ratio (Ae/Ao) and pitch (P). The objective is defining these values of attributes so that the efficiency is maximized, because the efficiency maximization is associated with engine power minimization and also with lower fuel consumption. The relation between the effective power and the power required of the engine is show in the equation:

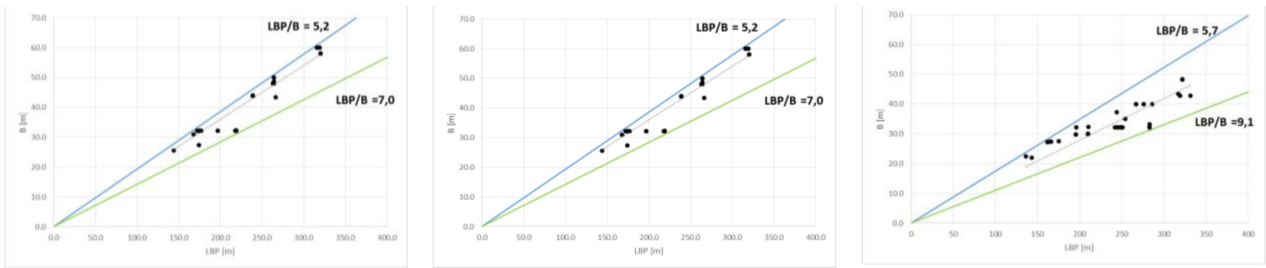
$$SHP = P_e / \eta_o \tag{18}$$

The η_o is a function of the propulsive force coefficient (Kt) and the torque coefficient (Kq). Both coefficients were determined by the polynomial interpolation for the series of Wageningen B-screw (Bernitgas; Ray; Kinley, 1981). The operation point is calculated to maximize the efficiency.

It is important to observe that the SHP actually is the power at the engine' shaft, but it is almost 99% of the real engine power BHP. So in this work, SHP is used as the engine power required.

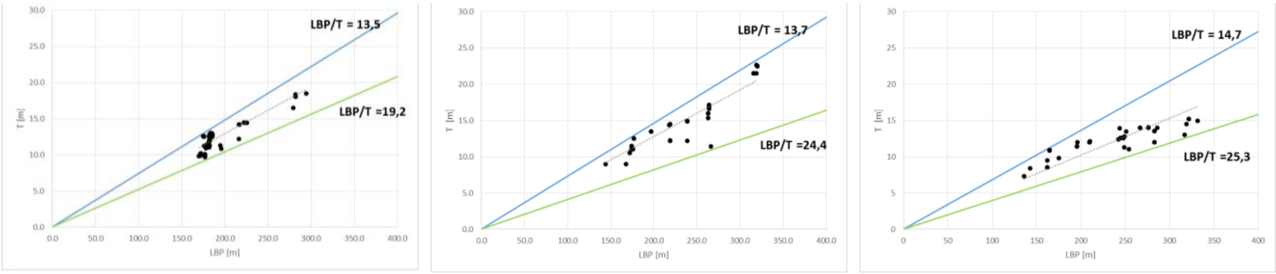
2.6 Constraints

The constraints associated with the coefficients: LBP / B, LBP / T and B / T, were obtained from the data of similar ships, and can be seen in Figures 3 and 4.

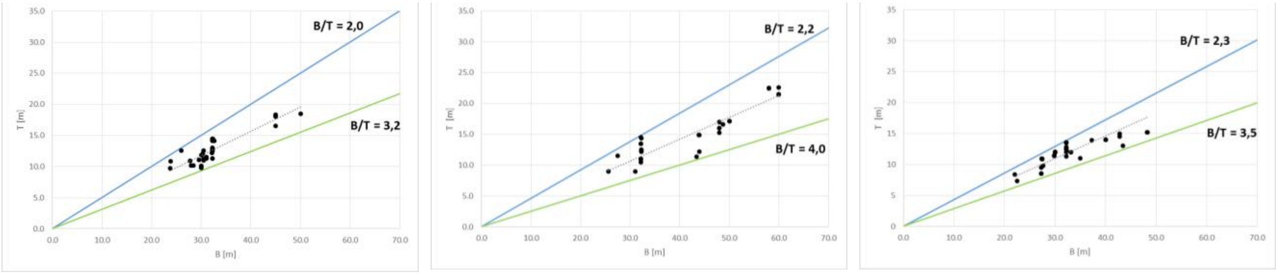


(a) (b) (c)

Figure 3. Ratio LBP / B: a) Bulk carrier b) Tank c) Container carrier.



(a) (b) (c)



(a) (b) (c)

Figure 4. Ratio LBP / T and B / T: a) Bulk carrier b) Tank c) Container carrier.

In Table 4 are listed all the constraints used in the optimization model.

Table 4. Constraints of optimization model

1	L/B	> = < =	5.2 9.1
2	L/T	> = < =	13.5 25.3
3	B/T	> = < =	2.0 4.0
4	GM	>	0.10
5	Ae/Ao	=	(Kuiper, 1992)
6	D_h	< =	(0.74T)/(1-0.05)
7	D_h	> =	3
8	D_h	< =	12
9	P/D	<=	1.4
10	P/D	>=	0.5
11	Z	<=	7
12	Z	=	Integer
13	Z	>=	3

The first three constraints (Table 4) are related to the limits of geometric coefficients that were seen in Figure 3 and 4. The 4th constraint ensures that the ship's transverse stability criterion is respected. The constraints 5 and 6 assure the non-occurrence of cavitation and also that the propeller will not exceed the hull's space. Finally, the constraints of 8 until 14 are used to limit the propeller' size and also considers the limits allowed of Wageningen B-screw.

It is important to observe that the problem is iterative, because each modification of SHP value requires a new optimization process to maximize the propeller efficiency.

3. RESULTS

To evaluate the robustness and efficiency of the proposed optimization model, the multi-objective results are compared with traditional similar ships approach. In the Figure 6 the results about total resistance (Rt) are shown, while in Figure 7, are shown the results about engine power required (SHP).

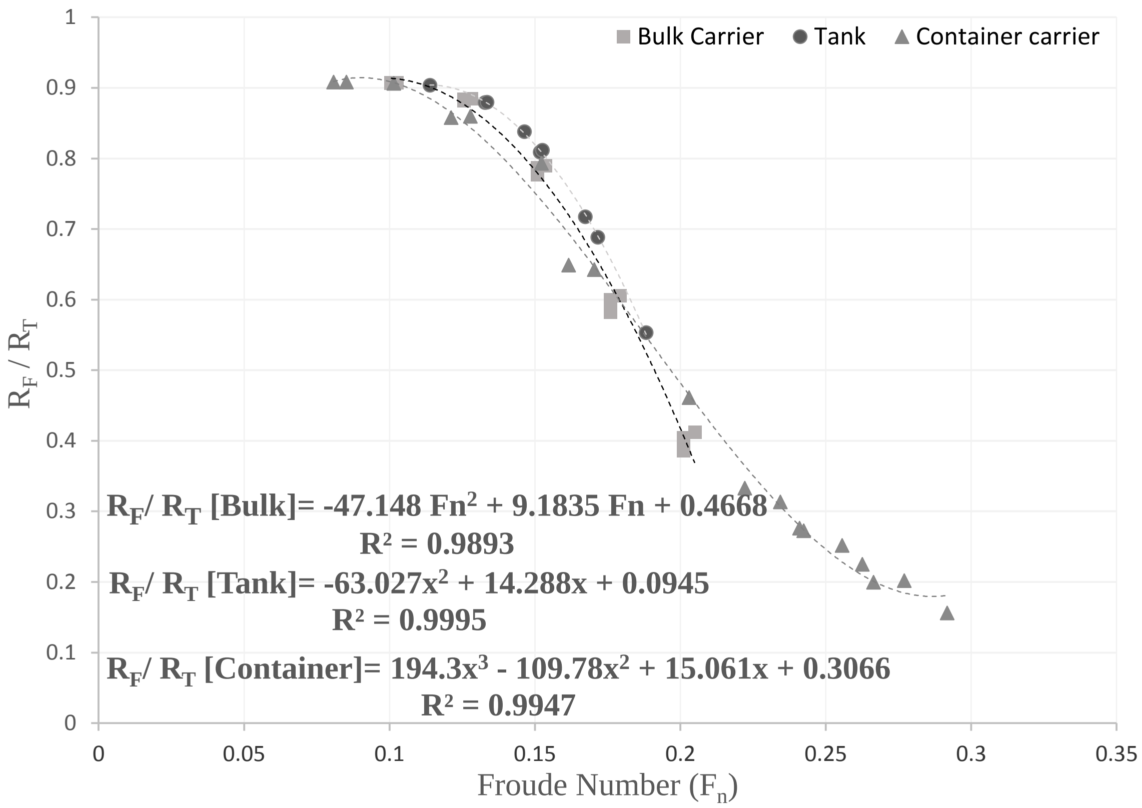


Figure 6. The total resistance in function of deadweight for the multi-objective optimization process and for the traditional similar ships approach: a) Bulk carrier b) Tank c) Container carrier.

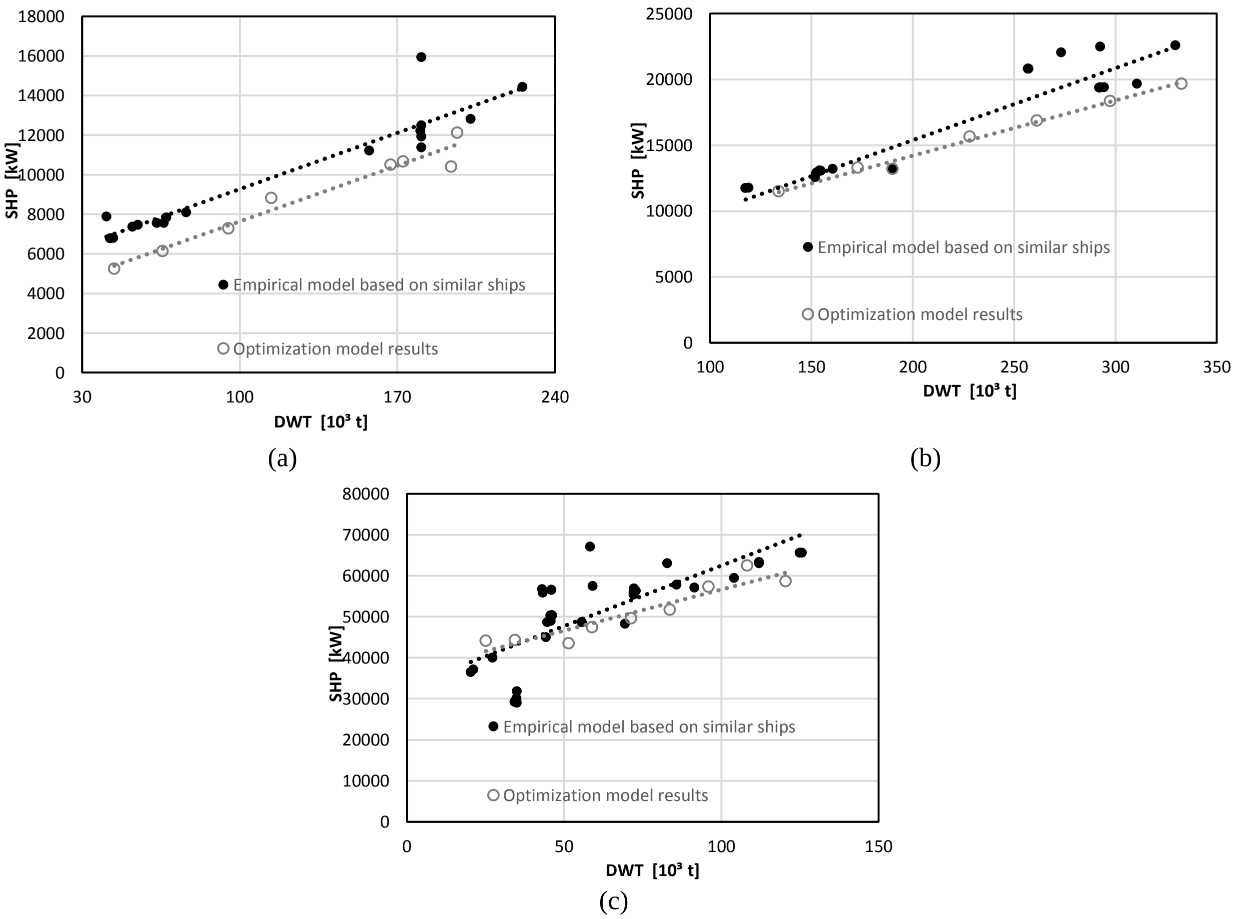


Figure 7. The engine power required in function of deadweight for the multi-objective optimization process and for the traditional similar ships approach: a) Bulk carrier b) Tank c) Container carrier.

3.1 Parametric model

The final results of this study are a set of empirical formulations that can estimate the design variables in function of the DWT required. These equations are shown in Figure 8 to 10 and can be used for determining the dimensions and the block coefficient of a merchant ship according to the service speed and cargo capacity.

The obtained correlations were interpolated using a potential function. It is important to observe that the equations have a good performance. The lowest R^2 value was for the LBP and B functions for tank, which presented the value of 0.9309.

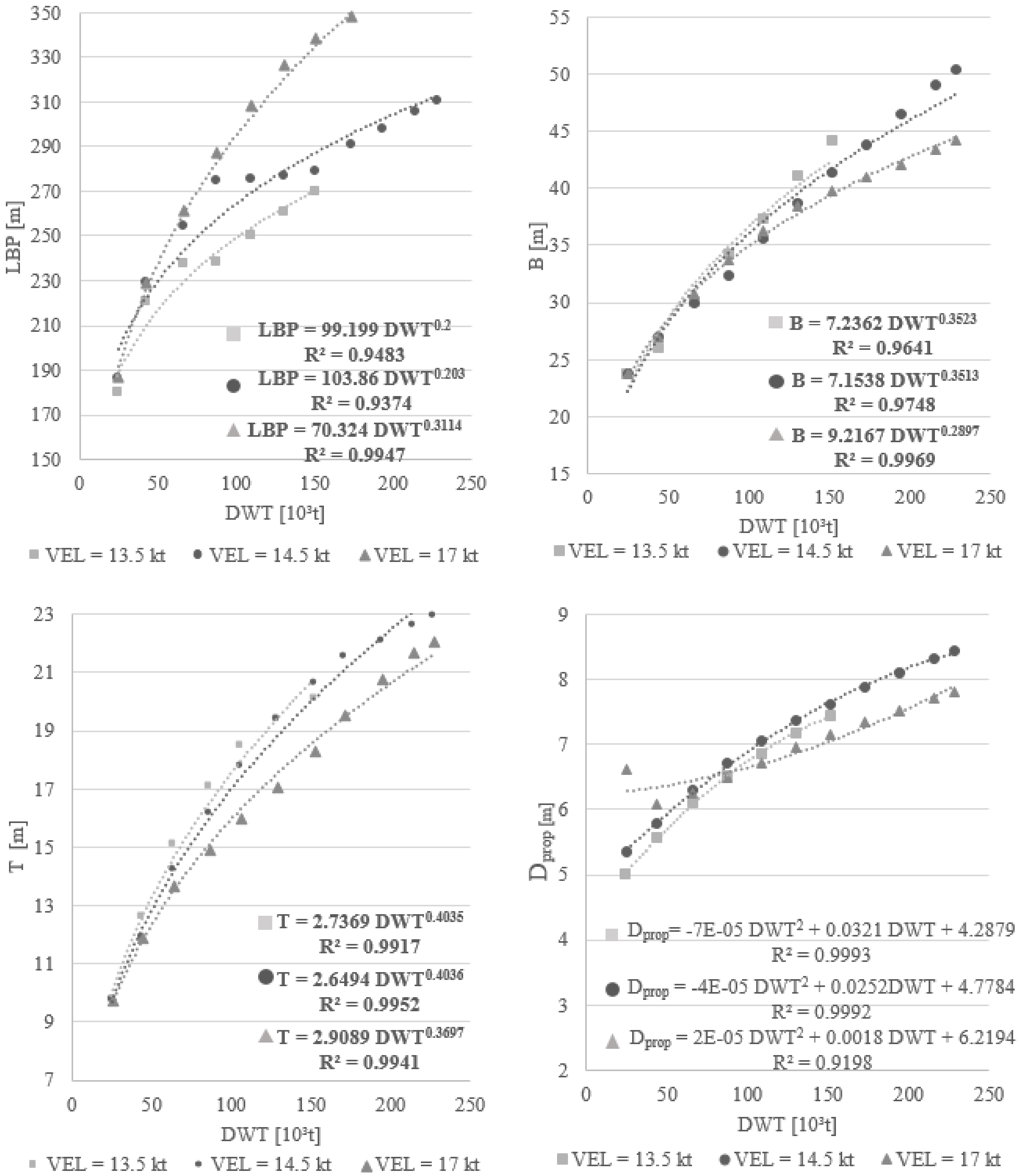


Figure 8. Results for Bulk Carrier.

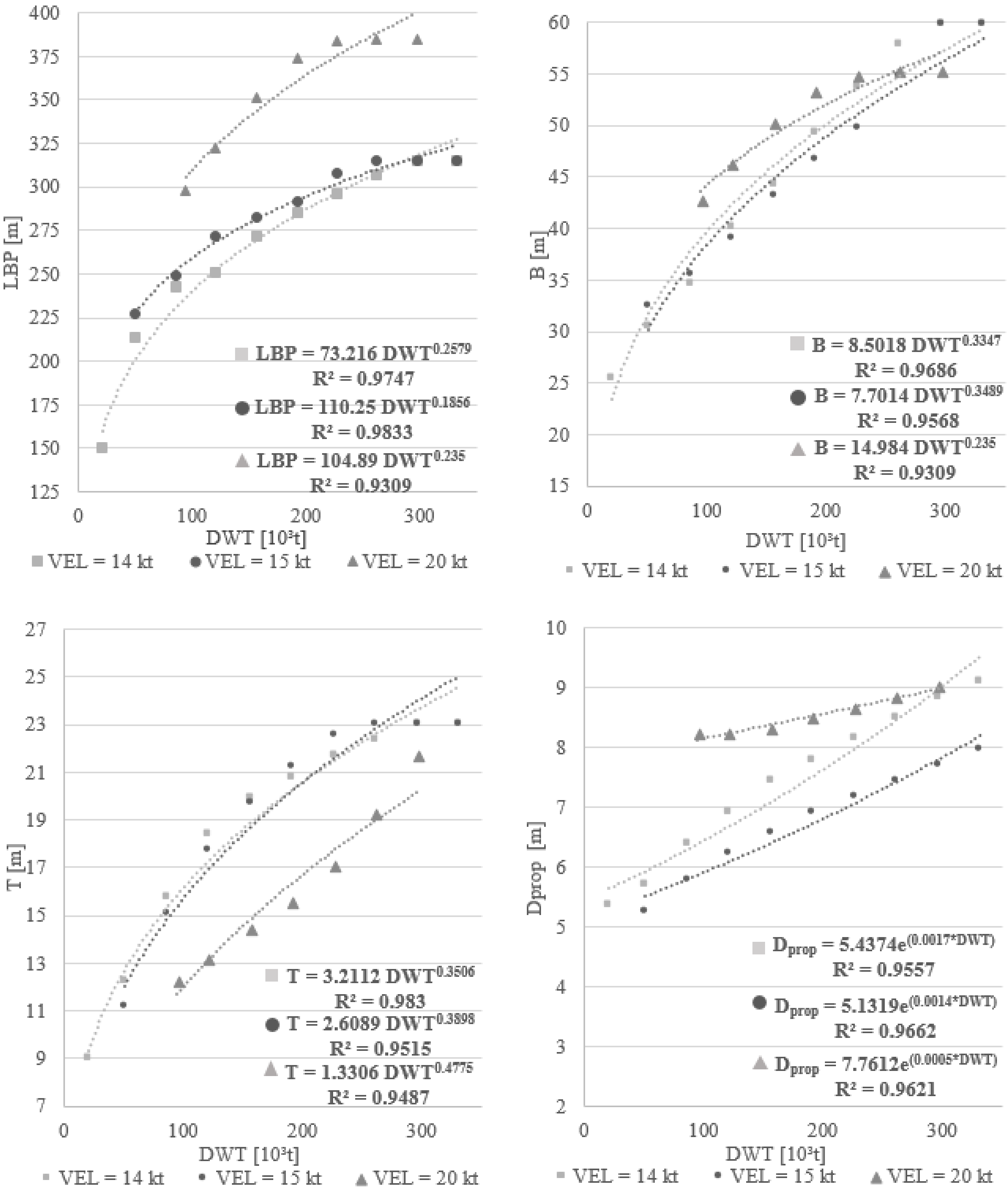


Figure 9. Results for Tank.

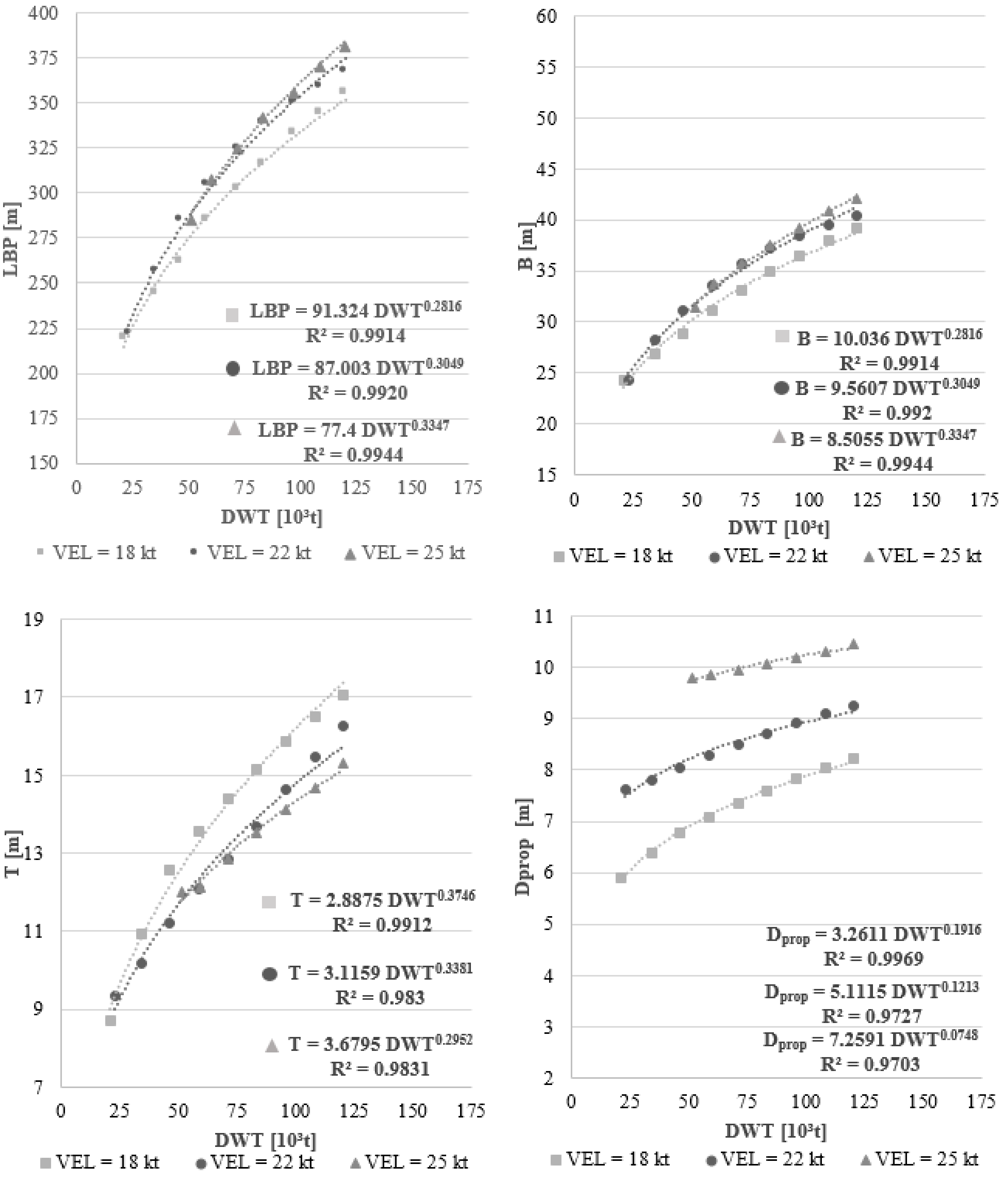


Figure 10. Results for Container Carrier.

The results show that the optimum value to the block coefficient trends to a constant value for each ship type. Which for bulk carrier is 0.77, tank is 0.78 for DWT< $276X10^3$ t and container carrier is 0.65.

4. CONCLUSIONS

The designer of a new vessel must be prepared to solve design conflicts, reduce manufacturing and operating costs, attend the owner's requirements and international standards, accompany the new trends, identify the most appropriate methods for each design, understand the structural and manufacturing limitations, seeking a differential economic or of performance.

Within this context, this paper presented an automated procedure for the conceptual design of vessels, which use a new approach for development the complex products. The results of the design model proposed were compared with data of real ships, and also with the results of traditional approach of design using similar ships.

The final result is the set of 36 equations to be used in preliminary phase of a merchant ship design, and considers the usual service speed the 13.5, 14.5 and 17 knots for bulk carriers, 14, 15 and 20 knots for tanks and 18, 22 and 25 knots for container carriers.

The objective proposed has been reached and the empiric model for estimation of the parameters of the ship design was tested and worked properly. The optimization model can be easily manipulated to consider others service speeds, which makes it a robust and efficient process.

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