Upgrading weight prediction in small craft concept design

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ABSTRACT: The method for lightship weight prediction of small craft, developed in previous work, is upgraded after additional data for several aluminum and FRP hulls become available. Practical parametric equations for weight prediction are developed from the database, while the quality of these equations for lightship weight estimate is tested by the vessels from the second database (containing craft with only lightship weight known). In this way the confidence in lightship weight prediction is much higher. The standard deviation obtained for the lightship estimate is 6,6 % and 10,3 % for the FRP and aluminum hulls, respectively. Additional data for the deckhouse weight estimate are provided, since in many cases they are made of different materials form the hull structure and sometimes are even physically separated by resilient foundations. Additional effort was made in order to improve hull structural weight prediction. A midships section was approximated and average scantlings determined in order to find unit weight amidships. A longitudinal structural weight distribution function appropriate for small fast craft was devised in order to predict the major part of the structural weight. Parametric equations for other component weights are adapted based on the previous work published.

1 INTRODUCTION

Ship weight estimating methods are the principal tools of the profession since the introduction of Archimedes' law in practical ship design. The iterative nature of ship design makes detailed calculations at the concept design stage impractical, since design is not yet defined in enough detail to find individual weights.

In classical works on design in naval architecture: Watson (1998), Schneekluth (1998) and Parsons (2003), presented a number of methods developed through the history of profession, intended for the weight prediction of large steel ships, both commercial and naval. Not much attention was paid to the small craft although they are different from large vessels in many aspects, relative speed, hull form, structural material, propulsion, to mention the most important. Here "small craft" is defined as: vessels of up to approximately 60 m length (Figure 1), made of different structural materials, for different services at sea and relatively fast as defined by IMO HSC.

Additional possibilities of improving reliability of weight prediction are discussed.

2 DATABASES

Much of the work has gone into collecting and checking of the fast small craft data, including weight data, to be used as a basis for structuring weight prediction method. Initial data were collected when study of the Maritime administration vessels was made, (Grubisic et al. 1999). Later new data were added to the original database as they become available. Since the database is collected from different sources, the reliability is not always satisfactory so the data must be checked and rechecked before accepted or rejected for further use. Finally, two groups of vessels in two databases are prepared, as summarized in Table 1:

- The first group consists of the vessels for which weight subdivision is available (DB1).
- The second group consists of the vessels for which only lightship weight is known (DB2).

Table 1. Vessels in the DB1 and DB2 by hull material

material	hull structural mat.	Nº craft in DB1	Nº craft in DB2
AL	aluminum	12	75
FRP	fiber reinforced plastic	20	41
HTS	high tensile steel	13	3
MS	mild steel	7	21
WLAM	laminated wood	0	3
	TOTAL	52	143

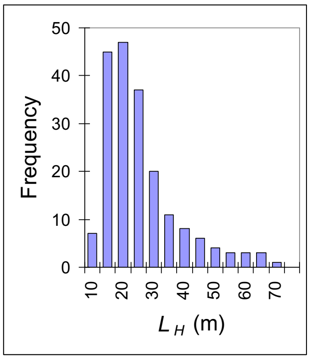

Figure 1. Histogram of hull lengths in DB1 and DB2

The databases are structured in EXCEL work sheet containing all basic ship design data. The idea behind this division is to be able to develop procedure using DB1, and after that, to test the procedure using DB2. Since there are no vessels from the DB1 included in DB2, it is expected that this test is very realistic.

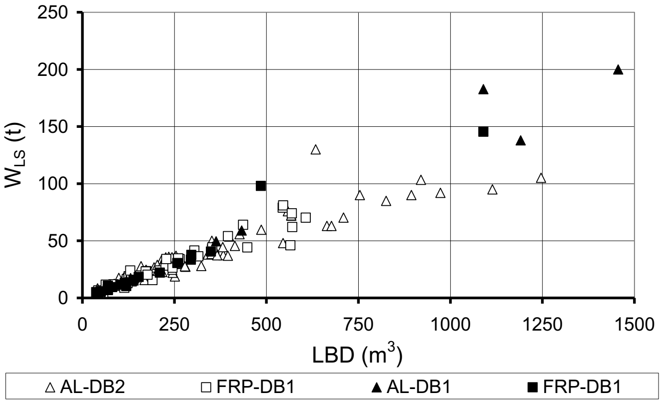

Figure 2. Lightship weight of vessels in DB1 and DB2

Hull lengths and lightship weights of the vessels in DB1 and DB2 are presented in Figure 1 and Figure 2, respectively.

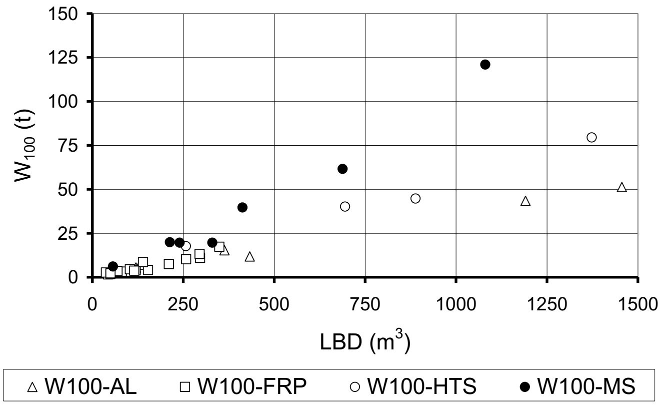

Figure 3. Structural weight of the DB1 vessels

The structural weights (W_{100}) for different hull structural materials are shown in Figure 3.

3 WEIGHT BREAKDOWN

3.1 *Grouping of weights*

Group weight data stored in the DB1 is quite variable regarding the applied system of weight breakdown, different origin, different practices, different countries, different rules and different time. Sometimes partial reverse engineering was necessary in order to group weights consistently. Obviously, here is the potential for introducing error but every precaution was taken to minimize it.

3.2 *Basic weight subdivision*

A common weight breakdown had to be introduced. The system is based on the USN SWBS since it is widely used and adaptable to different types of vessels.

$$W_{FL} = W_{LS} + W_{DWT} \tag{1}$$

$$W_{LS} = W_{100} + W_{200} + W_{300} + W_{400} + W_{500} + W_{600} + W_{700} \tag{2}$$

$$W_{DWT} = W_{PL} + W_{FO} + W_{FW} + W_{CR} \tag{3}$$

3.3 *Weight distribution curve*

Weight distribution curve for displacement type ships was traditionally calculated from the "coffin" diagram adapted to the ship block coefficient as presented in (Watson 1998 and Schneekluth 1998). Fast small craft are in most cases very different in way of the longitudinal distribution of the cross section unit weight.

In order to provide useful guidance for the designer, the weight distribution of a 40 ft aluminum fast boat (presented in Figure 4) is calculated and approximated by a simple cubic parabola giving unit weight for a section at given longitudinal location, as a percentage of the weight of maximal section.

$$\mathrm{w}_x = \frac{\left[\left(5,3476 - x\right)\cdot x + 66,02\right]\cdot x + 4739}{51,2}\ \% \tag{4}$$

In equation (4) the value of x corresponds to the no dimensional number of the station (i.e. stations 1 to 20). Given dimensional abscissa x_S, the abscissa in terms of 20 sections is calculated from (5)

$$x = 20 \cdot \frac{x_S}{L_H} \tag{5}$$

Majority of fast craft will demonstrate similar distribution, since their block coefficients (up to the deck level) are not very variable. Therefore, it is reasonable proposition to use presented curve for all fast craft with transom stern.

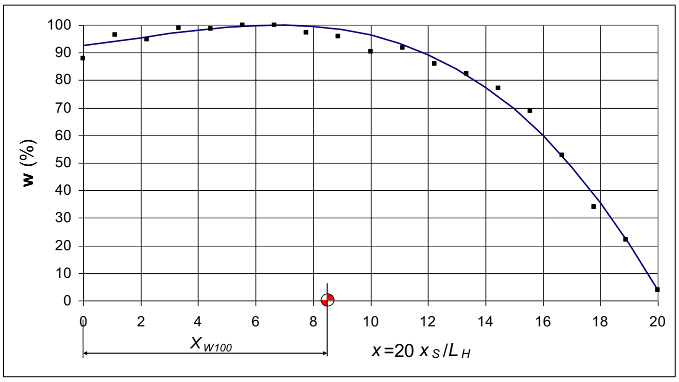

Figure 4. Weight distribution curve for transom stern hull

Total structural weight is defined as an integral of the weight distribution curve, where w_X is unit weight at the maximal section.

$$\frac{W_{100}}{L_H \cdot w_X} = 0,8031 \tag{6}$$

Center of gravity of the structural weight is longitudinally located at 7,58 % of L_H behind amidships, or 42,42% L_H, forward of the transom, which would fit majority of fast craft.

$$\frac{X_{W_{100}}}{L_H} = 0,4242 \tag{7}$$

Corrections must be added to the weight prediction from the distribution curve, in order to account for transverse bulkheads, tanks, foundations, stern frame and additional local structure.

3.4 *Midship section*

Maximal section weight may be calculated from the structural data based on the simple midship section that is easily programmed in EXCEL.

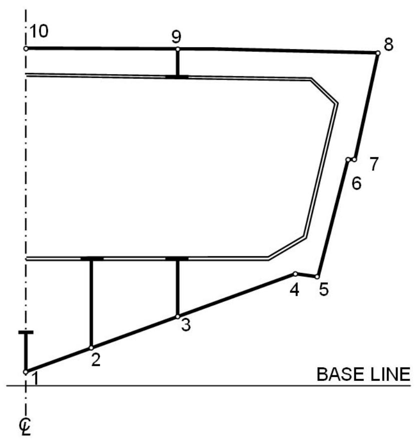

Figure 5. Typical midship section

Alternatively, an approximation of the cross structure amidships may be defined from the relations based on Figure 6. The same relations may be used several times if sectional area curve, deck, chine and bottom curves are defined.

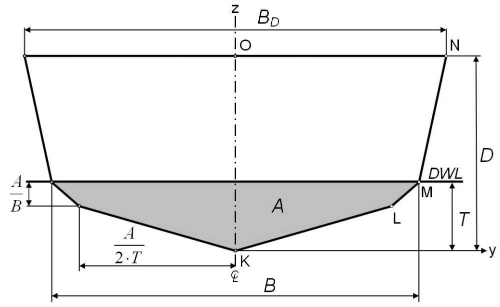

Figure 6. Approximation of the midship section

Girth of the cross section is determined from the summation of the following relations:

$$G = 2 \cdot \left(\overline{KL} + \overline{LM} + \overline{MN} + \overline{NO} \right) \tag{8}$$

$$\overline{KL} = \sqrt{\left(\frac{A}{2 \cdot T}\right)^2 + \left(T - \frac{A}{B}\right)^2} \tag{9}$$

$$\overline{LM} = \sqrt{\left(\frac{A}{B}\right)^2 + \left(\frac{B}{2} - \frac{A}{2 \cdot T}\right)^2} \tag{10}$$

$$\overline{MN} = \sqrt{\left(D - T\right)^2 + 0,25 \cdot \left(B_D - B\right)^2} \tag{11}$$

$$\overline{NO} = 0,5 \cdot B_D \tag{12}$$

Effective thickness is assumed constant for the complete girth G. Structural weight as calculated from construction drawings (i.e. exact thickness and no welding) should be increased to account for the additional weights that will be included into completed vessel. Suggestion by (Straubinger et al., 1998) may be used as a base (Table 2).

Table 2. Compensation for structural weight (metal hulls)

Element	Bottom & Side plating	Deck & Bulkhead plating
Welding	1,5%	1,5%
Mill Tolerance	2,0%	2,0%
Inserts, Doublers, Local Stiffening	1,5%	3,0%
Total Additional Weight	5,0%	6,5%

For composite craft additional weight is heavily dependent on technology and weight control procedures applied and therefore much more variable than for metal structures.

Table 3. Compensation for structural weight (composite hulls)

Element	Bottom & Side plating	Deck & Bulkhead plating
Overlapping of layers	6,0%	6,0%
Filler & Putty & Bonding	1,0%	1,0%
Fairing & Filleting & Core Soakage	1,0%	2,0%
Inserts & Doublers & Local Stiff.	1,5%	3,0%
Metal Fastenings & Bolts	0,5%	0,5%
Total Addition to Respective Component Weight	10,0%	12,5%

It is assumed that weight calculation will include matrix, fiber reinforcements, core (foam, balsa, and honeycomb), gel and top coats and nonstructural foam for stiffeners. Additions to weight of FRP hull may be estimated from Table3.

3.5 *Deckhouse weight*

Deckhouses and superstructures on small craft are extremely variable in design, form and material. Therefore exact calculation is not an option at the concept level.

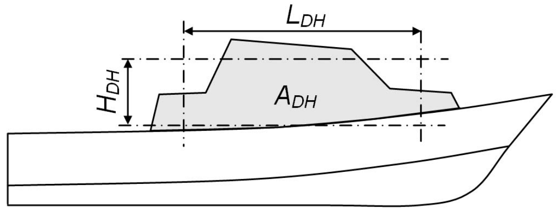

Figure 7. Averaging deckhouse dimensions

Lateral projected area is transformed by averaging longitudinal and vertical dimensions and replacing the area by a product of mean length L_{DH} and mean height H_{DH}, (Equation(13)).

$$A_{DH} \approx L_{DH} \cdot H_{DH} \tag{13}$$

Width of the deckhouse is averaged in similar manner to find B_{DH}. Volume (14) of the deckhouse is used as a basis for weight estimating (Table 4). Specific weight of deckhouse is given by equation(15).

$$V_{DH} \approx L_{DH} \cdot B_{DH} \cdot H_{DH} \tag{14}$$

$$q_{DH} = \frac{W_{DH}}{L_{DH} \cdot B_{DH} \cdot H_{DH}} \tag{15}$$

Table 4. Deckhouse volume and weight in small craft

VESSEL SERVICE TYPE	DECKHOUSE MATERIAL	V_{DH} m³	W_{DH} t	q_{DH} kg/m³
FISH-heavy	Steel	42,0	3,15	76,0
FISH-light	Steel	19,7	1,26	64,0
PAX-light	Steel	16,1	0,93	57,3
PATROL	Aluminum	182,0	4,19	23,0
MY	Aluminum	139,0	3,18	22,9
PATROL	FRP	81,7	1,77	21,7

Weight of the deckhouse may be now estimated via equation (16) using appropriate material dependent specific weight from Table 4.

$$W_{150} = W_{DH} = q_{DH} \cdot L_{DH} \cdot B_{DH} \cdot H_{DH} \tag{16}$$

It is assumed that the weight of window cutouts are compensated by a weight of glass (or other material) and window frame. This may be questioned for some modern light materials but it is taken as a working proposal. Weight of aluminum deckhouse is close to the weight of similar FRP deckhouse, as shown in Table 4. although, FRP will probably save some weight of insulation. The weight advantage of aluminum and FRP over steel is obvious.

4 STRUCTURAL WEIGHT MODEL

4.1 *Developing the numeral*

Weight of the hull structure is based on estimating plating area of the four major components, i.e. bottom, sides, deck and bulkheads. This approach was developed by Grubisic and Begovic (2003) and applied to small fast craft. Four principal surface areas are estimated as:

Bottom: $$S_1 = 2,825 \cdot \sqrt{\Delta_{FL} \cdot L_P} \tag{17}$$

Sides: $$S_2 = 1.09 \cdot \left(2 \cdot L_{OA} + B_M\right) \cdot \left(D_X - T_X\right) \tag{18}$$

Deck: $$S_3 = 0,823 \cdot \left(\frac{L_{OA} + L_{WL}}{2}\right) \cdot B_M \tag{19}$$

Bulkheads: $$S_4 = 0.6 \cdot N_{WTB} \cdot B_M \cdot D_X \tag{20}$$

Since specific weight of each area is different, a reduced surface area is predicted by taking into account the different loading of the respective parts of complete area:

$$S_R = S_1 + 0,73 \cdot S_2 + 0,69 \cdot S_3 + 0,65 \cdot S_4 \tag{21}$$

A correction factor for the effect of full load displacement is developed from the Lloyds' Register standard displacement (Equation (22)).

The correction factor is given by the equation(23)

. $$\Delta_{LR} = 0,125 \cdot \left(L_{LR}^2 - 15,8\right) \text{ t} \tag{22}$$

$$f_{DIS} = 0,7 + 2,4 \cdot \frac{\nabla}{L_{WL}^2 - 15.8} \tag{23}$$

Correction factor for the T/D ratio defined by the equation (24).

$$C_{T/D} = 1.144 \cdot \left(T_X / D_X\right)^{0.244} \tag{24}$$

Effective surface area (used as a numeral) is estimated from the reduced surface area S_R corrected for displacement and *T/D*, respectively. Finally the new structural numeral is given by equation (25).

$$E_S = f_{DIS} \cdot C_{T/H} \cdot S_R \quad \text{m}^2 \tag{25}$$

By the analogy to the method of (Watson 1998), exponential curve fits data well and the exponent was found to differ by a small amount, i.e. 1,33 instead of the original 1,36. Therefore, structural weight will be found from the relation (26):

$$W_{100} = K \cdot E_S^{1,33} \tag{26}$$

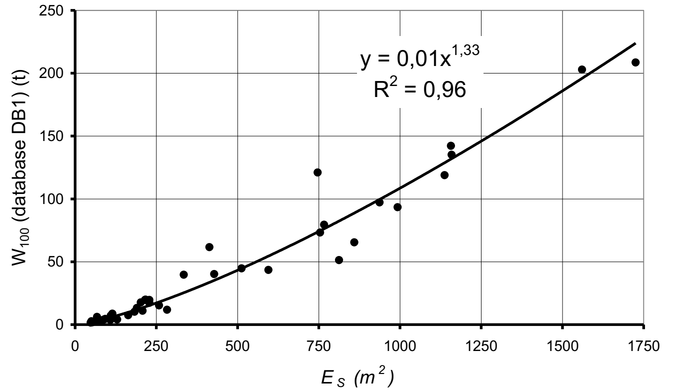

Figure 8. Structural weight (DB1) - relation to the numeral

4.2 *Influence of service type and area*

In the previous work (Grubisic 2008) it was attempted to find the influence of the vessel service and navigating area to hull structural weight from the vessel data directly. Now a better relation to the service type notation (Table 5) and service area notation (Table 6) factors, as given in the (LR SSC 1994) rules, is found advantageous.

Table 5. Service type notation factor, LR SSC

Service type	G_f
CARGO	1,00
PASSENGER	1,00
YACHT	1,10
PATROL	1,20
PILOT	1,25
WORKBOAT	1,25

Table 6. Service area notation factor, LR SSC

Service area notation	Range to refuge NM	Minimal wave height $H_{1/3}$ m	S_f
G1	sheltered waters	0,6	0,60
G2	20	1,0	0,75
G3	150	2,0	0,85
G4	250	4,0	1,00
G5	>250	>4,0	1,20
G6	unrestricted service	>4,0	1,25

Structural weight constant, K (equation (27)), for the aluminum and FRP hull structures, is related to the product of the service factors from (Table 5 and Table 6), as shown in (Figure 9).

Equations (28) and (29) yield constant K, for the respective hull materials, entering equation (26).

$$K = \frac{W_{100}}{E_S^{1,33}} \tag{27}$$

$$K_{AL} = 0,002 + 0,0064 \cdot G_f \cdot S_f \tag{28}$$

$$K_{FRP} = 0,0135 \cdot G_f \cdot S_f - 0,0034 \tag{29}$$

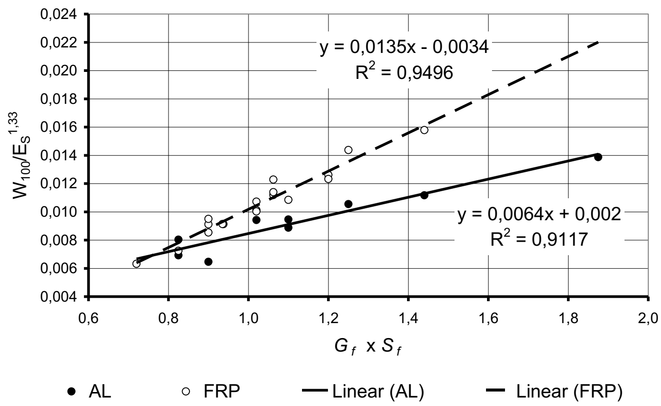

Figure 9. Structural weight - relation to service type and area

The procedure applied to the database vessels reproduced original data with relatively high level of confidence as shown in Figures 10, 11, 12 and 13).

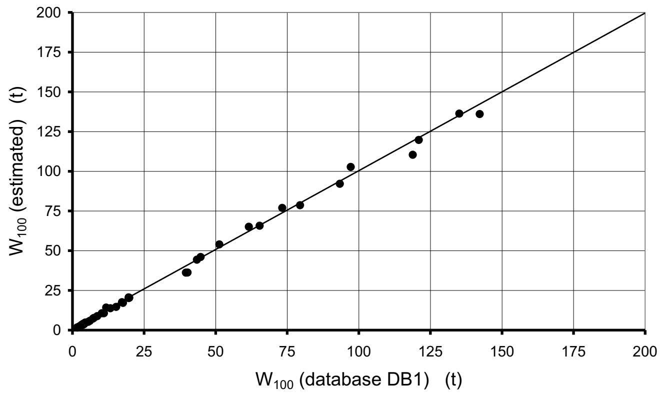

Figure 10. Estimate of the DB1 structural weight

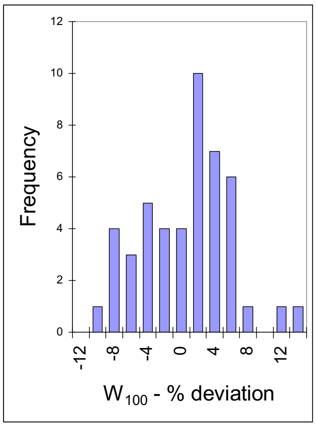

Figure 11. Deviation of the DB1 structural weight estimate

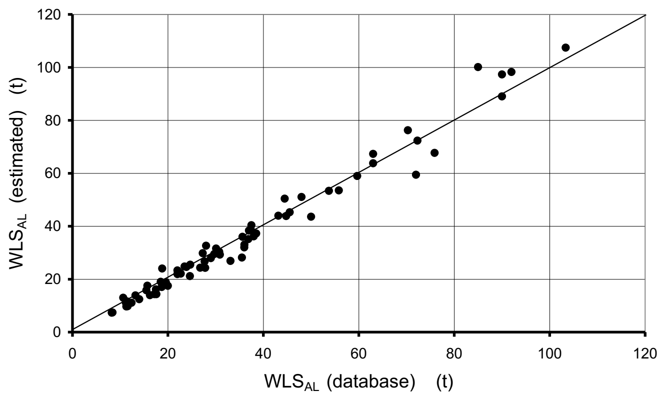

Figure 12. Reproduction of DB2 lightship for aluminum hulls

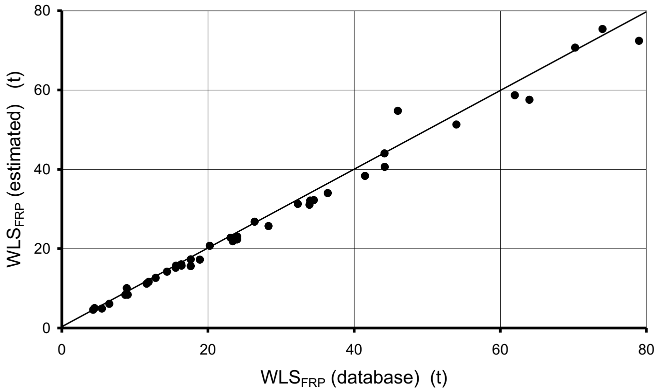

Figure 13. Reproduction of DB2 lightship for FRP hulls

Table 7. Structural weight estimate statistics

W_{100} STATISTICS	All materials in DB1
Mean	-0,178 %
Standard Error	0,853 %
Standard Deviation	5,85 %
Sample Variance	34,19 %
Count	47
Confidence Level(95,0%)	1,72 %

5 PROPULSION WEIGHT MODEL

Propulsion weight is closely related to the propulsion power but general size of the vessel also has some influence. Watson (1998) proposed that engine weight should be separated and the rest of the engine room weight estimated separately. In the small craft the propulsion systems are much more variable than is the case with big ships. Rating of the same engine (having practically the same weight) depends on the service type and a number of operating hours per year. Table 8. gives the guide on diesel engine selection suitable for small craft as proposed by CATERPILLAR.

Table 8. Propulsion engine ratings

Rating	% time at rated power	Service	Rated power time	min h/yr	max h/yr
A	100%	tugs trawlers	12 / 12 hours	5000	8000
B	85%	crew boats supply boats	10 / 12 hours	3000	5000
C	50%	ferries offshore service displ. yachts	6 / 12 hours	2000	4000
D	16%	fast ferry patrol craft naval vessels planing hulls	2 / 12 hours	1000	3000
E	8%	pleasure craft harbor craft pilot boats	30 min / 6 hours	250	1000

Weight of dry diesel engine should be increased to compensate for the liquids that are permanently present within the engine in service. The analysis of high performance diesel engines indicated an average ratio of wet to dry engine weight of 1,066.

$$\frac{W_{WET}}{W_{DRY}} \cong 1,066 \qquad (30)$$

Propulsor weight estimates were published in Grubisic and Begovic (2003). Weight of the average propeller, strut and shaft arrangement is estimated by.

$$W_{FPP} \cong 1,1 \cdot D_P^3 \cdot \frac{A_E}{A_0} \ \text{t} \qquad (31)$$

Weight of the SPP installation depends on different setups, equation (32) applies to LDU (Levi Drive Unit) as a representative.

$$W_{SPP} \cong \frac{P_S^{1,271}}{8375} \ \text{t} \qquad (32)$$

Total weight of the water jet includes entrained water since it is the added weight to be transported by the vessel.

$$W_{WJW} \cong \frac{P_S^{1,286}}{8771} \ \text{t} \qquad (33)$$

If the engines are not selected at this stage of design, it is possible to estimate weight of the propulsion group W_{200} from the analysis of database (Figure 14.).

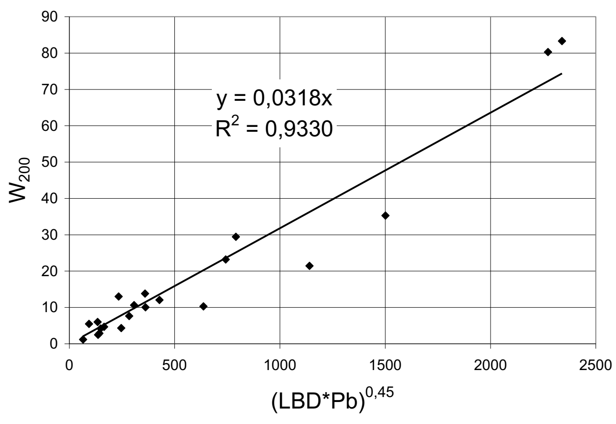

Figure 14. Propulsion machinery weight

Weight of propulsion engines, including gearboxes and fluids, is estimated by the equation (34), unless catalog weight is known.

$$W_{250} = \frac{\sum P_B}{286} \ \text{t} \qquad (34)$$

Remaining machinery weight is correlated to the vessel size (equation (35))

$$W_{200} - W_{250} = \frac{(L \cdot B \cdot D)^{0,94}}{45,66}$$
(35)

Alternatively, machinery weight is estimated as:

$$W_{200} = 1,6 \cdot W_{250} \quad (36)$$

6 REMAINING LIGHTSHIP WEIGHTS

All remaining weights (i.e. groups 300...700) are taken from (Grubisic 2008) with minor rearrangements.

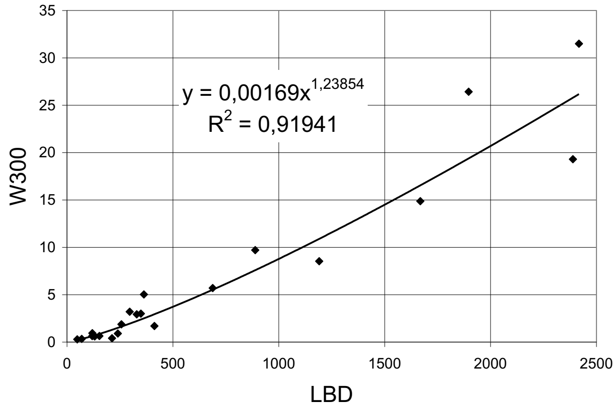

Figure 15. Electrical machinery weight -LBD

$$W_{300} = \frac{(L \cdot B \cdot D)^{1,24}}{592} \quad \text{t} \quad (37)$$

Electronic equipment rate of change is probably the highest in engineering practice. Database provided limited information. The relation (equation (38)) from (Grubisic 2008) was retained (Figure 16).

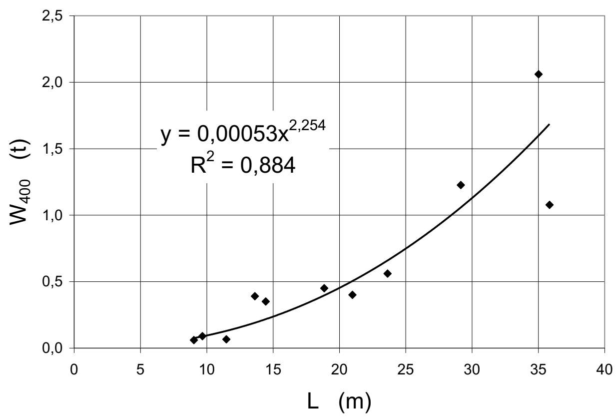

Figure 16. Electronic equipment weight

$$W_{400} = \frac{L^{2,254}}{1887} \quad \text{t}$$
(38)

Auxiliary machinery systems are correlated with ship size and type but it is difficult to account for the variability of owners requirements. The relation (equation (39)) from (Grubisic 2008) was retained (Figure 17).

$$W_{500} = \frac{(L \cdot B)^{1,784}}{1295} \quad \text{t} \quad (39)$$

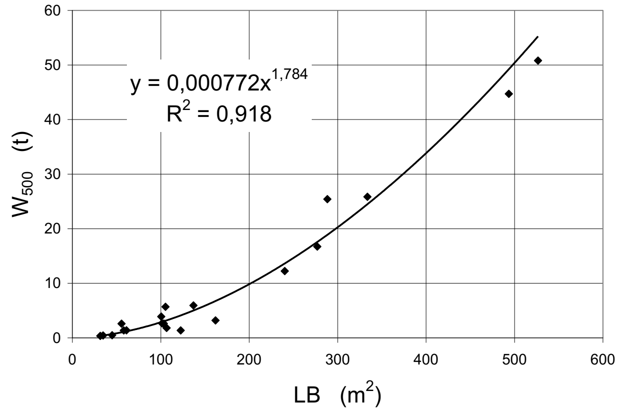

Figure 17. Auxiliary machinery weight

Weight of outfit is highly dependent on the equipment standard of the vessel. The relation from (Grubisic 2008) (equation (40)) was retained as shown in Figure 18.

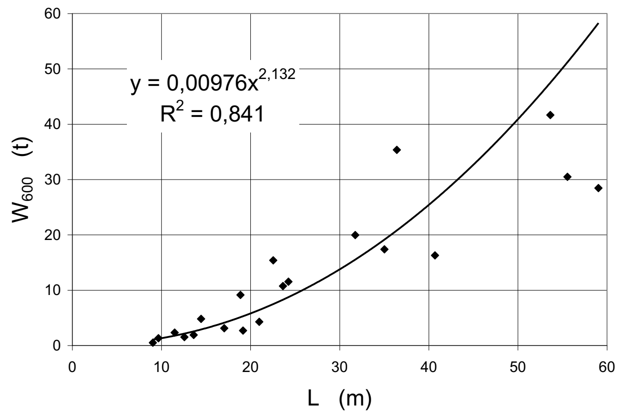

Figure 18. Outfit weight

$$W_{600} = \frac{L^{2,132}}{102,5} \quad \text{t} \quad (40)$$

Weight of special systems was originally meant to relate to the armament only, but here we consider that W_{700} means all weight that is specific to the ship main purpose, i.e. passenger equipment for ferries, research equipment for research ships, etc.

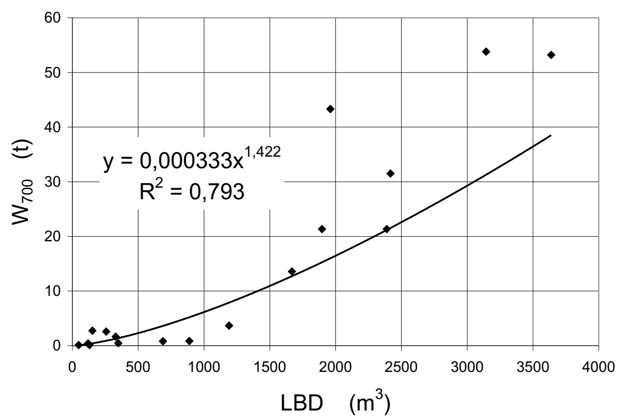

Figure 19. Special systems weight

$$W_{700} = \frac{\left(L \cdot B \cdot D\right)^{1,422}}{3000} \text{ t} \quad (41)$$

In principle this group is not meant to cover the equipment that is found on every type of vessel, only the specific weight for the purpose of vessel function. The relation (equation (41)) from (Grubisic 2008) was retained as shown in Figure 19.

7 TEST OF THE UPGRADED METHOD

As before (Grubisic, 2008), the method was tested using only vessels from the database DB2. Equation (2) is rewritten as:

$$\begin{aligned} W_{LS} &= W_{100} + W_{150} + W_{200} + W_{250} + \\ &+ W_{300} + W_{400} + W_{500} + W_{600} + W_{700} \end{aligned} \quad (42)$$

When this predicted lightship weight is subtracted from the recorded lightship weight of the database vessels (DB2), the percentage of the remaining unexplained weights (positive and negative) are distributed as shown in Figure 22. while Table 9 contains the statistics of the prediction.

Table 9. Statistics of the lightship weight prediction for the aluminum and for the FRP structure, respectively

W_{LS} STATISTICS	Al structure	FRP structure
Mean	-2,10%	-3,12%
Standard Error	1,23%	1,00%
Standard Deviation	10,31%	6,43%
Sample Variance	106,26%	41,34%
Count	70	41
Confidence Level(95,0%)	2,46%	2,03%

The lightship weight prediction by the upgraded method gives predictions with standard deviation of 10,31% and 6,43% for the aluminum and fiber reinforced composite construction, respectively (Table 9).

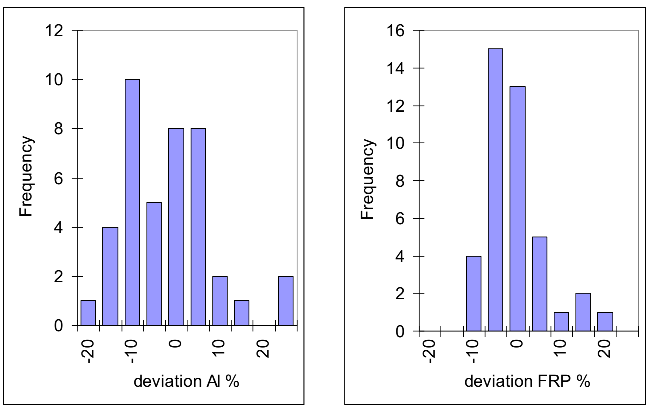

Figure 22. Unexplained lightship weights (%) distribution, for aluminum and FRP hulls

To be on the safe side, designer will usually add margin that amounts to one standard deviation (Grubisic 2008).

8 CONCLUSIONS

After upgrading, the proposed method of lightship weight prediction gives much better results, for aluminum and FRP hull structures.

Standard deviation of the prediction improved from about 13% (Grubisic 2008) to about 10%. Aluminum vessels prediction obtained standard deviation of 10,31% and for the FRP vessels standard deviation obtained is as low as 6,64%.

The method of "weight per unit length" is easy to apply to fast craft after taking care of structural characteristics of the material.

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