RELIABILITY OF WEIGHT PREDICTION IN THE SMALL CRAFT CONCEPT DESIGN

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SUMMARY

Weight prediction is an important part of naval architect's work. Reliability of weight prediction in the concept phase of small craft design is scrutinized in order to aid designers in selecting appropriate margins. Two databases are formed, one consisting of 34 vessels for which a detailed weight breakdown is available and the other consisting of 143 vessels where only lightship weight is known. Included are small craft of variable service type, hull structural material and propulsion devices. Different approaches to weight estimating ere attempted and compared to the database. Structural and nonstructural weight is analyzed separately according to the first level weight breakdown. A practical weight prediction method is developed which is specialized for small fast craft. Parametric equations for predicting weight of each group will be useful not only in concept design but also in cost estimate. Statistical analysis of the unexplained weight difference gives standard deviation of about 13%.

1. INTRODUCTION

1.1. BACKGROUND

Ship weight estimating methods are the principal tools of the profession since the introduction of Archimedes' law in practical ship design. Archimedes lived from 298 BC to 212 BC, but his law was used for ship design purposes almost 2000 years later by Pierre Bouguer in "Traité de navire", (1746) and by Fredrik Henrik af Chapman in his "Architectura Navalis Mercatoria" (1775).

In principle everything is simple with weight estimating. A sum is made of the individual weights of all elements that go into the ship. The problem is that 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.

For the concept design phase of ship design a "numeral" approach is usually the most utilized. It is supposed that weight of the ship is proportional to the numeral. The numeral itself is composed of readily available principal dimensions and coefficients.

At this level usually a simple weight breakdown is necessary. Many systems of weight breakdown were developed and almost every designer has his/her own favorite system. This makes it difficult to compile and compare weight data based on different and not always published systems.

1.2. SCOPE OF VESSELS

In a well known classical works on design in naval architecture: Watson (1998), Schneekluth (1998), Parsons (200), presented is a number of methods developed for the weight prediction of the large steel ships, both commercial and naval.

In present work special attention will be given to small craft which 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 overall, made of different structural materials, for different services at sea and relatively fast as defined by a IMO HSC code.

A database of small vessels was compiled through several years. Unfortunately weight data are not often published, therefore, a personal contacts with designers and shipyards are necessary in order to collect enough data. Some of the data are given in confidence and it would be appropriate here to acknowledge this contribution.

Reliability of the data is tested by comparison with other vessels. Obviously, it is not possible to guarantee 100% correct data, but every effort is made to eliminate error and to homogenize the sample. Sometimes data had to be sacrificed and eliminated from the sample because they are evidently erroneous and far away from trends.

1.3. DEFINITION OF FAST VESSEL

According to the HSC (art.1.4.24) the maximum sustained speed of the fast vessel should be over the speed defined by (1).

$$v > 3,7 \cdot \nabla^{0,1667} \text{ m/s} \tag{1}$$

where, ∇ is maximal operating displacement volume in m^3. On the other hand a minimal speed of the planning hull, that is completely dynamically supported, is defined via volumetric Froude number of 3,5, i.e.

$$F_{N\nabla} = \frac{v}{\sqrt{g \cdot \nabla^{0,3333}}} = 3,5 \tag{2}$$

By evaluating the expression and inserting g=9,80665 m/s^2, the minimal speed of completely dynamically supported craft is:

$$V_{DYN} = 21,3 \cdot \nabla^{0,1667} \text{ kn} \tag{3}$$

as compared to the HSC defined speed of fast vessels:

$$V_{HSC} = 7,19 \cdot \nabla^{0,1667} \text{ kn} \tag{4}$$

Therefore, both, semi displacement and full planning hulls are included in the sample.

2. DATABASE

2.1. DATABASE STRUCTURE

Initial data were collected when study of the Maritime administration vessels was made by Grubisic et al. (1996). After completion of that work, new data were systematically gathered and added to the original database. Database is collected from different sources and sometimes the reliability is not as satisfactory as expected.

The database is structured in EXCEL work sheet containing all basic ship design data. Actually there are two groups of vessels:

- the first group (DB1) consists of vessels for which weight data subdivided into groups is available
- the second group (DB2) consists of the vessels for which only lightship weight is known.

The idea behind this division is to be able to develop procedure using the first database and after that to test the procedure using the second database.

2.2. DATABASE CONTENTS

Describing database in detail would use to much space, therefore only principal information are given here.

All data necessary for the weight analysis are not available from the original sources. Therefore, some of the data were synthesized by the application of the following approach:

- Scaling from the published general arrangement plans to find missing L_{WL} or D_X or T_X.
- If GT was available depth could be estimated as:
$$D_X \approx 10,29 \cdot \frac{GT}{(L_{OA} + L_{WL}) \cdot B_M} \tag{5}$$
- Often the maximal beam at waterline was missing. Regression provided the relation:
$$B_X \approx 0,897 \cdot B_M \tag{6}$$
- Synthesizing lightship weight by subtracting all variable weights (as published) from the full load displacement.
$$W_{LS} = W_{FL} - (W_{PL} + W_{FO} + W_{FW} + W_{CR}) \tag{7}$$
where,
$$W_{CR} = 0,125 \cdot N_{CR} \tag{8}$$
The payload W_{FL} includes passengers and luggage with assumed weight of:
$$W_{PAX} = 0,105 \cdot N_{PAX}$$
Fuel density was assumed to be 860 kg/m^3

2.3. DATABASE DB1

The first database (DB1) consists of 34 vessels that are grouped by the service type as shown in Table 1:

Table 1. Vessels in the DB1 by type

N	service	service description
2	WORK	work boat
1	FIRE	fire vessel
12	MIL	military / naval
5	MY	motor yacht
8	PATROL	patrol / paramilitary
3	PAX	passenger & ferry
3	SAR	search & rescue

Grouping by hull structural material is shown in Table 2:

Table 2. Vessels in the DB1 by structural material

N	material	hull structural material
7	MS	mild steel
12	HTS	high tensile steel
7	FRP	fiber reinforced
8	AL	aluminum

Mean hull length of the sample, as defined by (24), is shown in Figure 1:

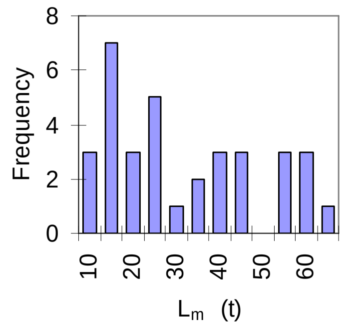

Figure 1. Database DB1 -vessel length distribution

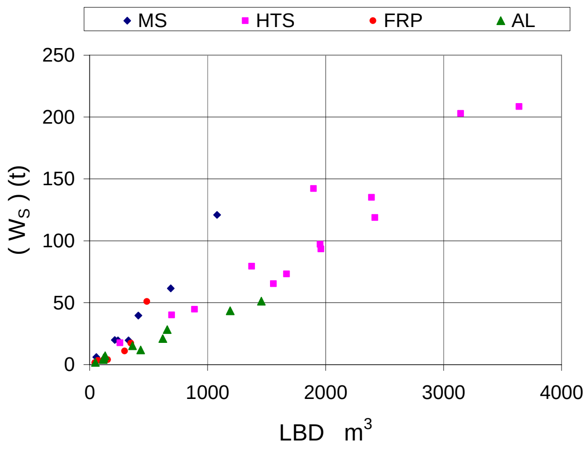

Figure 2. Structural weight of the DB1 vessels

In Figure 2 the structural weight of the vessels is shown grouped per hull material in relation to the cubic number.

2.4. DATABASE DB2

The second database (DB2) is much larger, since lightship weight data is easier to obtain, and it consists of 143 vessels. More service types are included than in the first database comprising the types in Table 3:

Table 3. Vessels in the DB2 by type

N	service	serv. description
2	CARGO	cargo transport
6	PAX	passenger & ferry
5	CREW	crew boat
3	FISH	fishing vessels
9	FIRE	fire vessel
1	MEDIC	medical service
4	MIL	military / naval
14	MY	motor yacht
56	PATROL	patrol/paramilitary
19	PILOT	pilot vessel
1	POLICE	police craft
3	RESEARCH	research vessel
12	SAR	search & rescue
8	WORK	work boat

Hull structural material is distributed as in Table 4:

Table 4. Vessels in the DB2 by type

N	material	hull structural mat.
21	MS	mild steel
3	HTS	high tensile steel
41	FRP	fiber reinforced
75	AL	aluminum
3	WLAM	laminated wood

Mean hull length of the sample is distributed as shown in Figure 3.

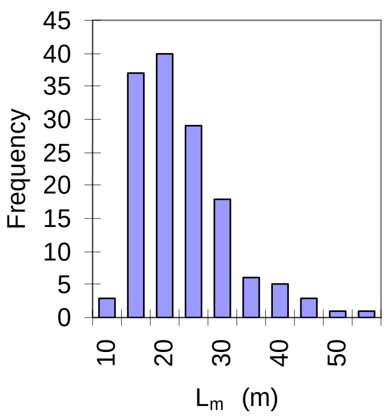

Figure 3. Histogram of length of the DB2 vessels

Spread of lightship weight of the vessels from DB2 is shown in Figure 4 related to the cubic number.

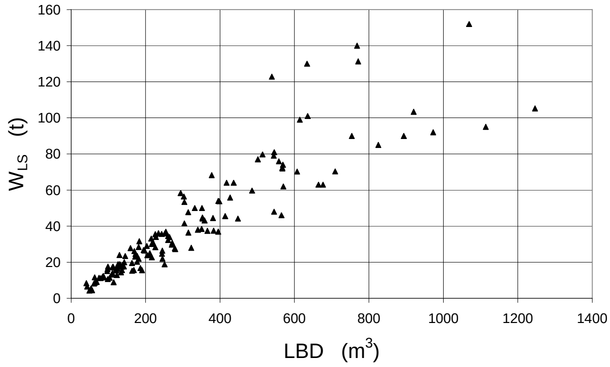

Figure 4. Lightship weight of the DB2 vessels

3. WEIGHT BREAKDOWN

3.1. FIRST LEVEL WEIGHT BREAKDOWN

Data collected and saved in the DB1 are quite variable regarding the applied system of weight breakdown, different origin, different practices, different countries, different rules, etc. Basically the system of grouping is shown in Figure 5.

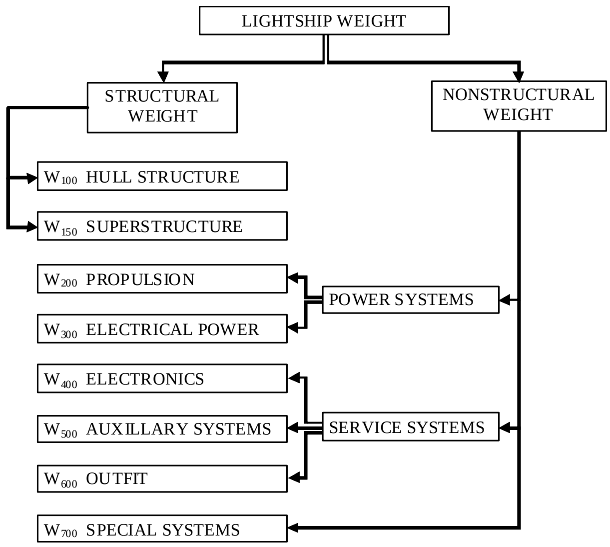

Figure 5. First level weight breakdown

Before proceeding with further analysis, a common weight breakdown had to be introduced.

Basically grouping is treated as if a USN SWBS system was applied to all vessels. If data did not provide enough information, redistribution of weight was necessary in order to group weight consistently.

Here is obviously a potential for introducing error but every precaution was taken to minimize it.

3.2. GROUPING OF WEIGHTS

Full load weight of the vessel is divided into lightship and deadweight (9).

$$W_{FL} = W_{LS} + W_{DWT} \tag{9}$$

Deadweight is composed of payload, fuel, water, crew and provisions (10)

$$W_{DWT} = W_{PL} + W_{FO} + W_{FW} + W_{CR} \tag{10}$$

Lightweight may be subdivided in many different ways but two major approaches are in general usage:

- A breakdown system according to the naval ship practice is given by (11).

$$W_{LS} = W_{100} + W_{200} + W_{300} + W_{400} + W_{500} + W_{600} + W_{700} \tag{11}$$

- A breakdown system common to the merchant ship practice is given by (12).

$$W_{LS} = W_S + W_M + W_O \tag{12}$$

4. WEIGHT PREDICTION BY NUMERALS

4.1. SELECTION OF NUMERALS

In the history of ship design a great number of weight prediction methods and appropriate numerals were developed. All of them rely on the small number of ship parameters that are available at the concept design level.

Selection of suitable numeral depends on correlation of the numeral and the weight concerned. Therefore, it is highly recommended that there should be some physical relation between the numeral and the weight (e.g. power and weight of engine). Selection of the most frequently used numerals is shown in sequel.

Hull weight:

$$W_S = k \cdot L \cdot B \cdot D \tag{13}$$

$$W_S = k \cdot L \cdot B \cdot D \cdot C_{BD} \tag{14}$$

$$W_S = k \cdot \left[L \cdot (B + D) \right]^n \tag{15}$$

$$W_S = \left(K_1 \cdot L \cdot \frac{L}{D} + K_2 \cdot D \right) \cdot L \cdot B \cdot C_B^{1/2} \tag{16}$$

Machinery weight:

$$W_M = k \cdot P^n \tag{17}$$

$$W_M = k \cdot (L \cdot P)^n \tag{18}$$

Outfit weight:

$$W_O = k \cdot L \cdot (B + D) \tag{19}$$

$$W_O = k \cdot (L \cdot B \cdot D)^n \tag{20}$$

$$W_O = k \cdot L \cdot B \tag{21}$$

Coefficients in the equations (13) – (21) are found from prototype vessel or by the regression analysis of number of similar vessels.

The similarity is here the most problematic element since the data for a homogenous group of vessels is not easily found. Therefore, the analysis must deal with vessels which are only partly similar (maybe here word "similar" should be replaced by "affine").

Additional difficulty comes from the vessels being built at different times when requirements, materials, practices and rules, were different from what is used today. All this influences the reliability of the weight prediction.

4.2. SELECTION OF PARAMETERS

At the concept design level only small number of parameters is known. They comprise: length, beam, depth, draft, block coefficient, displacement, installed power, etc. Due to the variability of hull forms it is necessary to somehow neutralize influence of unusual shapes on the weight prediction. Typically the length is suspect due to the variability of stem and stern shapes. The length to be used in the numerals may be taken as:

$$L = L_{PP} \tag{22}$$

$$L = 0,96 \cdot L_{WL} \tag{23}$$

$$L = \left(L_{OA} + L_{WL} \right) / 2 \tag{24}$$

$$L = \left(L_{OA} + 2 \cdot L_{WL} \right) / 3 \tag{25}$$

4.3. STRUCTURAL WEIGHT –WATSON

Structural weight estimating that produces reliable prediction in the merchant and in the naval ship design was introduced by Watson and Gilfillan (1976). Since the method was developed for the usage in "big" steel ship design, it should be tested when applied to the small craft.

The method is based on the early version of Lloyd's Register equipment numeral defined by (26).

$$E = L \cdot (B + T) + 0,85 \cdot L \cdot (D - T) + 0,85 \cdot \sum l_1 \cdot h_1 + 0,75 \cdot \sum l_2 \cdot h_2 \tag{26}$$

Watson and Gilfillan found that the structural weight data of steel ships in their database were best approximated by the exponential curve (27).

$$W_S = K \cdot E^{1,36} \tag{27}$$

Span of the coefficients and numerals for the small steel ships is given in the book by Watson (1998) of which an excerpt is given in Table 5:

Table 5. Coefficients and numerals - Watson's method

Type	*K*	*E*
Fishing vessels	0.041 – 0.042	250 – 1300
Coasters	0,028 – 0,032	1000 – 2000
Offshore supply	0,040 – 0,050	800 – 1300
Tugs	0,042 – 0,046	350 – 450
Fregates&Corvettes	0,023	

4.4. STRUCTURAL WEIGHT –KARAYANIS

By an approach based on Watson's method, Karayanis et al. (1999) proposed a weight prediction method suitable for fast ferries in the range of 40 - 120 m length. It is based on the numeral (28), that takes into account different specific weights of the underwater part of hull and above water part, but not superstructures and erections:

$$E_m = L\cdot(B+T)+0,85\cdot L\cdot(D-T) \quad (28)$$

Comparing database vessels it was established that an even older equipment numeral (29)

$$E_o = L\cdot(B+D) \quad (29)$$

is so highly correlated to the E_m numeral that it may replace it completely without loss of accuracy, Figure 6.

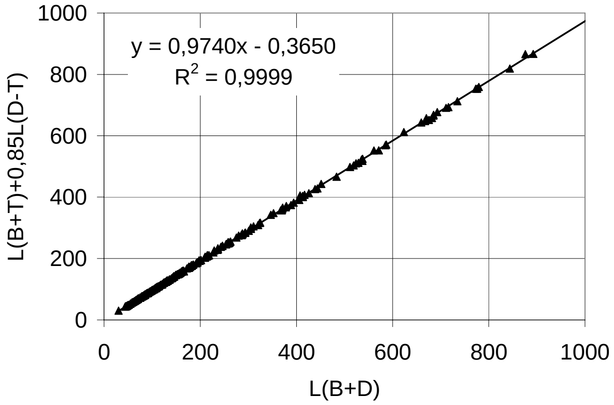

Figure 6. Correlation of numerals

Table 6. shows the results of the application of the Karayanis's procedure to the small fast craft from the database DB1.

Table 6. Coefficients and numerals - KARAYANIS'S method applied to the DB1 vessels

Hull material	K	E_m
Aluminum	0.0082 – 0.0169	47 – 523
FRP	0,0084 – 0,0169	44 – 176
Mild steel	0,0197 – 0,0283	57 – 407
HTS	0,0135 – 0,0213	140 – 988

The variability of the coefficients in Table 6. is somewhat high, therefore, for the high speed craft that are considered here, we need a new type of numeral that closer approximates structural surface areas and their respective relative specific weight.

5. SMALL CRAFT WEIGHT PREDICTION

5.1. PROPOSAL

Following the original idea of Watson and Gilfillan, i.e. that the prediction of structural weight is based on numeral representing structural surface area, new proposal is to use even closer approximation of the area that is possible by the statistical analysis of hull forms. The hull forms in databases of small vessels comprise only vessels with transom stern, therefore, surface approximation takes that as a starting point.

All other weights except the structural weight have to be predicted also. The idea is to find the most suitable numerals and to predict each of these weights by separate method. The sum of predicted weights should in theory equal the lightship weight. Since the variability of data, there will appear either positive or negative difference. The quality of weight prediction will be judged by the standard deviation of the residual weight (i.e. unexplained weight).
In sequel a systematic development of the prediction method is presented.

5.2. STRUCTURAL WEIGHT MODEL

Weight of the hull structure is based on estimating plating area of the four major components, i.e. bottom, sides, deck and bulkheads. Relative surface weights are estimated due to the differences in pressure loading of specific area. This approach was developed by Grubisic and Begovic (2003) and applied to small fast craft. Four principal surface areas were estimated by expressions (30) – (33).

Bottom: $S_1 = 2,825\cdot\sqrt{\Delta_{FL}\cdot L_P}$ (30)

Sides: $S_2 = 1.09\cdot(2\cdot L_{OA}+B_M)\cdot(D_X-T_X)$ (31)

Deck: $S_3 = 0,823\cdot\left(\dfrac{L_{OA}+L_{WL}}{2}\right)\cdot B_M$ (32)

Bulk.: $S_4 = 0.6\cdot N_{WTB}\cdot B_M\cdot D_X$ (33)

Since 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:

$$S_R = S_1 + 0,73\cdot S_2 + 0,69\cdot S_3 + 0,65\cdot S_4 \quad (34)$$

In order to make allowance for the influence of full load displacement a correction factor is applied. It is developed from the Lloyds' Register rules for fast craft where the standard displacement was defined as:

$$\Delta_{LR} = 0,125\cdot(L_{LR}^2-15,8)\ \mathrm{t} \quad (35)$$

Neglecting the 4% difference of the respective lengths, the displacement correction factor is determined by (36).

$$f_{DIS} = 0,7+2,4\cdot\frac{\nabla}{L_{WL}^2-15.8} \quad (36)$$

Correction for the influence of the T/D ratio is best described by:

$$C_{T/D} = 1.144\cdot(T_X/D_X)^{0.244} \quad (37)$$

When applied to the database vessels (DB1) both correction factors are estimated to be in the range from minimal to maximal values as shown in Table 7.

Table 7. Correction factors

Correction factor	f_{DIS}	$C_{T/D}$
minimal value	0,906	0,828
maximal value	1,274	1,042

Effective surface area is estimated from the reduced surface area S_R by correction for displacement and *T/D*, respectively. Finally the new structural numeral is given by (38).

$$E_S = f_{DIS} \cdot C_{T/H} \cdot S_R \quad \mathrm{m}^2 \tag{38}$$

By the analogy with the Watson's and Gilfillan's method the value of the exponent is found to be 1,33 as shown in Figure 7. This is surprisingly close to the original exponent of 1,36. The structural weight is now determined by the equation (39).

$$W_K = K_0 \cdot E_S^{1,33} \quad \mathrm{t} \tag{39}$$

where:

K_0=0,0112

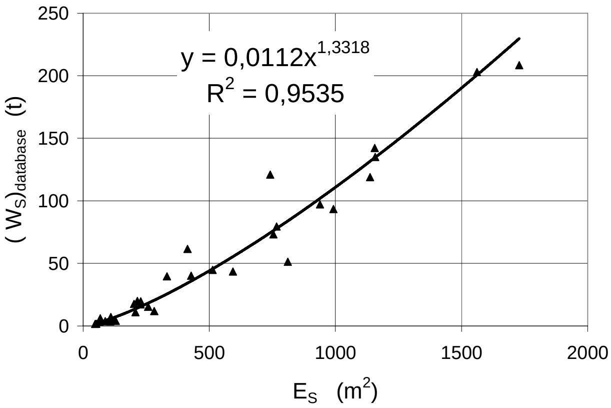

Figure 7. structural weight - relation to the numeral

The coefficient K_0 is subsequently replaced by the three factors taking care of the service area, service type and structural material influence as given by (40).

$$W_S = K_S \cdot f_{SAR} \cdot f_{SRV} \cdot f_{MAT} \cdot E_S^{1,33} \tag{40}$$

The remaining factor K_S describes each individual vessel and for general case is assumed to be unity. When prototype vessel is at hand the value of K_0 may be determined from that data.

Other factors in (40) are determined as follows:

Service area notation is related to the bottom pressure via design pressure factor. The bottom pressure is related to the weight of bottom structure. Table 8. is composed from the data given by the LR SSC rules (1996):

Table 8. LR SSC service areas definition

Service area notation	N_{LR}	Range to refuge NM	Min. wave height $H_{1/3}$ m	Design pressure factor
G1	1	sheltered waters	0,6	0,60
G2	2	20	1,0	0,75
G3	3	150	2,0	0,85
G4	4	250	4,0	1,00
G5	5	>250	>4,0	1,20
G6	6	unrestricted service	>4,0	1,25

The vessels in the database were of variable origin and not built at the same time neither according to the consistent set of rules. Therefore, a best estimate of the corresponding service area notation is made. The influence of service area is estimated by comparing complete hull weights of the database vessels to the LR service area notation. The best correlation is found as in equation (41).

$$f_{SAR} = 0,7202 + 0,0628 \cdot N_{LR} \tag{41}$$

Service type factors f_{SRV} determined from the database vessels are shown in Table 9.

Table 9. Service type correction factor

Service type	f_{SRV}
MIL	1,007
MY	1,013
PATROL	1,089
WORK	1,384
SAR	1,439

Hull material factors are determined by fitting data for the respective database craft grouped by hull material. The analysis of database produced tentatively the hull material factors in Table 10.

Table 10. structural material correction factor

Hull structural material	f_{MAT}
MILD STEEL	17,28
HTS	11,03
AL	7,86
FRP	11,36
FRPS	7,00
WLAM	9,00

Here it must be said that the separation of hull and superstructure material is not possible due to small number of data in each category. Therefore HTS hull, that is in all cases combined with the aluminum or FRP superstructure, reflects the combined effect of the two materials.

The procedure is applied to the database vessels and it reproduced original data with relatively high level of confidence as shown in Figure 8.

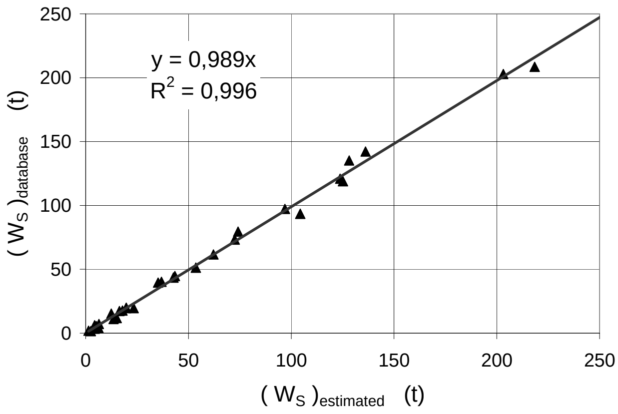

Figure 8. Reproduction of the DB1 structural weight

5.3. 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 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 11. gives the guide on diesel engine selection suitable for small craft as used by CATERPILLAR.

Table 11. 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	1/2 h / 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.

$$\frac{W_{WET}}{W_{DRY}} \cong 1,066 \qquad (42)$$

Propulsor weight estimates were published in Grubisic and Begovic (2003). Weight of the average propeller, strut and shaft arrangement is estimated by (42).

$$W_{FPP} \cong 1,1 \cdot D_P^3 \cdot \frac{A_E}{A_0} \quad \text{t} \qquad (43)$$

Weight of the SPP installation depends on different setups, equation (44) applies to LDU (Levi Drive Unit) as a representative.

$$W_{SPP} \cong \frac{P_S^{1,271}}{8375} \quad \text{t} \qquad (44)$$

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

$$W_{WJW} \cong \frac{P_S^{1,286}}{8771} \quad \text{t} \qquad (45)$$

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 9.).

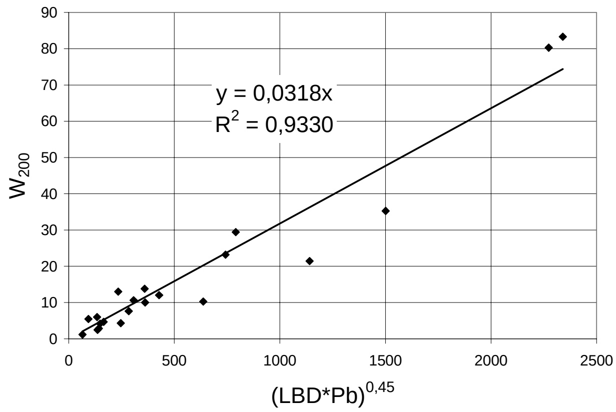

Figure 9. Propulsion machinery weight

$$W_{200} = \frac{\left(L \cdot B \cdot D \cdot \sum P_B\right)^{0,45}}{31,45} \quad \text{t} \qquad (46)$$

$$R^2 = 0,933$$

5.4. ELECTRICAL POWER WEIGHT MODEL

Sometimes the weight of the electrical power group is hidden within engine room weight where it is taken together with propulsion power.

Weight of the electrical power group is highly correlated to the cubic module irrespective of the ship type (Figure 10.).

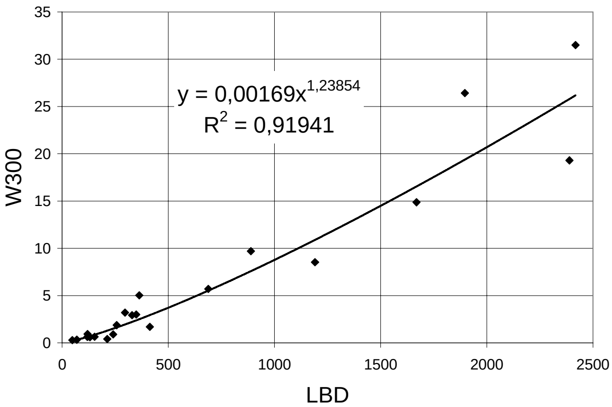

Figure 10. Electrical machinery weight -LBD

$$W_{300} = \frac{\left(L \cdot B \cdot D\right)^{1,24}}{592} \quad \text{t} \qquad (47)$$

$R^2 = 0,919$

If the generator power is known, weight may be found by the relation (48) as shown in Figure 11.

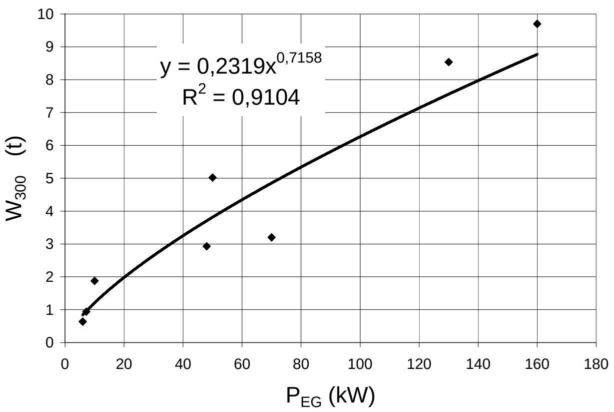

Figure 11. Electrical machinery weight -P_{EG}

$$W_{300} = 0,232 \cdot P_{EG}^{0,716} \quad \text{t} \qquad (48)$$

$R^2 = 0,910$

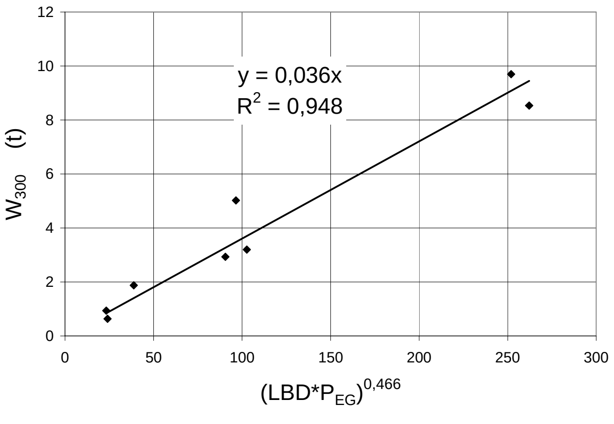

Figure 12. Electrical machinery weight –LBDxP_{EG}

Alternatively, (based on small number of data) electrical machinery weight that takes into account electrical power and size of the ship may be estimated by (49) as shown in Figure 12.

$$W_{300} = 0,036 \cdot \left(L \cdot B \cdot D \cdot \sum P_{EG}\right)^{0,466} \quad \text{t} \qquad (49)$$

$R^2 = 0,948$

5.5. ELECTRONIC EQUIPMENT WEIGHT MODEL

Electronic equipment is very variable and the rate of development is probably the highest in engineering practice. Besides it reflects the policy of the owner towards accepting new solutions. Database provided limited information (Figure 13. and 14.) that can be useful only at the very beginning:

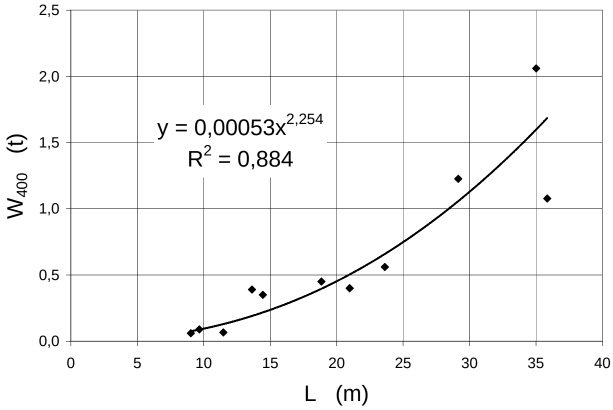

Figure 13. Electronic equipment weight

$$W_{400} = 0,00053 \cdot L^{2,254} \quad \text{t} \qquad (50)$$

$R^2 = 0,884$

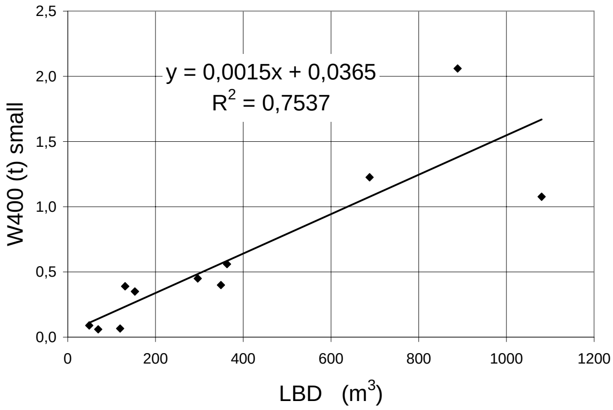

Figure 14. Electronic equipment weight –small vessels

$$W_{400} = 0,0365 + 0,0015 \cdot L \cdot B \cdot D \quad \text{t} \qquad (51)$$

$R^2 = 0,75$

5.6. AUXILIARY MACHINERY WEIGHT MODEL

Auxiliary machinery systems are correlated with ship size and type but it is very difficult to take into account variability of owners requirements. The best correlation was found as shown in (52) and Figure 15.

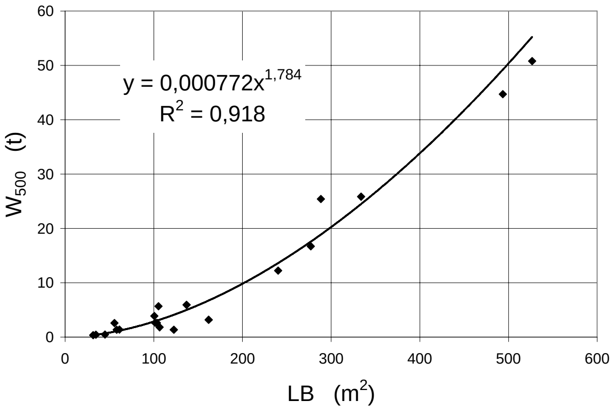

Figure 15. Auxiliary machinery weight

$$W_{500} = 0,000772 \cdot (L \cdot B)^{1,784} \ \text{t} \qquad (52)$$
$$R^2 = 0,918$$

5.7. OUTFIT WEIGHT MODEL

Weight of outfit is highly dependent on the equipment standard of the vessel. The best correlation was found relative to the length of the vessel (53) and Figure 16.

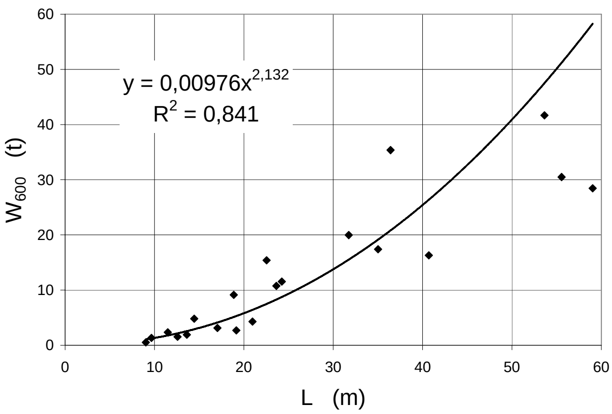

Figure 16. Outfit weight

$$W_{600} = 0,0097 \cdot L^{2,132} \ \text{t} \qquad (53)$$
$$R^2 = 0,841$$

5.8. SPECIAL SYSTEMS WEIGHT MODEL

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. 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 best correlation was found with ship length as shown in Figure 17.

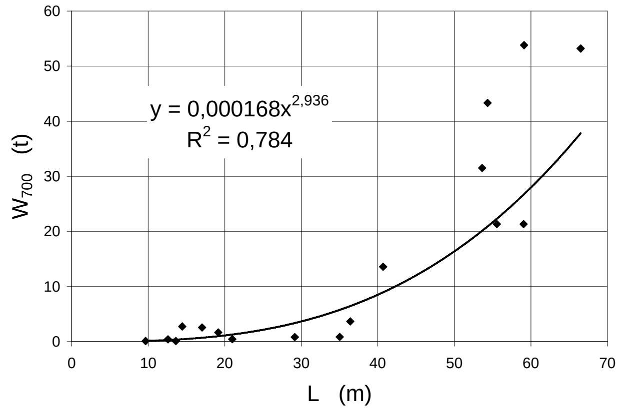

Figure 17. Special systems weight

$$W_{700} = 0,000168 \cdot L^{2,936} \ \text{t} \qquad (54)$$
$$R^2 = 0,784$$

Alternatively, the relation from Figure 18. may be used.

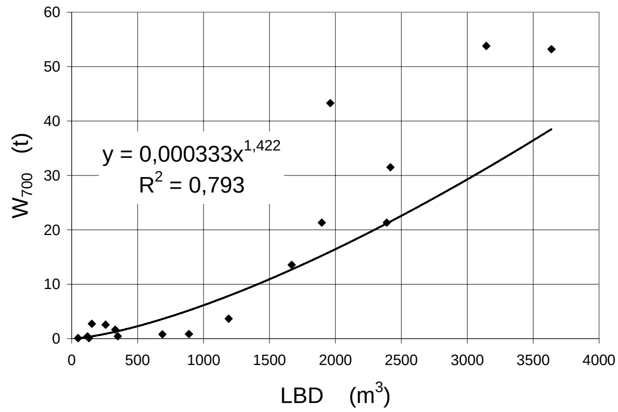

Figure 18. Alternative special systems weight

$$W_{700} = 0,000333 \cdot (L \cdot B \cdot D)^{1,422} \ \text{t} \qquad (55)$$
$$R^2 = 0,793$$

5.9. VARIABLE WEIGHTS MODEL

W_{800} comprises all variable weights including payload and all consumables.

Interestingly it was found that the lightship weight is highly correlated to the full load displacement (Figure 19.).

$$W_{FL} = 1,256 \cdot W_{LS} \ \text{t} \qquad (56)$$
$$R^2 = 0,995$$

Since the difference consists of the variable weight only, it means that the size of variable weight a fast small vessel can carry (i.e. payload, fuel, consumables etc.) may be pretty accurately estimated (57) or by (58) as soon as the full load displacement is decided upon.

$$W_{800} = 0,204 \cdot W_{FL} \quad \text{t} \tag{57}$$

$$W_{800} = 0,256 \cdot W_{LS} \quad \text{t} \tag{58}$$

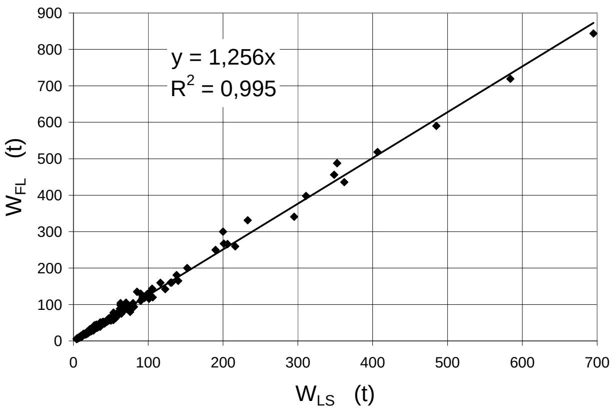

Figure 19. Variable weight

Alternatively the variable weight is related to the LB and LBD respectively, as shown in Figures 20. and 21.

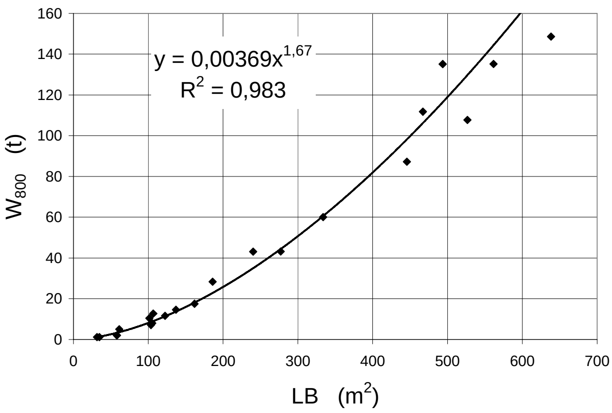

Figure 20. Alternative variable weight

$$W_{800} = 0,00369 \cdot (L \cdot B)^{1,67} \quad \text{t} \tag{59}$$

$$R^2 = 0,983$$

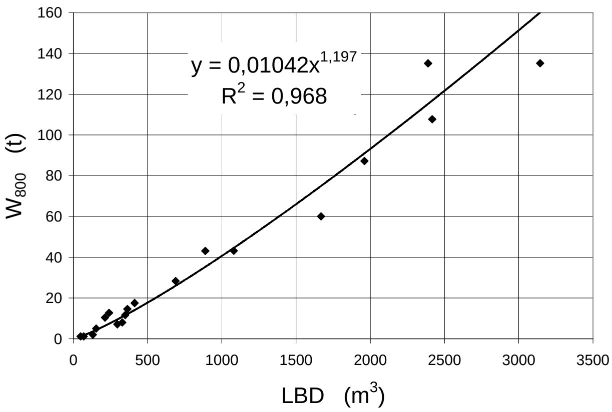

Figure 21. Alternative variable weight

$$W_{800} = 0,01042 \cdot (L \cdot B \cdot D)^{1,197} \quad \text{t} \tag{60}$$

$$R^2 = 0,968$$

5.10. TESTING THE METHOD

For the purpose of testing the method only vessels from the database DB2 are used. After summing up all weights as explained by the regression equations for individual groups there still remains the difference that could not be explained by the relations.

This remaining weight is examined and compared to several ship parameters. The best correlation was found with the full load displacement. Therefore this weight was treated as unknown weight. It can be added to some of the standard weight groups but it can also be treated separately:

$$W_U = 0,036 \cdot W_{FL} \quad \text{t} \tag{61}$$

Therefore, equation for prediction of lightship weight may be rewritten as:

$$\begin{aligned} W_{LS} &= W_{100} + W_{200} + W_{300} + W_{400} \\ &+ W_{500} + W_{600} + W_{700} + W_U \end{aligned} \tag{62}$$

When this predicted lightship weight is subtracted from the recorded lightship weight of the database vessels, the percentage of the remaining unexplained weights (positive and negative) are distributed as shown in Figure 22. while Table 12 contains the statistics of the prediction.

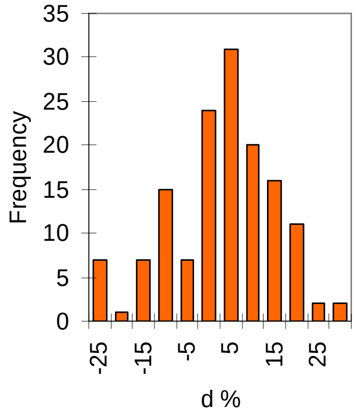

Figure 22. Unexplained weights (%) distribution

Table 12. statistics of the lightship weight prediction

Mean	0,285 %
Standard Error	1,105 %
Standard Deviation	13,22 %
Sample Variance	174,77 %
Confidence Level(95,0%)	2,185
Count	143

The weight prediction of the lightship weight by the proposed method gives predictions with the standard deviation of 13,22 %.

To be on the safe side designer will usually add reserve weight that amounts to one standard deviation. Margin policy will be treated in sequel.

6. WEIGHT MARGINS AND RELIABILITY

6.1. MARGINS

Weight estimating is not an exact procedure. Therefore a wise addition of a margin is necessary. There are several kinds of margins that apply and for different reasons:

- Margin to cover unreliable initial data
- Margin to compensate error of the weight prediction method
- Margin that covers expected but unintentional growth of weight in the future (applies to all ships)
- Margin that will be used in the future when upgrading some systems and when new generation of technology will become available (usually for naval craft)

The first two margins will change while the design is developed from the concept phase to the final design and actually building the vessel. More data and more reliable data will become available as the design develops. There will be less space for errors to creep in the weight prediction. More detailed methods for weight prediction will be used and it will lead to the additional reduction of margins.

The second two margins are usually decided in advance when design requirements are made and will not be treated here.

Margins for the structural weight are also dependent on the structural material.

- Steel structures are subject to variability of thickness due to the mill tolerance and due to the corrosion treatment applied.
- Composite structures weight is variable depending on the technology applied, i.e. hand layup, vacuum bagging, infusion, ..etc. Fiber content in the laminate will vary depending on the work force training and on the quality control of the process. Variable overlapping of composite layers and variability of materials are also present.

At the concept design level margins are necessarily high, since the level of insecurity is high and reducing them will often result in repeating the design from the scratch when insufficient buoyancy would lead to cutting off some of essential deadweight and, therefore, make the design infeasible.

Tentatively, margins at the concept design level may be estimated from Table 13.

Table 13. Tentative margins by weight groups

	WEIGHT ELEMENT	MARGIN
M_{100}	Steel structure	12%
M_{100}	Aluminum structure	10%
M_{100}	Composite structure	15%
M_{200}	Propulsion system	10%
M_{300}	Electrical power system	10%
M_{400}	Electronic systems	50%
M_{500}	Auxiliary systems	10%
M_{600}	Outfit	12%
M_{700}	Special systems	5%
M_{800}	Deadweight	6%

Assuming that margin is related to the uncertainty that is quantified by a standard deviation, it is reasonable to add a margin of one standard deviation to the mean value. Finding standard deviation requires a database of previous cases. If there is not sufficient previous knowledge it is possible to use subjective method as borrowed from the operations research.

If two estimates of the respective weight are made:

W_{MAX} -Pessimistic weight prediction
W_{MIN} -Optimistic weight prediction

Standard deviation is predicted by the expression:

$$\sigma = \frac{W_{MAX} - W_{MIN}}{5} \qquad (63)$$

6.2. RELIABILITY

Dividing weight into several groups reduces the uncertainty of the light ship prediction as a whole.

An example calculation in Table 14. shows the advantage of using several groups instead of only one.

Table 14. Margins by weight groups

	W_{MEAN}	σ	W_{MARGIN}	W_{TOTAL}
Lightship	83,0	10%	8,3	91,3
Hull	40,0	10%	4,0	44,0
Power	25,0	10%	2,5	27,5
Outfit	18,0	10%	1,8	19,8
Lightship	83,0	6,083%	5,049	88,049

Standard deviation of a whole is related to the standard deviations of components as defined by (64)

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2} \qquad (64)$$

For the example case it means:

$$W_M = \sqrt{4,0^2 + 2,5^2 + 1,8^2} = \sqrt{25,49} = 5,049 \text{ t}$$

Therefore:

$$\sigma_M = 6,083$$

It means that by dividing the lightship weight into three groups and estimating each of them with the same standard deviation, the reliability of lightship weight prediction is improved from 10% to 6,083%

Obviously, every further division, i.e. increasing n, brings less improvement as defined by the equation:

$$\sigma_M = \frac{\sigma_0}{\sqrt{n}} \quad (65)$$

7. CONCLUSIONS AND PROPOSALS

7.1. CONCLUSIONS

- The proposed method of lightship weight prediction gives acceptable results for the concept design stage.
- Standard deviation of the prediction is about 13% and it is expected that further reduction will be possible by different treatment of some component weights.
- The method is sensitive to hull structural material variation, takes care of the service area and service type. It makes the method suitable for inclusion in the concept design model that will be used in the optimization procedure.

7.2. PROPOSALS FOR FUTURE WORK

- Obviously, weight data are scarce and the quest for increasing database is a permanent occupation of designer. In that respect all information is welcome.
- The weight of superstructures is at present not treated adequately since it is hidden within structural weight. Implicitly it is assumed that all vessels have an average proportions of the superstructures. This is obviously not the case. Future work will include collecting data on the superstructure and some rearrangement of equations for structural weight prediction.
- Weight of individual propulsion engines together with gearboxes, transmission and propulsors should be collected with more precision in order to split the machinery weight into propulsion engines and the rest of engine room weight. It is expected that accuracy will be improved.

NOMENCLATURE:

B_X	Waterplane beam at max. section (m)
B_M	Maximal molded beam (m)
C_B	Block coefficient
D_P	Propeller diameter (m)
D_X	Hull depth amidships (m)
GT	Gross tonnage
$H_{1/3}$	Significant wave height (m)
L_{OA}	Length over all (excluding extensions) (m)
L_{WL}	Length on water line (m)
M	Margin (%)
P	Engine power (kW)
S	Surface area (m^2)
Δ	Full load displacement (t)
∇	Displacement volume (m^3)
W	Weight in general (t)

REFERENCES

1. WATSON, D. G. M., and GILFILLAN, A. W., “Some Ship Design Methods”, *Transactions RINA*, Vol. 119, 1977.
2. WATSON, D. G. M., "Practical Ship Design", Elsevier Science & Technology Books, 1998
3. SCHNEEKLUTH and BERTRAM, "Ship Design for Efficiency and Economy", Butterworth-Hainemann, 1998
4. PARSONS, M., G., “Parametric Design, in Ship Design and Construction”, Edited by Lamb, T., *The Society of Naval Architects and Marine Engineers*, New Jersey, pp 11-1 to 11-48, 2003.
5. BAS engineering, "The Ship Weight concept", www.**shipweight**.com/download/swbackground.doc
6. KARAYANIS, T., MOLLAND, A. and SARAC-WILLIAMS, "Design Data for High-Speed Vessels", FAST 1999, Seattle, p.p. 605-615
7. GRUBISIC, I. et al., "Study of the Development of the Maritime Administration Fleet", Ministry of Maritime Affairs (in Croatian), Zagreb, 1999.
8. LLOYD'S REGISTER, "Rules and Regulations for the Classification of Special Service Craft", London, 1996.
9. GRUBISIC, I. and BEGOVIC, E., "Multi-Attribute Concept Design Model of Patrol, Rescue and Antiterrorist Craft", FAST 2003
10. CATERPILLAR Application Guidelines for Marine Propulsion Engines, http://www.cat.com/cda/layout?m=37601&x=7