DETERMINATION OF REGRESSION FORMULAS FOR KEY DESIGN CHARACTERISTICS OF CONTAINER SHIPS AT PRELIMINARY DESIGN STAGE

DOI 10.2478/ntpe-2018-0031

2018
Volume 1
Issue 1
pp. 247-257

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Abstract. This article presents regression equations to estimate container ship design characteristics based on the most up-to-date data and deadweight capacity, the number of containers and their combination at the preliminary design stage. These design formulas could have application for the estimation of key container ship characteristics such as: main ship dimensions, geometric parameters, main engine total power, ship velocity, final price and others. Regression equations were performed on the basis of IHS Maritime & Trade main container ship data built from 2005-2015. All equations presented in this paper could have practical application at the preliminary design stage and increase ship design theory development.

Keywords: preliminary, ship, containership, design, main dimensions, regression

INTRODUCTION

Ship design is a multistage process. This process consists of: preliminary design, contract design and detailed design stage.

The preliminary design is an early stage of the process. Major design parameters and initial line plan, general arrangement and propulsion system are conceptualized at this stage. Rawson and (Tupper 2001, Watson 1998, Papanikolaou 2014) argue that the purpose of the parametric design is, among others to:

- select, calculate or estimate main ship dimensions, geometric parameters as well as main propulsion and powering parameters,
- arrange main spaces and compartments,
- appraise buoyancy calculations, freeboard, stability and strength on the basis of preliminary design parameters.

As noted by (Chądzyński 2001) the main objectives of the geometric design phase are to:

- design initial line plan and general arrangement,
- conduct model tests for resistance and propulsion,
- examine the calculation integrity.

The parametric design phase is greatly important for the entire design process because the design parameters that determine key ship characteristics are defined in this phase.

The modification of these parameters, at a later stage, or after the vessel is completed is far too expensive and can lead to actually making a loss. For example modifying the length of the ship after the construction of the hull is prohibitively expensive.

The main problem relating to the parametric design phase is the need to estimate different technical properties of the vessel, simply on the basis of preliminary design parameters such as a DWT deadweight capacity or a number of TUE containers.

As noted by (Papanikolaou 2014, and Chądzyński 2001) this problem can be solved by selecting a relational, statistical and a parametric design method.

Regression formulas for the determination of design parameters are usually the basis for statistical design methods.

The authors also used a theory of artificial neural networks for this purpose. A number of papers present mathematical functions to estimate key design parameters developed through artificial neural networks theory.
The container ship is usually categorized as volume carrier in which major input design parameters are deadweight capacity and the number of containers that can be in the hold. Therefore determining container ship key design characteristics are based on these parameters.
Piko (1980) prepared regression analysis and statistical equations for many types of ships. Kalokairinos, Mavroeidis, Radou, Zachariou (2000–2005) (as cited in Papanikolaou, 2014) developed regression equations for different types of ships, including containers ship built from 2000-2005. These articles present mathematical functions for estimating container ship design characteristics based primarily on deadweight capacity.
In contrast the formulas presented by Kristensen in 2013 are based on a number of containers. These formulas were developed on the basis of ship data built to 2013. These formulas do not take into account deadweight capacity.
Ekincia et al. (2011) through the use of various computational intelligence techniques to determine general ship principal parameter, also including main engine power. Lin and Shaw (2016) developed a parametric method to accurately estimate the steel weight of a new ship at the preliminary design stage. Hou et al proposed an (2011) artificial neural network model for the principal dimension estimation of naval vessels. Though it should be noted that these methods are difficult to apply at the early parametric design stage.

THE AIM OF THE RESEARCH

All design equations should be updated frequently to increase their practical application at the preliminary design stage. But there are no regression equations to estimate container ship design characteristics based on the most recent data and a DWT deadweight capacity, a number of TUE containers and theirs combination in any literature.
Therefore, the intention of this research was to develop design formula (f) to estimate container ship design parameters (Y), based on a DWT deadweight capacity, a number of TUE containers and others:

$$Y = f(DWT, TEU, X_1, X_2, .., X_n) \quad (1)$$

where:
Y, is estimated design parameter,
$X_1, X_2, .., X_n$, are input design parameters,
f, is a design formula to calculate selected design parameter Y.
The following Y design parameters were taken into account:

- length between perpendicular LBP from 47.5 to 383 m,
- breadth B from 9.5 to 59 m,
- depth D from 4.5 to 30.5 m,
- draught d from 2.18 to 16.5 m,
- displacement Disp from 6471 to 258360 t,
- light vessel mass LV from 2032 to 61881 t,
- gross tonnage GT from 355 to 194850 t,
- main engine total power PME from 404 to 81250 kW,
- Froude number Fr from 0.11 to 0.28,
- block coefficient CB from 0.56 to 0.83,
- waterplane area coefficient CW from 0.74 to 0.96,
- final price SP from 2500 000 to 171000000 $,
- velocity v from 9.3 to 29.2 knots ,
- product of the main dimension LBD from 11655 to 684590.
- ratio LV/LBD from 0.03 to 0.25,
- ratio LBP/Disp.vol^1/3 from 4.39 to 6.61.

vs deadweight DWT from 500 to 200000 tons and the number of containers from 20 to 20000 TEU's.

Regression equations were performed on the basis of IHS Maritime & Trade main container ship data built from 2005-2015.

REGRESSION METHOD

As a rule, a common regression method was applied to generating models for key design characteristics.

But the regression formulas for a number input design parameters were developed using the author’s method based on a heuristic algorithm.

Standard multiplicative regression methods require simultaneous insertion to the model all independent variables and all their combinations. This may lead to an over-expanded regression model and searching for optimal equations can result in too many iterations and computations. Therefore, standard methods are ineffective for a large number of base functions and data sets. The author developed a new algorithm to find the best result on the basis of evolution theory methods to resolve this problem. The best combinations of independent variables were randomly searched through all their possible combinations in this algorithm.

The general algorithm scheme is shown in Fig 1.

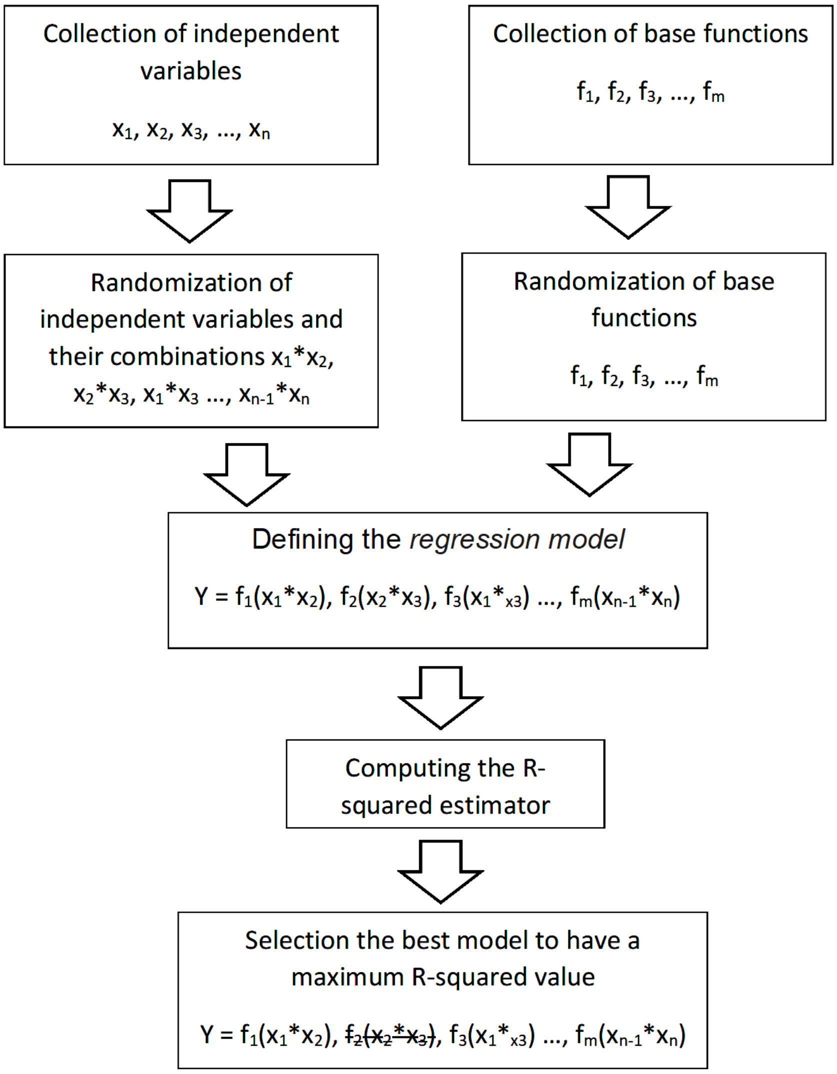

Fig. 1. The general algorithm scheme, where: Y, is estimated design parameter, $X_1, X_2, .., X_n$, are input design parameters, f, is a design formula to calculate selected design parameter Y, m is the number of formulas, n is the number of input design parameters.

The base function collection included 360 arrays of nonlinear, exponential, power and logarithmic functions. NdCurveMaster software was applied to develop regression equations presented in this paper.

THE REGRESSION FUNCTIONS FOR THE ESTIMATION OF CONTAINER SHIP DESIGN PARAMETERS

In this section, the key container ship design parameters have each been regressed against DWT deadweight, the number of TEU containers and combinations of DWT and TEU.
The following design formulas are for the estimation of:

- length between perpendiculars
- breadth
- draught
- depth D
- gross tonnage GT
- final price SP
- block and waterplane area coefficient
- main engine total power PME
- light vessel mass LV
- displacement mass Disp
- velocity v
- L·B·D product
- L·B·d product
- ratio LV/LBD
- LBP/Disp.vol1/3

and relationship between deadweight and number of containers are presented in the next part of the article.
The study resulted in the following design formulas for the calculation of key design characteristics:

$LBP = 35.8527+0.0013355\cdot \ln^5(DWT)$ (2)

$LBP = 1.5022+0.413355\cdot \ln3(TEU)$ (3)

$LBP = 46.4416+3.3E\text{-}06\cdot \ln7(DWT)+0.029471\ \ln4(TEU)-1.99E\text{-}07\cdot (DWT\cdot TEU)^{0.9}$ (4)

$B = 11.095+0.1\cdot DWT^{1/2}$ (5)

$B = 7.425+0.96\cdot\ EU^{0.4}$ (6)

$B = -2.328+0.283\cdot \ln^2(DWT)-2.99E\text{-}15\cdot TEU^{4.2}+1.06E\text{-}15\cdot TEU^{4.3}+3.19E\text{-}09\cdot DWT^{-1/12}\cdot TEU^{2.6}$ (7)

$d = -32.785+21.956\cdot DWT^{1/15}$ (8)

$d = -51.665+43.288\cdot TEU^{1/21}-4.41E\text{-}09\cdot TEU^2$ (9)

$d = 8.177-4.19E\text{-}01\cdot DWT^{1/3}-3.949\cdot TEU^{1/4}+0.0073\cdot \ln^3(DWT\cdot TEU)$ (10)

$D = -2.422+0.594\cdot DWT^{1/3}$ (11)

$D = -7.766+3.442\cdot TEU^{1/4}$ (12)

$D = -1.589+0.012\cdot \ln^3 DWT+0.092\cdot TEU^{1/} + -1.19E\text{-}78\cdot DWT^{14}\cdot TEU$ (13)

$GT = 2826.289+8.81E\text{-}02\cdot DWT^{1.2}$ (14)

$GT = -1097.4+11.049\cdot TEU$ (15)

$GT = 1490.274+0.585\cdot DWT+8.93E\text{-}03\cdot TEU^{1.7}-3.85E\text{-}10\cdot (DWT\cdot TEU)^{1.5}$ (16)

$SP = 80.85769+9.83E\text{-}15\cdot DWT^{3.1}-699.365\cdot DWT^{-1/4}$ (17)

$SP = -84.438789+1.41E\text{-}20\cdot TEU^{5.3}+31.2796862\cdot TEU^{1/6}$ (18)

$SP = -789.87766+3.91E\text{-}08\cdot DWT+8.93E\text{-}03\cdot TEU^{1.7}-3.85E\text{-}10\cdot (DWT\cdot TEU)^{1.5}$ (19)

$CB = 0.669+5.7E\text{-}17\cdot DWT^{2.8}$ (20)

$CB = 0.669+3.23E\text{-}11\cdot TEU^{2.1}$ (21)

$CB = 0.45886+5.60E\text{-}07\cdot DWT^{1.1}+6.44E\text{-}01\cdot \exp(Fn)^{-4}+229799.062\cdot TEU^{-2.5}-3410882.2\cdot DWT^{-2.5}\cdot Fn^{-3}+1.35E\text{-}17\cdot DWT^2\cdot TEU^{1.4}-1.52E\text{-}05\cdot Fn^{-1/2}\cdot TEU-1.60E\text{-}32\cdot DWT^4\cdot Fn^{1.3}\cdot TEU^{2.6}$ (22)

$CWL = 1.0566 + -2.48E\text{-}05\cdot DWT+2.40E\text{-}05\cdot TEU^{1.3}+2.40E\text{-}35\cdot DWT^7\cdot TEU^{-1/6}+1.13E\text{-}04\cdot DWT\cdot CB^{3.1}-4.97E\text{-}03\cdot TEU^{0.8}\cdot CB^{2.3}-2.67E\text{-}13\cdot DWT^{1.9}\cdot TEU\cdot CB^{3.4}$ (23)

$PME = -11798.783+2.89E\text{-}02\cdot \ln^6 DWT$ (24)

$PME = -15087.496+2\ 10.644\cdot \ln^4 TEU$ (25)

$PME = -1064.61+3.90E\text{-}06\cdot DWT^2+5.269\cdot TEU^{1.1}+ -3.31E\text{-}04\cdot DWT^{0.9}\cdot TEU$ (26)

$PME = -2420.3994-4.58E-02 \cdot DWT^{1.2}+115590.89 \cdot Fn^{2}+4.5857 \cdot TEU^{1.1}+4.27E-01 \cdot DWT^{1.6} \cdot Fn^{4.3}+8.88E-24 \cdot DWT^{6} \cdot TEU^{-0.9}-1791.82 \cdot Fn^{4.2} \cdot TEU-3.44E-07 \cdot DWT^{1.7} \cdot Fn^{0.9} \cdot TEU^{0.8}$ (27)

$LV = 228.81+0.979 \cdot DWT^{0.9}$ (28)

$LV = 109.363+6.44E-03 \cdot \ln^{7}TEU$ (29)

$LV = 2365.363+0.003 \cdot DWT^{1.2}+6.60E-03 \cdot TEU^{1.7}-3.70E-05 \cdot (DWT \cdot TEU)$ (30)

$Disp = 1897.963+1.2898 \cdot DWT$ (31)

$Disp = 3526.844+2.91E-03 \cdot \ln^{8}TEU$ (32)

$Disp = 1588.5+1.2578 \cdot DWT+1.77E-03 \cdot TEU^{1.8}-5.89E-07 \cdot DWT^{1.3} \cdot TEU$ (33)

$v = 27.1856-985.3918 \cdot DWT^{-1/2}$ (34)

$v = 27.19-276.836 \cdot TEU^{-1/2}$ (35)

$v = 81.667+90.1 \cdot DWT^{-1/8}-162.29 \cdot TEU^{-1/12}-5.59E-08 \cdot DWT^{-0.3} \cdot TEU^{2.3}$ (36)

$LBD = -184.56765+1.044 \cdot DWT^{1.1}$ (37)

$LBD = -20143.62+104.422 \cdot TEU^{0.9}$ (38)

$LBD = -10716.896+1.2148 \cdot DWT+27.9396 \cdot TEU-1.30E-05 \cdot (DWT \cdot TEU)$ (39)

$LBd = -5545.44+6.194 \cdot DWT^{0.9}$ (40)

$LBd = -9615.46+145.23 \cdot TEU^{0.8}$ (41)

$LBd = 907.2+1.63 \cdot DWT+0.1439 \cdot TEU^{1.5}-5.81E-09 \cdot DWT^{1.1} \cdot \ln^{8}TEU$ (42)

$LV/LBD = 0.017+1.3785 \cdot DWT^{-1/4}$ (43)

$LV/LBD = 1.95E-02+7.13E-01 \cdot TEU^{-1/4}$ (44)

$LV/LBD = 8.79E-02-1.55E-05 \cdot DWT^{0.6}-3.5887 \cdot TEU^{-1/2}+10.55 \cdot (DWT \cdot TEU)^{-1/4}$ (45)

$LBP/Disp.vol^{1/3} = 10.3491-11.208 \cdot DWT^{-1/12}$ (46)

$LBP/Disp.vol^{1/3} = 8.007-8.74 \cdot TEU^{-1/6}$ (47)

$LV/LBD = 5.439- -2.71E-04 \cdot DWT^{0.9}-1.05E-02 \cdot TEU^{0.7}+4.77E-10 \cdot \ln^{8}(DWT \cdot TEU)$ (48)

$DWT = 1317.745+2.24E-03 \cdot \ln^{8}(TEU)$ (49)

$TEU = 372.53+7.94E-03 \cdot DWT^{1.2}$ (50)

where:

LBP – length between perpendiculars [m],

B – breadth [m],

d – draught [m],

D – depth [m],

TEU – number of containers,

DWT – deadweight capacity [t],

LV – light vessel mass [t],

LBd – the result of L·B·d [m^3],

LBD – the result of L·B·D [m^3],

v – velocity [kts.],

Disp – displacement mass [t],

SP – light vessel mass [t],

PME – main engine total power [kW],

CB – block coefficient [-],

CWL = waterplane area coefficient [-]

SP – final price [$ million],

GT – gross tonnage [-],

Fn – Froude number [-].

The values of standard SE and the R-squared errors relating to elaborated relationships (2-50) are given in Table 1. Figures 2-5 show the relationship between design parameters and deadweight or TEU capacity calculated using formulas (2-50).

Table 1
The values of standard SE and the R-squared errors relating to elaborated relationships (2-50)

Item	Output design parameter	Input design parameter	Equation no	Standard error SE	R-Squared
1.	LBP	DWT	(2)	11.53 m	0.976
2.	LBP	TEU	(3)	11.27 m	0.978
3.	LBP	DWT, TEU	(4)	10.32 m	0.982
4.	B	DWT	(5)	1.84 m	0.961
5.	B	TEU	(6)	1.82 m	0.962
6.	B	DWT, TEU	(7)	1.67 m	0.968
7.	d	DWT	(8)	0.51 m	0.967
8.	d	TEU	(9)	0.57 m	0.959
9.	d	DWT, TEU	(10)	0.47 m	0.971
10.	D	DWT	(11)	1.2 m	0.963
11.	D	TEU	(12)	1.21 m	0.962
12.	D	DWT, TEU	(13)	1.17 m	0.965
13.	GT	DWT	(14)	3847	0.992
14.	GT	TEU	(15)	3555	0.993
15.	GT	DWT, TEU	(16)	2833	0.995
16.	SP	DWT	(17)	$ 16.82 million	0.738
17.	SP	TEU	(18)	$ 16.17 million	0.758
18.	SP	DWT, TEU	(19)	$ 16.82 million	0.765
19.	CB	DWT	(20)	0.028	0.05
20.	CB	TEU	(21)	0.028	0.03
21.	CB	DWT, TEU, Fn	(22)	0.025	0.28
22.	CWL	DWT, TEU, CB	(23)	0.026	0.44
23.	PME	DWT	(24)	7727 kW	0.878
24.	PME	TEU	(25)	7626 kW	0.882
25.	PME	DWT, TEU	(26)	6683 kW	0.909
26.	PME	DWT, TEU, Fn	(27)	5086 kW	0.947
27.	LV	DWT	(28)	1892 t	0.979
28.	LV	TEU	(29)	1729 t	0.983
29.	LV	DWT, TEU	(30)	1573 t	0.986
30.	Disp	DWT	(31)	1952 t	0.999
31.	Disp	TEU	(32)	4380 t	0.994
32.	Disp	DWT, TEU	(33)	1581 t	0.999
33.	v	DWT	(34)	1.45 kts.	0.727
34.	v	TEU	(35)	1.42 kts.	0.736
35.	v	DWT, TEU	(36)	1.28 kts.	0.830
36.	LBD	DWT	(37)	14,816 m^3	0.991
37.	LBD	TEU	(38)	13,145 m^3	0.993
38.	LBD	DWT, TEU	(39)	11,851 m^3	0.994
39.	LBd	DWT	(40)	7591 m^3	0.999
40.	LBd	TEU	(41)	7484 m^3	0.991
41.	LBd	DWT, TEU	(42)	6179 m^3	0.993
42.	LV/LBD	DWT	(43)	0.01 t/m^3	0.824
43.	LV/LBD	TEU	(44)	0.01 t/m^3	0.812
44.	LV/LBD	DWT, TEU	(45)	0.01 t/m^3	0.826
45.	LBP/Disp.vol$^{1/3}$	DWT	(46)	0.25	0.647
46.	LBP/Disp.vol$^{1/3}$	TEU	(47)	0.24	0.669
47.	LBP/Disp.vol$^{1/3}$	DWT, TEU	(48)	0.22	0.728
48.	DWT	TEU	(49)	3823 t	0.992
49.	TEU	DWT	(50)	369	0.991

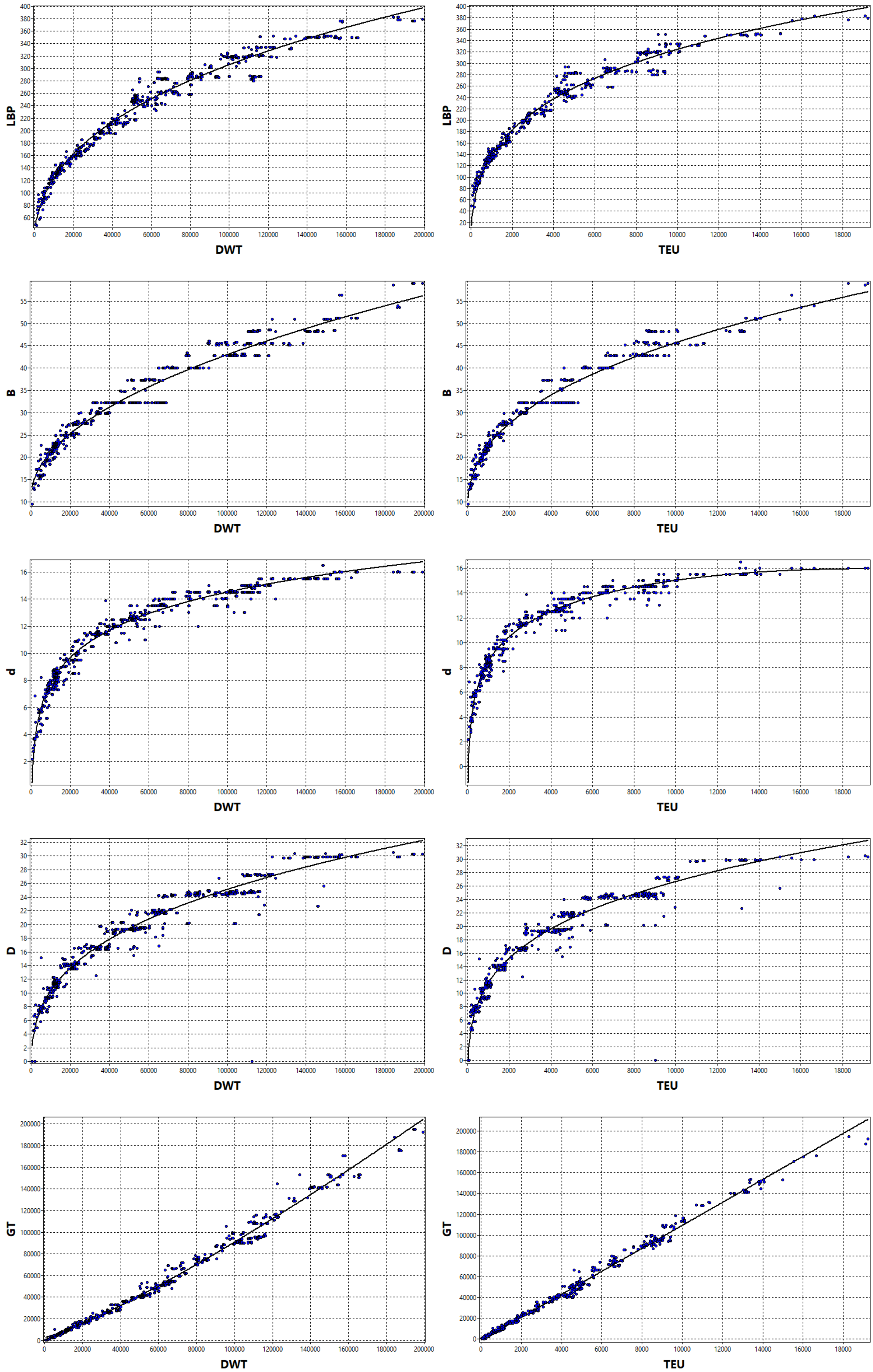

Fig. 2. Length between perpendiculars LBP, breadth B, draught d, depth and gross tonnage GT as a function of deadweight DWT or TEU capacity.

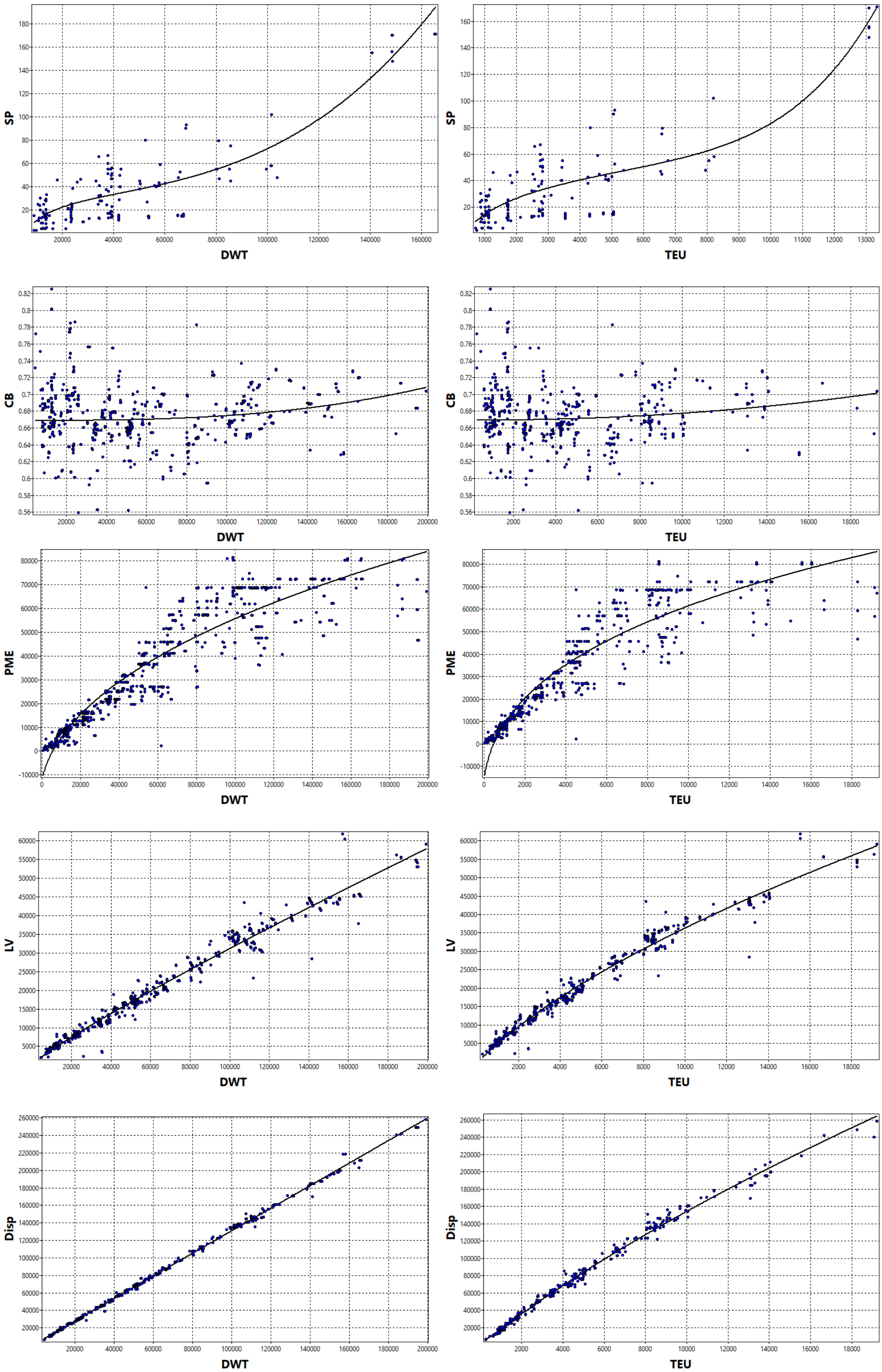

Fig. 3. Sale price SP, block coefficient CB, main engine power PME, light vessel mass LV and displacement mass Disp as a function of deadweight DWT or TEU capacity.

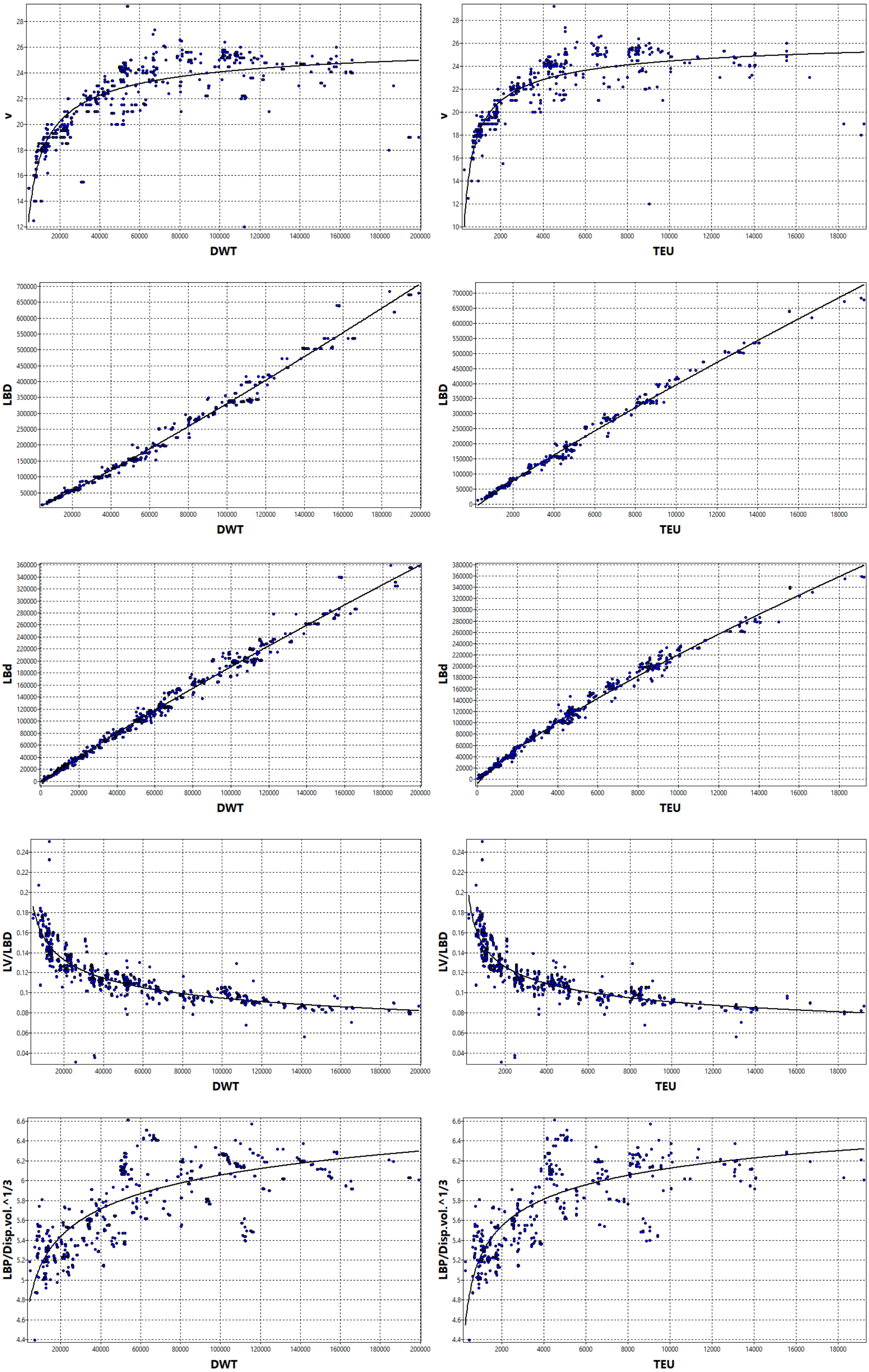

Fig. 4. Velocity v, LBD, LBd and LV/LBD and LBP/Disp.vol$^{1/3}$ product as a function of deadweight DWT or TEU capacity.

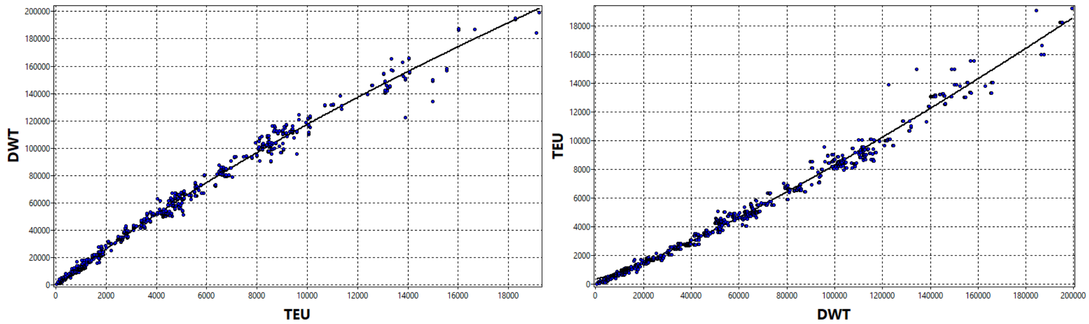

Fig. 5. Deadweight DWT against TEU capacity

SUMMARY

A new method to uncover the most suitable regression equations on the basis of evolution theory method was developed in this paper. This method uses heuristic techniques for the discovery of regression equations. The best combinations of independent variables were randomly searched through all their possible combinations in this method. The proposed method proved be effective and improved the discovery of better models.

This method has been applied to regress key container ship characteristics at the preliminary design such as:

- length between perpendiculars,
- breadth,
- draught,
- depth,
- gross tonnage,
- final price,
- block and waterplane area coefficient,
- main engine total power,
- light vessel mass,
- displacement mass,
- velocity,

and their combinations.

These design parameters have each been regressed against deadweight, the number of containers and combinations and several independent variables simultaneously, such as block coefficient or Froude number.

Generally, the accuracy of the equations presented here when using a container number variable is higher than equations only dependent on a deadweight variable.

The accuracy of all equations with many variables, is higher than equations only dependent on one deadweight or the container number variable.

The design formula accuracy for the estimation of the block and waterplane area coefficient, is low and these formulas do not have practical application. A comparison of block coefficient design formulas presented by Kristensen in 2013 indicated that the presented formulas give similar errors.

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Date of submission of the article to the Editor: 05/2018
Date of acceptance of the article by the Editor: 07/2018