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EARLY STAGE WEIGHT AND COG ESTIMATION USING PARAMETRIC FORMULAS AND REGRESSION ON HISTORICAL DATA

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ABSTRACT

Estimation of weight and center of gravity is an essential task in the design phase of a vessel, and the quality of this work will be crucial for the success of the project. It is important to have the best possible estimate for total lightship weight, but when it comes to construction and installation there will be a demand for detailed budgets. A certain detail level for the weight budget will also make it easier to find the reasons for any deviations that may occur during the monitoring phase.

The use of parametric estimation based on several reference ships and regression lines has traditionally been characterized as too demanding, because of time demands as well as complexity. This article will describe some assumptions and methods that make it possible and preferable to use parametric estimation on a regular basis when designing and building a ship, either by the use of built-in formulas and graphs found in spreadsheets, or by the use of database related weight control systems like ShipWeight. This article will discuss topics like breakdown structures, methods, selection of coefficients, selection of detail level, reporting and exporting of results, together with design changes and re-estimation.

Runar Aasen is one of the founders and technical sales manager of BAS Engineering, a SAWE corporate member. Mr. Aasen has a Master of Science Degree in Ship Design, has been extensively involved in the development of weight engineering software and user support for the last fourteen years, and became a SAWE Fellow Member in 2006. Since 1996, BAS Engineering has provided ship designers and builders around the world with naval architecture and mass properties support. BAS Engineering's ShipWeight software entered the US market for the first time in 1998 and has since been adopted by major US shipyards and designers.

Stein Bjørhovde is one of the founders and head of development of BAS Engineering. Mr. Bjørhovde has a Master of Science Degree in Ship Design, and has been developing the weight engineering software ShipWeight since 1993. He has also been involved in development of other weight control software, in addition to being a consultant doing weight estimation and monitoring in the offshore industry. He has more than 15 years experience in weight estimation of new ship designs for several Norwegian and international ship designers and yards.

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2 Background

Estimation of weight and center of gravity for vessels in an early design phase can be a challenging task, especially if the new ship to be estimated partially or completely differs from previously built ships. The lack of systematic empirical data can also make the job difficult and create considerable uncertainty around the results. Often there are few people who are involved in efforts to estimate the weight and their experience and understanding of the project are critical to the accuracy of the final results. The estimation results may be the deciding factor for success in winning a contract for design or construction of the vessel. In the case of a contract, the quality of the estimates will affect the as-built vessel when it comes to fulfillment of the requirements for load capacity, speed, stability, seaworthiness, delivery and financial gain on the building contract.

When using the term "weight estimation" in this paper, it will also refer to and include "center of gravity estimation."

3 The goal of this Paper

The purpose of this article is to present how regression on past ship data can be used when estimating weight and center of gravity. In addition to explaining the basis for such estimation, practical applications and experiences will be presented. The goal is to contribute to increasing the understanding and knowledge about this type of estimation.

4 Parametric Estimation

A well known way of estimating is to use the ratio from one or more reference ships and multiply by known quantities for the new design.

Here is an example where, for a reference ship, we know that the ratio between lightship weight and the cubic number is 0.37.

Lightship weight, LW	Length between perpendiculars, Lpp	Beam, B	Height, D	Ratio number, k $k = \frac{LW}{Lpp * B * D}$
5 821	79.8	22.0	9.0	0.37

Table 1: Reference ship

This ratio number can be used to calculate the lightship weight for a ship with other main dimensions.

Ratio, k	Length between perpendiculars, Lpp	Beam, B	Height, D	Lightship weight, LW $LW = k * Lpp * B * D$
0.37	85	22	9.5	6 545

Table 2: Estimate

The basis for this method is that there is a correlation between weight and other physical parameters of the ship that can be expressed mathematically. A problem here would be the "validity" of the method; how much can a ship differ from previous projects without invalidating the method?

It’s important to note that parametric methods are not only suitable for high level weight groups like lightship, but even for details such as small deck areas, similar methods can be used.

$$W = k \times \rho \times A \times t$$

where

W	- weight of deck
k	- ratio / coefficient
ρ	- density of material
A	- deck area
t	- plate thickness

In the example above, the coefficient represents the ratio between total weight of a deck including stiffeners, brackets, milling tolerance, and welding, and the theoretical weight of the plates.

5 Breakdown Structure

It will most often be necessary to estimate weights to a detailed level. In this case it will be appropriate to divide the ship into a standardized hierarchical breakdown structure such as SWBS, Marad, or SFI.

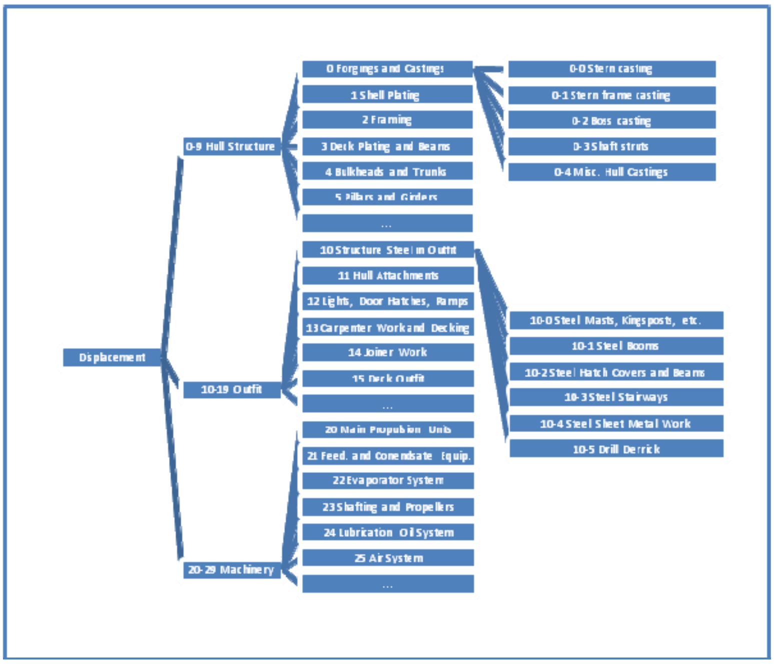


Figure 1: Extraction of the MARAD weight coding system

5.1 Estimation on Detailed Levels

A detailed weight estimate could be required for several reasons. In the following we will comment on some factors that influence the level of detail required for weight estimates.

5.1.1 Increased Certainty in Estimates

Usually, the uncertainty will decrease when the detail level for weight and center of gravity estimates increase. This will be explained further in Chapter 6 (Methods) and Chapter 8.1 (Calculation of Uncertainty). But in any case it will be easier to determine the center of gravity the more detailed and defined the weight groups are.

5.1.2 Documentation, Verification, and Control Against Budget

It is easier to verify the content of more detailed estimates, and deviations against budgets are easier to explain. A certain level of detail will often be a requirement when establishing a budget.

5.1.3 Lifting, Transport, and Installation

In connection with lifting and transportation of modules and hull in the building phase, there will be a need to know the correct weight and center of gravity to perform these operations in a safe manner. A high detail level of the weight estimates will make it easier to calculate these often complex combinations of incomplete weight groups.

5.1.4 Calculation of Weight Distribution and Gyration

Strength and motion characteristics are important properties of a vessel that must be determined early in the design phase. When it comes to calculation like weight distribution curve and gyration figures, the results will be more precise the more detailed the weight estimates are. This assumes, of course, that the total uncertainty does not increase when the level of detail increase.

5.2 Number of Levels

Generally one can say that the more levels a work breakdown structure (WBS) contains, the more flexible and suitable the WBS will be for estimating weight and center of gravity. Since the most detailed levels normally will be fixed, this means that it is beneficial to post as many intermediate levels / subgroups as possible.

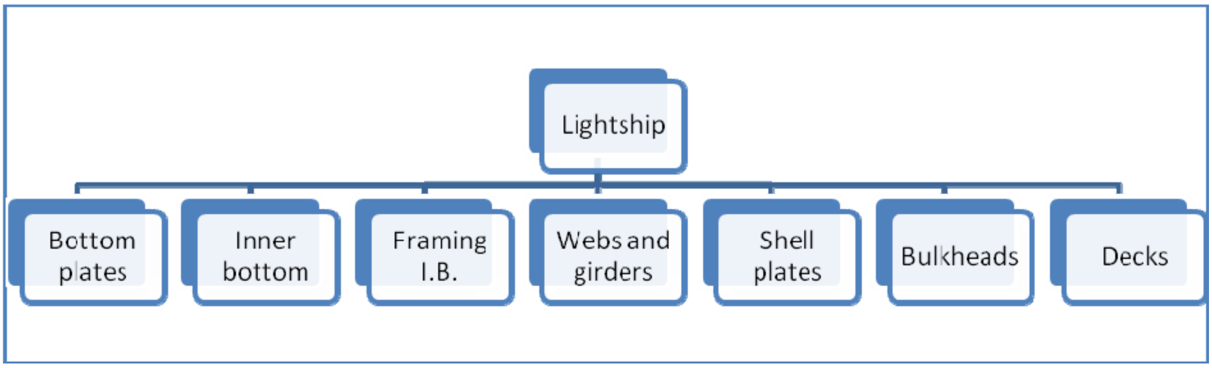


Figure 2: Work breakdown structure with only two levels

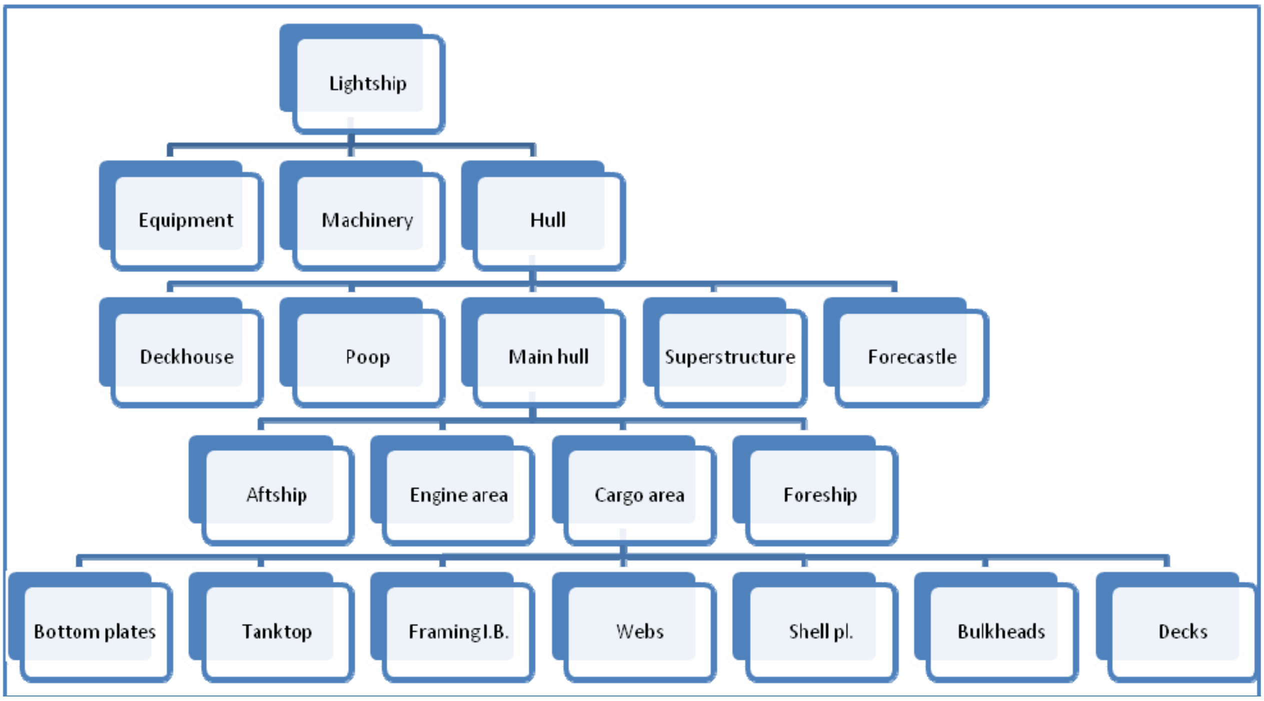


Figure 3: Work Breakdown Structure with several levels (extraction)

5.3 Relation to Outline Specification

It's a great advantage if there is a clear relation between how the outline and building specifications for the ship is organized, and the breakdown structure for weight estimates. The specifications describe how the vessel is equipped, as well as quantities and capacities. A good check to make sure nothing is left out is to make sure that all groups / codes / chapters in the specification also are included in the estimates.

5.4 Harvesting of Reference Ship Data

It's important to collect and organize past ship data, but this can be a difficult job if the weight monitoring is not performed according to the same weight breakdown structure that is used for estimation or, even worse, there has not been any weight monitoring at all. But in any case it's important that the weight group structure is adapted to the level of detail that corresponds to the empirical data that exists.

It is difficult to utilize weights of hull units/sections if the weight group structure doesn't have any mid-level groups like the example in Figure 2. But for a weight group structure like the one in Figure 3, unit weights can be grouped according to the hull areas such as aft ship, engine area, cargo area, etc.

It is also important that the group structure used for estimating is as permanent as possible so that the reference ship data stays consistent as time goes by. This is important because you need to know that historical data for a certain weight group is equivalent to what is estimated for a new ship.

Since new ship concepts are developed, and there are new types of equipment and applications, it might be necessary to add new weight groups, but content and use of existing weight groups should not be changed. This applies to those levels of the breakdown structure used for estimation, i.e. the uppermost levels.

6 Methods

To estimate the weight and center of gravity of a weight group, an estimation method must be established. As mentioned earlier, a widely used method for estimating lightship weight is:

$$LW = k \times Lpp \times B \times D \qquad (1.1)$$

where

LW – lightship weight

k – coefficient

Lpp – ship length between perpendiculars

B – ship beam

D – ship depth

A more complex method is

$$LW = k \times Lpp \times B \times D \times \sqrt{Cb} \qquad (1.2)$$

where

Cb – block coefficient

This method can also be used to estimate hull weight, but the coefficient value will then be lower.

6.1 Complex Methods

In the naval architecture literature, one can find various formulas for estimating weight. Many of these methods have a tendency to become quite complex because they try to take into account both the design of the ship, as well as powering and quantities.

Here is one example of a formula for estimating hull steel weight.

5.1.1 Steel weight Estimation – Watson and Gilfillan

From ref. (3),

Hull Numeral E = $L(B+T)+0.85\ (D-T)L+0.85\sum l_1\ h_1+0.75\sum l_2\ h_2$ in metric units where

l_1 *and* h_1 : length and height of full width erections

l_2 *and* h_2 : length and height of houses.

$$W_s = W_{s7}\ \left[1+0.5(C_{B1}-0.70)\ \right]$$

where W_s : Steel weight of actual ship with block C_{B1} at 0.8D

W_{s7} : Steel weight of a ship with block 0.70

$$C_{B1} = C_B + (1-C_B)\left(\frac{0.8D-T}{3T}\right)$$

Where C_B : Actual block at T.

Formula 1: Watson and Gilfillan estimation formula for hull steel weight

$$W_{s7} = K.\ E^{1.36}$$

Ship type	Value of K	For E
Tanker	0.029 – 0.035	1,500 < E < 40, 000
Chemical Tanker	0.036 – 0.037	1,900 < E < 2, 500
Bulker	0.029 – 0.032	3,000 < E < 15, 000
Open type bulk and Container ship	0.033 – 0.040	6,000 < E < 13, 000
Cargo	0.029 – 0.037	2,000 < E < 7, 000
Refrig	0.032 – 0.035	E 5,000
Coasters	0.027 – 0.032	1,000 < E < 2, 000
Offshore Supply	0.041 – 0.051	800 < E < 1, 300
Tugs	0.044	350, E < 450
Trawler	0.041 – 0.042	250, E < 1, 300
Research Vessel	0.045 – 0.046	1, 350 < E < 1, 500
Ferries	0.024 – 0.037	2,000 < E < 5, 000
Passenger	0.037 – 0.038	5, 000 < E < 15, 000

Table 3: Coefficients for Watson and Gilfillan method for estimating hull steel weight

In this case it becomes quite difficult to understand what the various formulas and terms within the formula represents, and it is not an easy job to pick the correct K value. The solution to this might be that instead of estimating the complete hull weight by the use of one formula, the hull is divided into subgroups that are estimated separately.

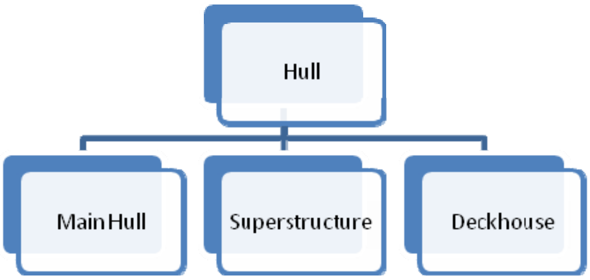


Figure 4: Basic breakdown structure for hull

6.2 Basic Methods

Main Hull in the following discussion represents all structure up to the uppermost continuous deck, while superstructure represents all structure in full ship beam above the Main Hull. Everything else is regarded as Deckhouse.

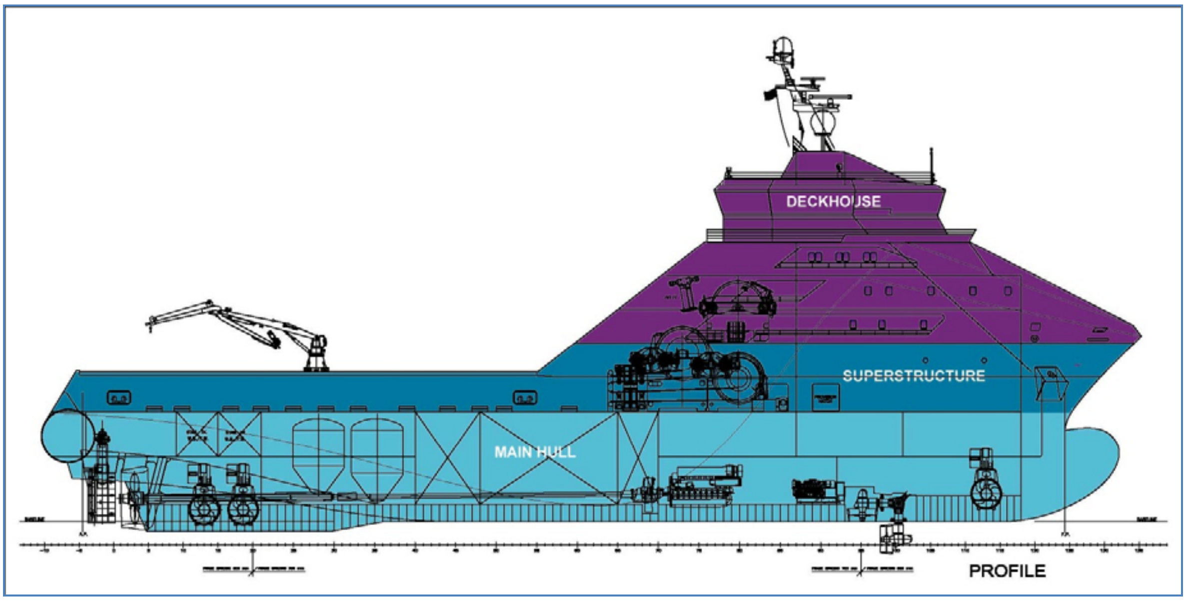


Figure 5: Hull divided into 3 areas

Within each of these areas weight can be estimated using basic formulas corresponding to the various terms in the Watson and Gilfillan formula.

$$W = k \times l \times b \times h \qquad (1.3)$$

where

l – length of a hull area

b – width of a hull area

h – height of a hull area

As an alternative the following formula can be used for estimation of hull areas:

$$W = k \times v \qquad (1.4)$$

where

v – volume of a hull area

Dividing into subgroups thus makes the estimates more precise, and also far more intuitive and verifiable.

In the example of estimating hull weight, it will be beneficial to divide the hull into even more areas with individual coefficients.

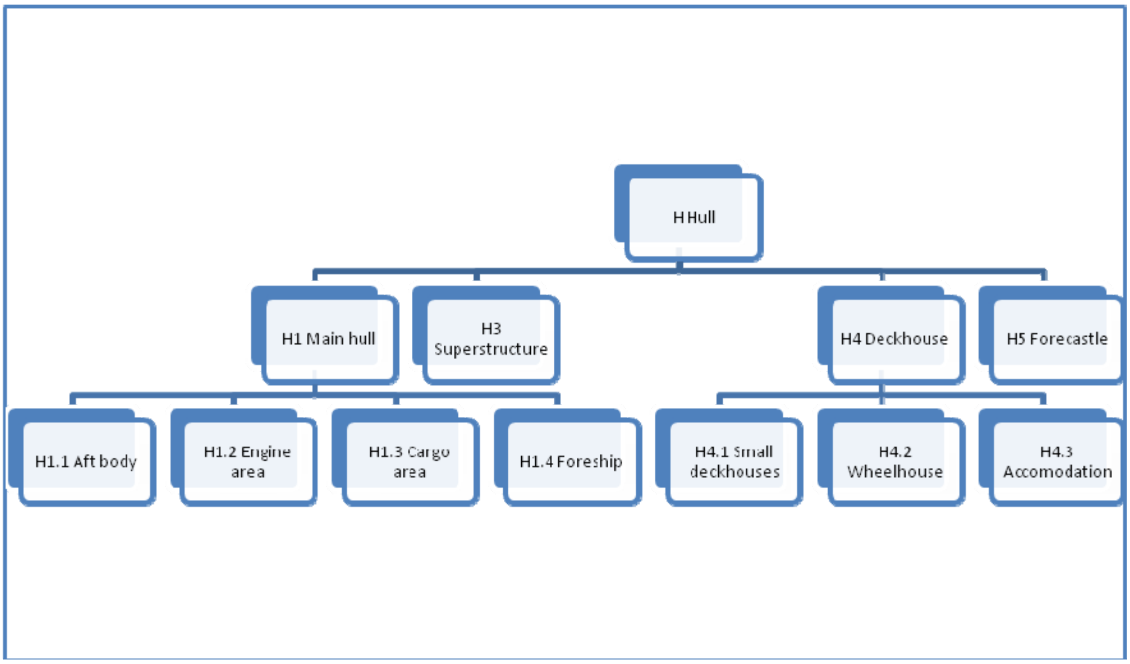


Figure 6: Extraction of weight group structure for hull (ShipWeight)

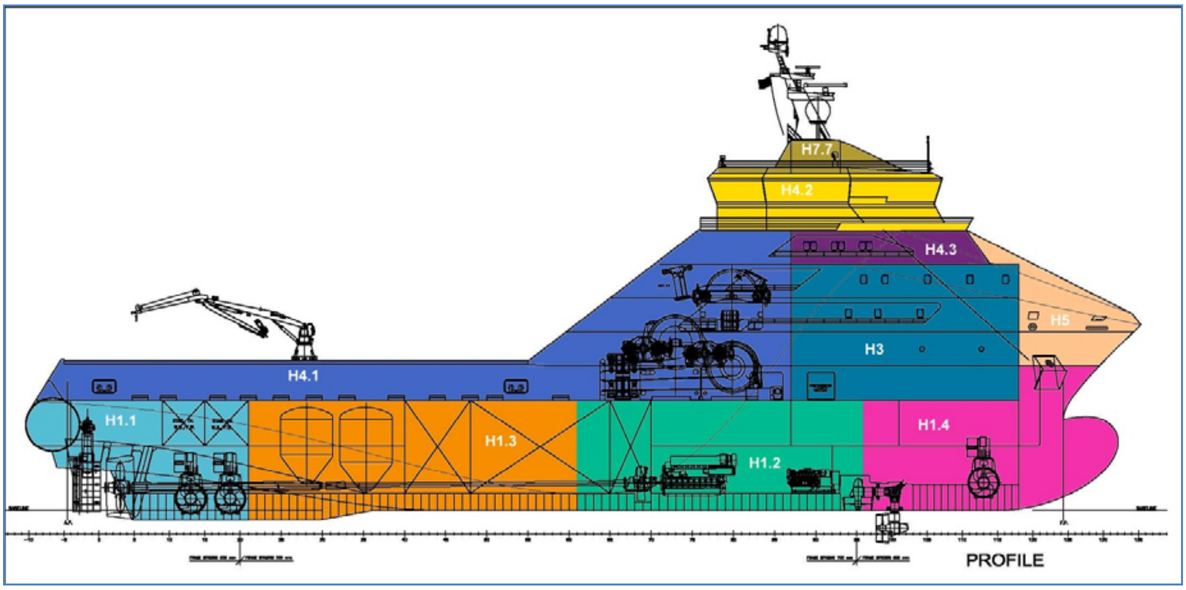


Figure 7: Hull divided according to ShipWeight coding structure

Another positive effect of having several levels and basic methods is the reduced risk of excluding reference ships because one or more parameter values according to the estimation formula are missing. By using Formula 1.2 instead of Formula 1.1, all reference ships with unknown block coefficient will be excluded.

7 How to Select the Most Appropriate Coefficient

7.1 Static Coefficients

When estimating weight or center of gravity by the use of parametric methods, coefficient values can be found in literature as shown in Table 3. You don't need to have your own reference data, but the use of such standardized coefficients is very risky because of the limited knowledge of any assumptions, accuracy, and data selection that form the basis of these coefficients. Therefore, it's highly recommended to use your own data to calculate the coefficients as shown in Table 2.

7.2 Coefficients Based on a Sister Ship

Using one particular reference ship, often referred to as a sister ship, might be the most common way to find coefficients for parametric estimation. In the simple example in Chapter 2, the calculation is based on one reference ship.

7.3 Coefficients Based on Several Reference Ships

In the case where several reference ships are available, the coefficient can be calculated as an average of all of the ships. This is shown in the table below.

ID	LW	Lpp	B	D	Cb	LBD	k
Sea001	2 024	70.0	17.0	6.4	0.70	7 616	0.27

Sea002	2 008	70.0	17.0	6.0	0.82	7 140	0.28
Sea003	2 008	70.0	17.0	6.0	0.82	7 140	0.28
Sea004	2 024	70.0	17.0	6.4	0.74	7 616	0.27
Sea005	1 470	64.0	14.0	6.0	0.80	5 376	0.27
Sea006	1 735	64.0	15.0	6.0	0.78	5 760	0.30
Sea007	1 961	60.8	15.0	6.1	0.76	5 559	0.35
Sea008	2 247	70.0	16.0	7.0	0.69	7 840	0.29
Sea009	2 096	66.0	16.0	7.0	0.66	7 392	0.28
Sea010	3 424	75.0	18.0	8.0	0.74	10 800	0.32
Sea011	3 424	75.0	18.0	8.0	0.74	10 800	0.32
Hav001	5 821	79.8	22.0	9.0	0.71	15 800	0.37
Hav002	4 177	73.5	19.9	8.8	0.72	12 871	0.32
Hav003	4 177	73.5	19.9	8.8	0.72	12 871	0.32
Hav004	2 828	64.8	17.2	8.0	0.75	8 916	0.32
Hav005	2 828	64.8	17.2	8.0	0.75	8 916	0.32
Hav006	5 821	79.8	22.0	9.0	0.71	15 800	0.37
Average	**2 945**						**0.31**

Table 4: Reference ships found on web sites for Seacor Marine and Havila Shipping

7.3.1 Average Coefficient

Based on an average coefficient we can calculate lightship weight as shown in the table below.

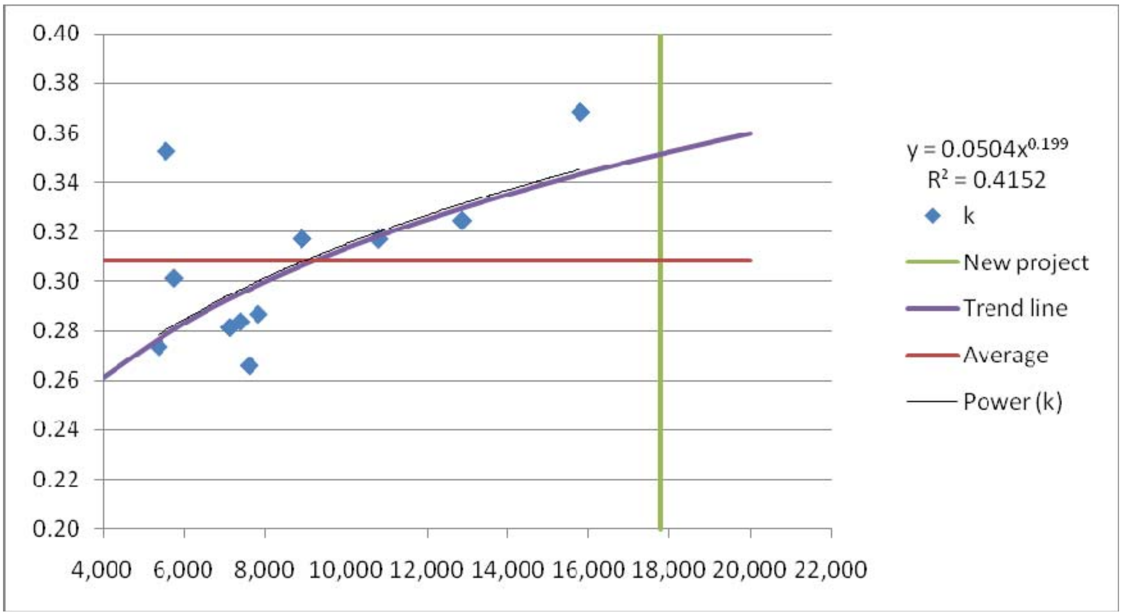
Coefficient, k	Length, Lpp	Beam, B	Height, D	LBD	Lightship weight, LW $LW = k \times Lpp \times B \times D$
0,31	85	25	9,5	17 765	5 482

Table 5: Estimate based on average coefficient

This estimate using the average coefficient differs quite a lot (-16%) from the estimate in Chapter 3, Table 2 using one reference ship.

7.3.2 Regression Coefficient

As we can see in Table 4, the coefficients varies between 0,25 and 0,37, and an average coefficient is not necessarily very suitable for estimation of a new project near the ends or outside of the data range. We see this clearly when we plot coefficients against cubic numbers as shown in the graph below.



Graph 1: Plot of data from Table 4 with coefficient k on y-axis

As we can see in the graph, there is a clear trend that the coefficients for lightship weight increases when the size of the ship increases. So if instead of using an average coefficient, we use the coefficient in the intersection between the current cubic number (LBD) and the trend (regression) line, we will have an estimate like the one in the table below.

Coefficient, k	Length, Lpp	Beam, B	Height, D	LBD	Lightship weight, LW $LW = k \times Lpp \times B \times D$
0,35	85	25	9,5	17 765	6 239

Table 6: Estimate based on a regression coefficient

7.3.3 Selection of Coefficient

The table below shows a comparison between the results of lightship weight estimates based on one reference ship, an average, and a regression line.

Method	k	Weight [t]
One reference ship	0,37	6 545
Average of 17 reference ships	0,31	5 482
Regression of 17 reference ships	0,35	6 239

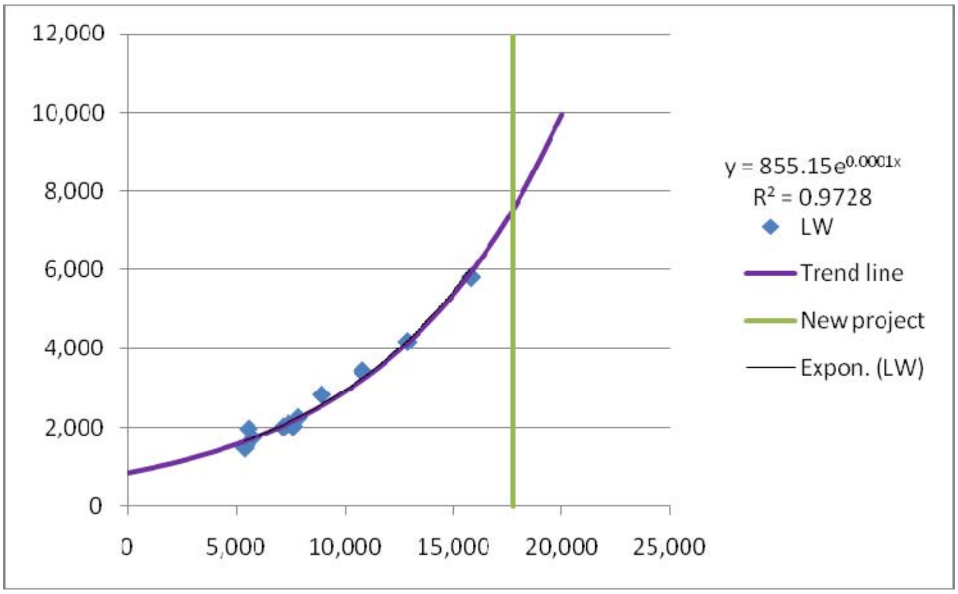
Table 7: Comparison of estimation results based on different approaches of selecting coefficients

As we can see the results vary quite a lot depending on the choice of coefficient. The “correct” coefficient depends on how much knowledge you have of the different reference ships. If you know that a specific reference ship is very similar to the one you are estimating, it will be appropriate to emphasize this coefficient. On the other hand, if there are no reference ships that could be described as being very similar to the one to be estimated, or the reference ships deviate significantly in respect of equipment or size, it would be wise to rely on a trend line but still adjust the coefficient based upon the knowledge of the reference ships. For example, if we are estimating a ship with ice-class, and all the reference ships with ice-class are positioned above the regression line, we should select a coefficient above the trend line. Alternatively, if there are many reference ships, one might exclude ships without ice-class from the plot.

The use of average coefficients should be limited to those cases when reference data doesn't form a clear trend and the plot is very scattered.

7.3.3.1 Plotting of Coefficients or Weights?

Until now, we have plotted the ratio figures, or coefficients, on the y-axis. An alternative method is to plot the lightship weight on the y-axis like in the graph below.



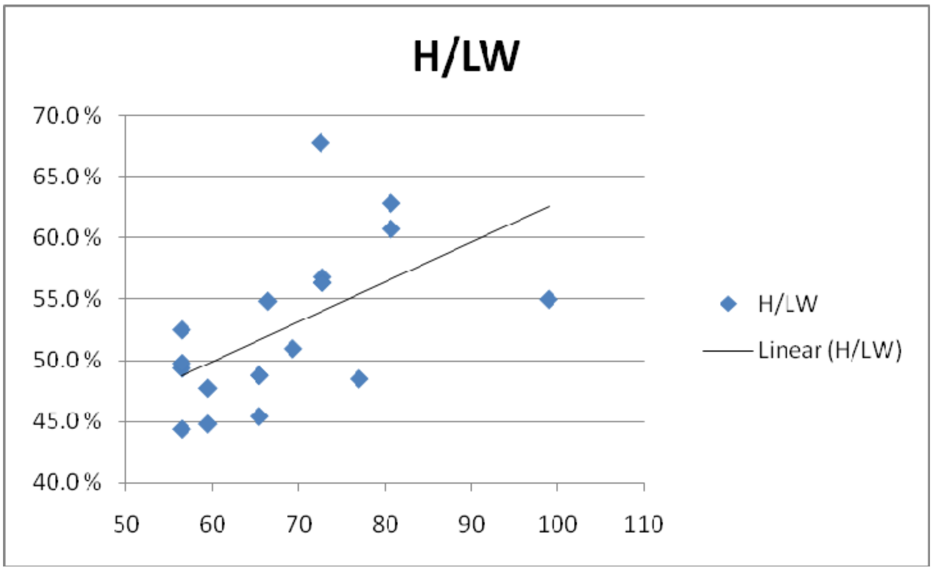
Graph 2: Plot of data from table 4 with LW on y-axis

Based on the exponential regression line, the estimate for lightship weight will be 7 565 tonnes. The disadvantage of this method is that we could lose valuable information from the graph telling whether the relationship between lightship weight and ship size increases, decreases, or is constant when the vessel size increases. A plot of absolute figures for weight will always show a growing trend because weight necessarily increases when the ship becomes larger.

7.3.4 Selection of Reference Ships

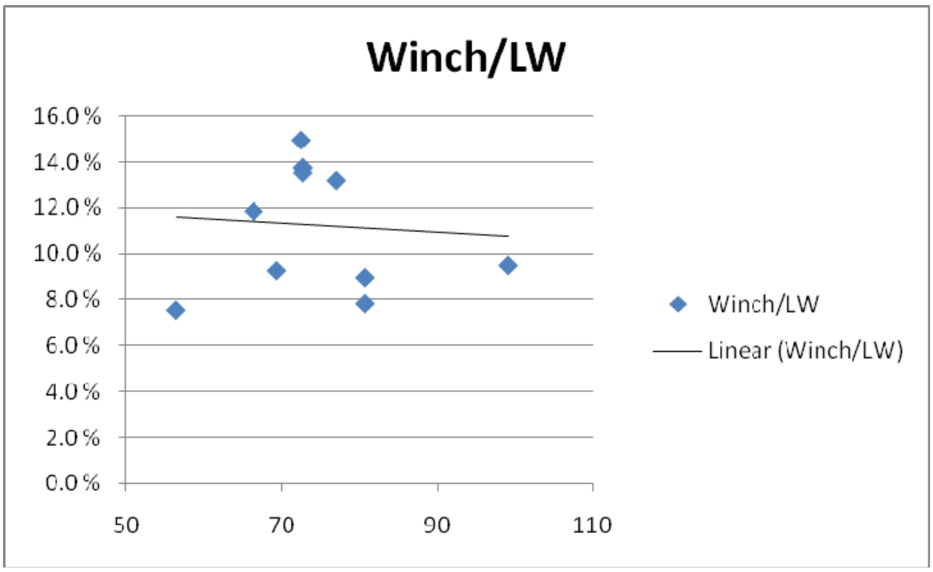
A plot of absolute values as in Graph 2 provides a better curve fit than the plot of the ratio as in Graph 1. But it's harder to tell by looking at Graph 2 which data deviates from the trend. In Graph 1 there are 3 relatively equal sized ships with cubic number approximately 5 000 m^3. These vessels have lightship coefficients varying between 0.27 and 0.35. It's crucial to find an explanation for this discrepancy.

The specifications show that the heaviest ships have substantially more power on winches and main engines than the lightest ship. There are also more propellers, thrusters, cranes and beds on the heaviest ships. But there is no single reason for the difference, and this shows the necessity of estimation of weights on more detailed levels where these conditions can be taken into account in methods and selection of reference ships. For anchor handling vessels (AHT) that are shown in these examples, the relative amount of equipment and machinery weight is greater on smaller vessels, and differences in equipment configuration will have greater impact on the lightship weight for these vessels. The ratio between hull weight and lightship weight for anchor handling vessels is shown in the graph below.



Graph 3: The ratio between hull weight and lightship weight for anchor handling vessels of various sizes

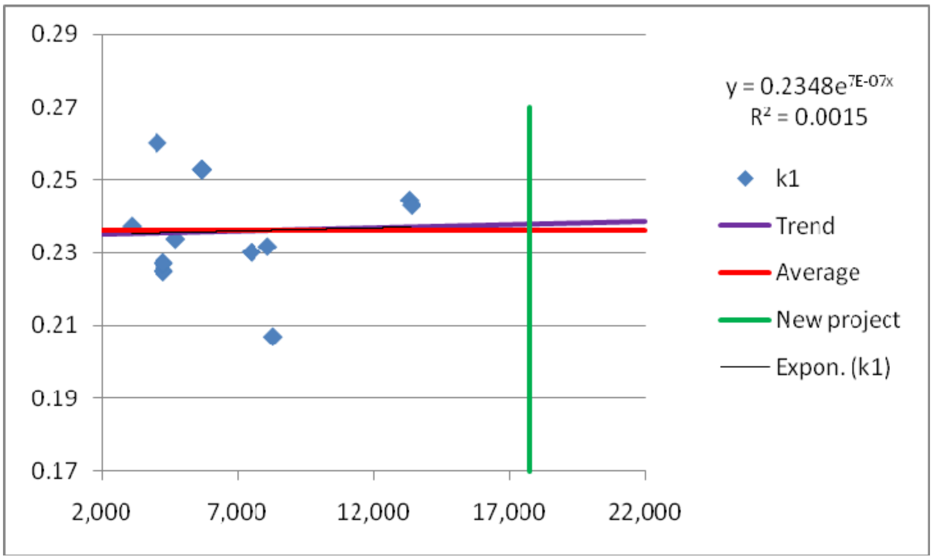
Because the weight of the towing winch represents a high percentage of the lightship weight of an anchor handling vessel, the capacity and power of these winches will be an important estimation parameter. The relation between weight of the towing winch package and lightship weight is shown in the graph below.



Graph 4: The ratio between towing winch and lightship weight for anchor handling vessels of various sizes

7.3.4.1 Ship Types

On a high weight group level such as lightship weight, it will be suitable to filter by ship types. In our example we have chosen to plot only anchor handling vessels. A similar plot as in Graph 1 of platform supply vessels (PSVs) is shown in the graph below.



Graph 5: Plot of lightship coefficients for plattform supply vessels (PSV)

A lightship estimate based on such reference data will give quite different estimation results compared to a plot based on AHTs.

But if we are estimating on level 4 according to the breakdown structure shown in Figure 3, it will be relevant to use weight data for both AHTSs and PSVs in all the weight groups for the hull, except for the aft ship, as the aft body of an AHT is significantly heavier because of the stern roller.

So estimation on more detailed levels will in most cases increase the range of empirical data that can be included. When estimating weight groups like outfitting in accommodation, machinery components, machinery systems, ship equipment (not cargo handling) and electrical, reference data from a large number of different ship types can be included when plotting data to create a regression line. The weight of these groups will mainly be determined by parameters such as propulsion power, generator capacity, and vessel size.

8 Uncertainty and Verification of Estimates

If we consider an estimation of a new concept ship design where no sister ship can be used for adjustment, a certain detail level is necessary. As mentioned in Chapter 3, there are many factors influencing the choice of detail level. The higher the detail level, the more weight groups must be estimated. So in an early design phase where a large number of re-estimates must be performed, it would be preferable to use as few weight groups as possible.

8.1 Calculation of Weight Uncertainty

Calculation of weight uncertainty can be a useful both for documentation of the validity of the total (lightship) estimate, but also as an aid when considering which weight groups should be further investigated.

8.1.1 Calculation of Uncertainty in Sub-estimates

The uncertainty (standard deviation) of a weight estimate can be calculated based upon the deviation of the data plotted compared to the regression line. The formula for calculating standard deviation is

$$s = \sqrt{\frac{S^2}{(n-2)} \times \left(1 + \frac{1}{n} + \frac{(x-\bar{x})^2}{Xdiff}\right)} \qquad (2.1)$$

where

s	- standard deviation
n	- number of reference ships in plot
x_n	- x value to item n
$\bar{x} = \frac{\sum_1^n x_n}{n}$	- average x value
$Xdiff = \sum_1^n (x_n - \bar{x})^2$	- product of distance to average x value
y_n	- y value for item n
Y_n	- y value according to regression line for item n
$S^2 = \sum_1^n (y_n - Y_n)^2$	- standard deviation for regression curve

The standard deviation for an estimate is therefore dependent on:

- The number of reference data in the plot that make up the regression line. The more points, the lower the standard deviation.
- The deviation of the reference ships from the regression line. The higher the deviation, the higher the standard deviation
- Where the estimation project is positioned on the x-axis compared to the reference data. The closer to the outer bounds of the estimate, the higher the standard deviation.

The table below shows calculation of standard deviation for the reference ships in Table 4.

ID	LW	LBD	Xdiff	k	Yn	S2
Sea001	2 024	7 616	2858690.3	0.27	0.298466	0.000102
Sea002	2 008	7 140	4694875.7	0.28	0.294657	0.000194
Sea003	2 008	7 140	4694875.7	0.28	0.294657	0.000194
Sea004	2 024	7 616	2858690.3	0.27	0.298466	0.000102
Sea005	1 470	5 376	15450923	0.27	0.278479	0.000906
Sea006	1 735	5 760	12579550	0.30	0.282328	0.000689
Sea007	1 961	5 559	14048562	0.35	0.280336	0.000797
Sea008	2 247	7 840	2151403	0.29	0.300192	7.03E-05
Sea009	2 096	7 392	3666329.5	0.28	0.296698	0.000141
Sea010	3 424	10 800	2229747.3	0.32	0.31995	0.000129
Sea011	3 424	10 800	2229747.3	0.32	0.31995	0.000129
Hav001	5 821	15 800	42167280	0.37	0.345116	0.001335
Hav002	4 177	12 871	12706044	0.32	0.331318	0.000517
Hav003	4 177	12 871	12706044	0.32	0.331318	0.000517
Hav004	2 828	8 916	152323.3	0.32	0.307978	3.56E-07
Hav005	2 828	8 916	152323.3	0.32	0.307978	3.56E-07
Hav006	5 821	15 800	42167280	0.37	0.345116	0.001335
17		**9 307**	**177514689**	**0.31**		**0.00716**

Table 8: Calculation of uncertainty for reference ships

Based on these figures the standard deviation for the coefficient at the point of intersection between the regression line and the cubic number for the estimate ship in Graph 1 can be calculated.

$$s = \sqrt{\frac{0.00716}{(17-2)} \times \left(1 + \frac{1}{17} + \frac{(17765 - 9307)^2}{177514689}\right)} = 0.0264$$

$$s_{rel.} = \frac{0.0264}{0.35} = 7{,}52\%$$

8.1.2 Uncertainty for Parameters

It is also possible to take into account any uncertainty for the parameters used in the estimation formula. Estimation of uncertainty for weight of furnished areas can be done by use of the following formula:

$$W = k \times A$$

where

A - area of furnished spaces

Absolute standard deviation can be calculated based on this formula:

$$s_W = \sqrt{(s_k \times W)^2 + (s_A \times W)^2}$$

where

sW - absolute standard deviation for weight

sk - absolute standard deviation for coefficient

sA - absolute standard deviation for area

The table below shows an example of calculation of standard deviation for an estimate where standard deviation for area is 0% and 10%.

	K	A	Weight
Parameter	0.05	1000	50
Std.dev.	0.01	0	10
Std.dev. [-]	20 %	0 %	20 %
Std.dev.	0.01	100	11
Std.dev. [-]	20 %	10 %	22 %

Table 9: Uncertainty for parameters taken into account when estimating weight

8.1.3 Calculation of Total Uncertainty

When summarizing standard deviation for subgroups, we need to take into account whether the different groups are statistically dependent or not.

If the groups are statistically independent, this formula is used for calculating summarized standard deviation

$$S_{tot} = \sqrt{s_1{}^2 + s_2{}^2 + \cdots + s_n{}^2} \qquad (3.1)$$

where

s - standard deviation for each separate weight group

The formula for calculating standard deviation when the weight groups are statistically dependent is:

$$S_{tot} = s_1 + s_2 + \cdots + s_n \qquad (3.2)$$

Based on this the standard deviations for total hull weight can be calculated as shown in the table below

Wgt.grp.	Weight [t]	Std.dev.	s^2 [t^2]	Rel. [-]
H1.1	610	80	6 400	13 %
H1.2	630	55	3 025	9 %
H1.3	800	85	7 225	11 %
H1.4	280	45	2 025	16 %
Total	**2 320**	**265**	**18 675**	**11 %**
Min.std. (eq.3.1)		*137*		*6 %*
Max.std.(eq.3.2)		*265*		*11 %*

Table 10: Calculation of total standard deviation for H1 – Main hull

We see that even if the absolute standard deviation in tonnes remains the same after we split up a weight group, the relative standard deviation will be reduced as long as the subgroups are not 100% statistically dependent.

Normally in weight estimation, subgroups are considered to be statistically independent of each other. Although this will not be entirely true in reality, it is still considered to be a better approximation than assuming total dependency.

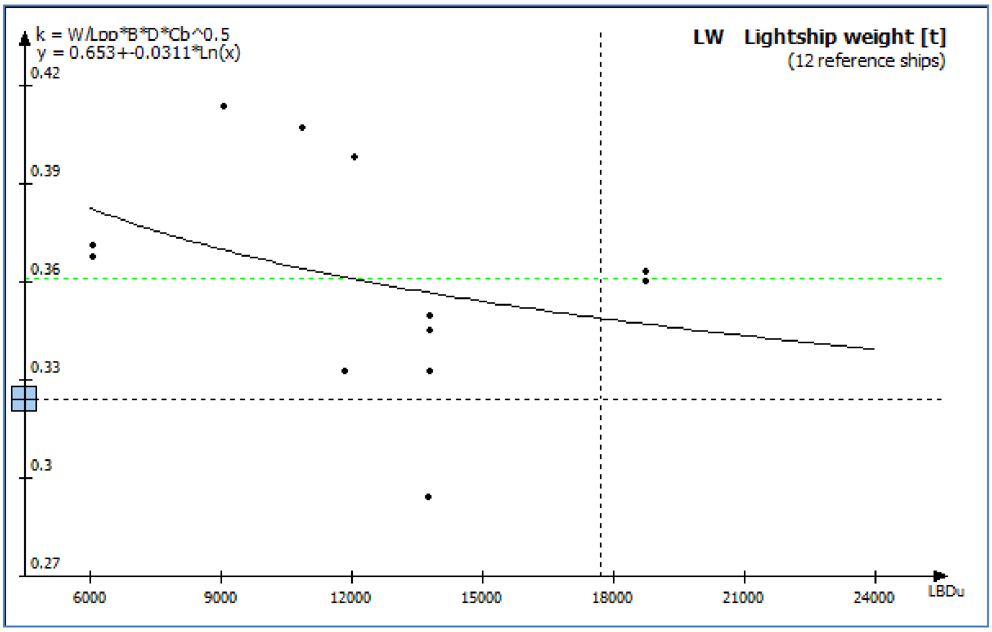
8.1.4 Successive Calculation

Successive calculation means that instead of estimating all weight groups at a given level, the focus is on finding the weight group with the highest absolute standard deviation, and estimate subgroups for this group to improve the total estimate. For the example in the previous chapter further estimation would have been done for cargo area (H1.3) because this is the weight group with the highest standard deviation (85 tonnes). It is worth noting that the group with the highest relative standard deviation (H1.4), is the group with the lowest absolute standard deviation (2 025 tonnes).

There will always be a consideration whether it is practical and appropriate to estimate subgroups for a weight group, even if this has the highest absolute standard deviation. In our example, there might not be available empirical data for decks, shell plating, bottom plates, bulkheads, etc. which represent the level below cargo area. The focus should then be on the group with the second highest standard deviation in tonnes.

8.2 Verification of Estimation Results

When the estimation is complete at the desired level of detail, the total estimate normally will be summarized from some tens of sub-estimates, or in special cases some hundreds of sub-estimates. When the detail level is increasing, there is a certain danger that we lose the overview of the result. It might therefore be a useful exercise to return to the estimate for total lightship weight to see how the coefficient calculated on summarized lightship weight and main parameters correspond to the regression line based on reference ships at this level. The graph below shows how a summarized estimate gives a lower coefficient than what we would expect to see if the estimate was done based on regression at this level.



Graph 6: Verification of total lightship weight based on estimation of 57 subgroups

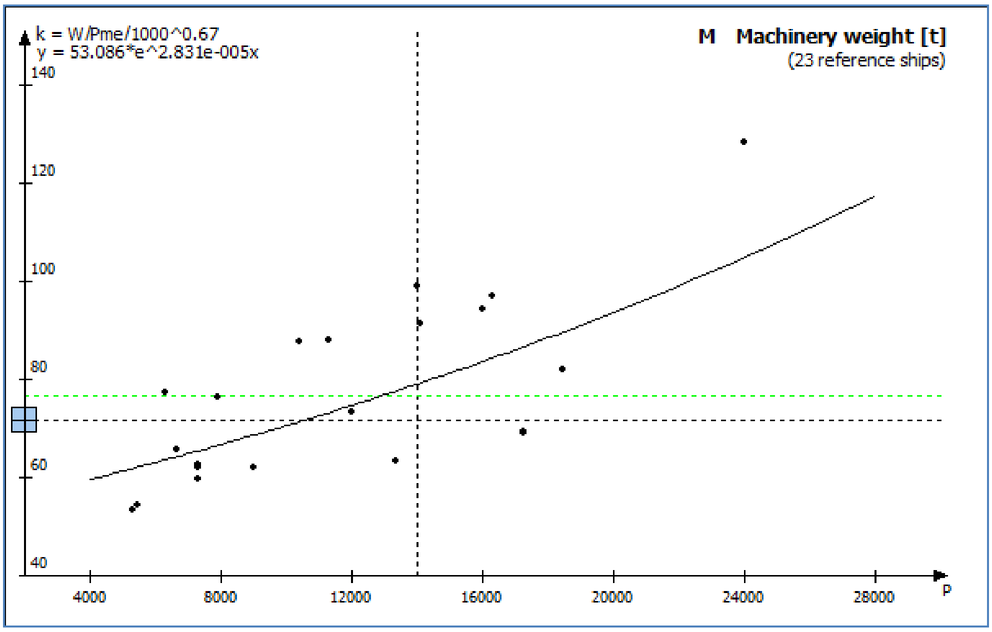
According to the regression line (solid) lightship weight should have been 5 227 tonnes, but the total estimate summarized from the estimated subgroups is 4 865 tonnes.

Coefficient, k	Length, Lpp	Beam, B	Height, D	Block coeff., C_b	LBD	Lightship weight, LW $LW = k \times Lpp \times B \times D \times$
0,35	84,8	22,0	9,5	0,72	17 765	5 227
0,32	84,8	22,0	9,5	0,72	17 765	4 865

Table 11: Comparison between summarized lightship weight and estimation based on regression line

In this case it is necessary to find a reasonable explanation for the deviation of 362 tonnes. To help us find the reason for the deviation we look at the corresponding plots for the lightship subgroups; Hull (H), Machinery (m) and Equipment (E). The dotted green lines in the plots show the average coefficient.

Summarized estimate for Machinery is 41 tonnes lower than the value that the regression line for the weight group indicates.

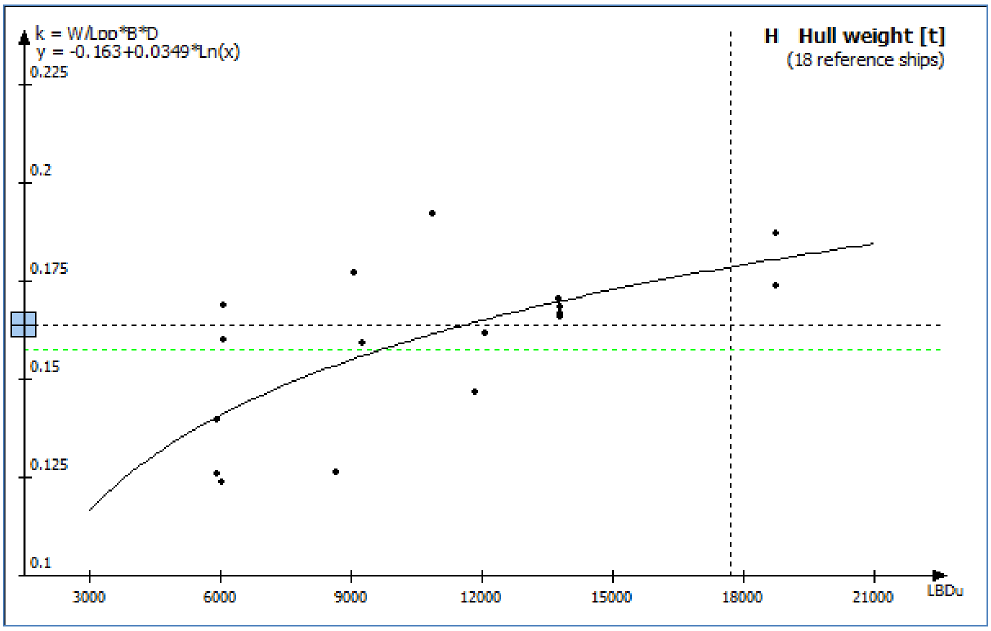


Graph 7: Verification of total machinery weight based on estimation of 14 subgroups

Coefficient, k	Power main engines, Lpp	Machinery weight, M $W_m = k \times \left(P_{me}/_{1000}\right)^{0,67}$
71,89	14 000	462
78,91	14 000	421

Table 12: Comparison between summarized machinery weight and estimation based on regression line

Summarized estimate for Hull is 260 tonnes lower than the value that the regression line for this weight group indicates.

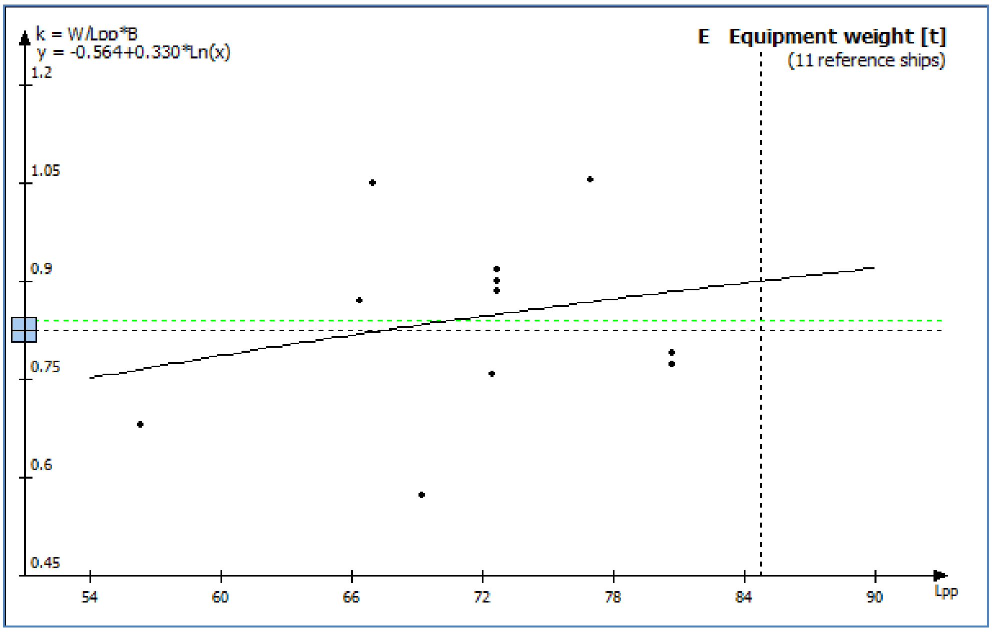


Graph 8: Verification of total hull weight based on estimation of 14 subgroups#

Coefficient, k	Length, Lpp	Beam, B	Height, D	LBD	Hull weight, LW $W_h = k \times Lpp \times B \times D$
0,18	84,8	22,0	9,5	17 765	3 163
0,16	84,8	22,0	9,5	17 765	2 903

Table 13: Comparison between summarized hull weight and estimation based on regression line

Summarized estimate for equipment is 139 tonnes lower than the value that the regression line for this weight group indicates.



Graph 9: Verification of total equipment weight based on estimation of 29 subgroups#

Coefficient, k	Length, Lpp	Beam, B	Hull weight, LW $W_{lk} = k \times Lpp \times B$
0,90	84,8	22,0	1 679
0,83	84,8	22,0	1 540

Table 14: Comparison between summarized equipment weight and estimation based on regression line

Having reviewed the project against the respective reference ships in this example, and looked into the deviation in more detailed weight groups, the conclusion is that the total deviation is reasonable based on the fact that the reference vessels of the same size have ice class, as well as more powerful engines.

8.3 Experiences from Estimation Based on Regression

In a typical estimate for an AHT as in Table 2, 57 different weight groups are estimated. 18 of these 57 weight groups have weight that represent more than 1% of the total lightship weight. The summarized weight for these 18 groups gives 85% of the lightship weight. These groups are listed in the table below.

Wgt.grp	Description	Rel.wgt.	Method	Ref. ships	Ship types
H1.3	Cargo area	14.90 %	$W = k*V_c$ [t]	23	9
E2.5.5	Towing equipment	11.90 %	$W = k*P_w*N_w$^0.7 [t]	12	4
H1.2	Engine area	11.60 %	$W = k*V_e$ [t]	24	10
H1.1	Aft ship	11.40 %	$W = k*V_a$ [t]	11	3
H3	Superstructure	5.70 %	$W = k*V_s$ [t]	24	8
H1.4	Fore ship	5.20 %	$W = k*V_f$ [t]	25	10
E3.2	Insul., pan. etc. in acc.	4.40 %	$W = k*A_{tot.}$ [t]	15	8
M1.1	Diesel-engine for prop.	3.60 %	$W = k*P_{me}$/1000^0.84*n_{me}^0.84*N_{me}^0.5 [t]	8	5
H5	Forecastle	2.30 %	$W = k*V_{fc}$ [t]	21	10
E2.5.7	Stern rollers	2.20 %	$W = k*A_{sr}$ [t]	10	3
H4.1	Small deckhouses	2.20 %	$W = k*V_{sd}$ [t]	4	4
H4.2	Wheelhouse	2.00 %	$W = k*V_w$ [t]	25	10
M1.5	Propel system	1.80 %	$W = k*d_{pr}*N_{pr}$ [t]	12	6
E2.2	Side thrusters	1.40 %	$W = k*P_{thr.}*N_{thr.}$^0.5 [t]	17	7
E4.6	Electric systems	1.40 %	$W = k*P_{el}*L_{pp}$^0.5 [t]	20	9
H4.3	Accommodation	1.30 %	$W = k*V_{ac}$ [t]	24	10
E2.4	Anchors w/chains	1.10 %	$W = k*LBD_u$ [t]	23	10
M1.4	Gear system	1.00 %	$W = k*P_{me}$/1000^0.67 [t]	14	7
Total		**85.40 %**			

Table 15: Listing of the heaviest weight groups and estimation methods for an estimate of an AHT

The table below lists the parameters used in weight estimation methods for the 18 heaviest weight groups listed in the previous table.

Symbol	Description	Source
A_{sr}	Area of stern roller	GA
$A_{tot.}$	Area of accommodation decks	GA
d_{pr}	Diameter propeller	GA
LBD_u	Cubic number	Specification
L_{pp}	Length between perpendiculars	Specification
n_{me}	Rot. speed main engine	Specification
N_{me}	Number of main engines	Specification
N_{pr}	Number of propellers	GA
$N_{thr.}$	Number of thrusters	GA
N_w	Number of drums towing winches	Specification
P_{el}	Total power capacity	Specification
P_{me}	Power of main engines	Specification
$P_{thr.}$	Power of thrusters	Specification
P_w	Power of drums towing winches	Specification
V_a	Volume aft body	Ship model
V_{ac}	Volume accommodation area	Ship model
V_c	Volume cargo area	Ship model
V_e	Volume engine area	Ship model
V_f	Volume forebody	Ship model
V_{fc}	Volume of forecastle	Ship model
V_s	Volume superstructure	Ship model
V_{sd}	Volume of forecastle	Ship model
V_w	Volume of wheelhouse	Ship model

Table 16: Listing of parameters included in estimation methods for the 18 heaviest weight groups

Both vertical (VCG) and longitudinal center of gravity (LCG) are estimated for 33 of the total 59 weight group. For the 26 remaining groups, VCG and LCG are measured from the General Arrangement (GA). For the heaviest 18 groups only 6 groups are estimated when it comes to center of gravity (CoG).

It takes about 3-4 hours to make all sub-estimates described in this case. In addition to this there might be an equivalent number of hours finding volumes, areas and other quantities to be used as input in the estimates.

8.4 Deviation between As-Built Weight and Estimated Weight

Experience shows that the estimated lightship based on these methods will differ by ±5% compared to as-built lightship weight reported when the ship is inclined. It's hard to tell how much of this deviation is caused by changes in specifications, but it is quite clear that a substantial part of the deviation is due to the fact that the estimate often is based on other assumptions that are not valid for the final vessel. Typically this can be a change of performance, the number of cranes and winches, or an increase in the amount of furnished spaces. Most of this should normally be identified as change orders, but some are caused by changes late in the design phase without updating the weight estimate.

9 Reports and Export of Estimation Results

9.1 Weight and Center of Gravity

When the final results of an estimation job are to be reported, it's important that the basis for the estimate is documented together with weight, uncertainty, center of gravity and extensions. This includes how the hull is divided into subgroups and all parameter figures. There must be a clear understanding and description of what is included in each weight group and what assumptions the estimates are based upon.

9.1.1 Margins

For a parametric estimate based on as-built data, the chance of underestimating equals the chance of overestimating, a so-called 50-50 estimate. This thesis has the following assumptions:

- All reference data in a weight group is 100% complete, meaning that no weights are missing. For example, when estimating total machinery, there should be no reference data that includes engines but no piping. Incomplete weight groups often occur when a weight database differs significantly from weighing/inclining results, and correction weights are not implemented in the correct groups but only as one single correction item, not included in any estimation groups.
- The parameter values for the estimation project must not be underestimated. For example, when estimating outfitting, weight in accommodation areas for all furnished spaces must be included. In an early design phase some spaces may be marked as void.
- All relevant weight groups are estimated. When the detail level increases, there might be a risk of forgetting to estimate some groups.

If the assumptions for a 50-50 estimate are satisfied, there should be no need for contingency to account for weight that is not included. However, a safe margin must be considered based on the risk of the project and the estimated standard deviation for the lightship weight and center of gravity.

9.2 Weight Distribution

A longitudinal weight distribution curve will be an important result of a weight estimation job. In addition to weight and longitudinal center of gravity (LCG) for each weight group, minimum (LCG_min) and maximum (LCG_max) extent for the weight group must be defined.

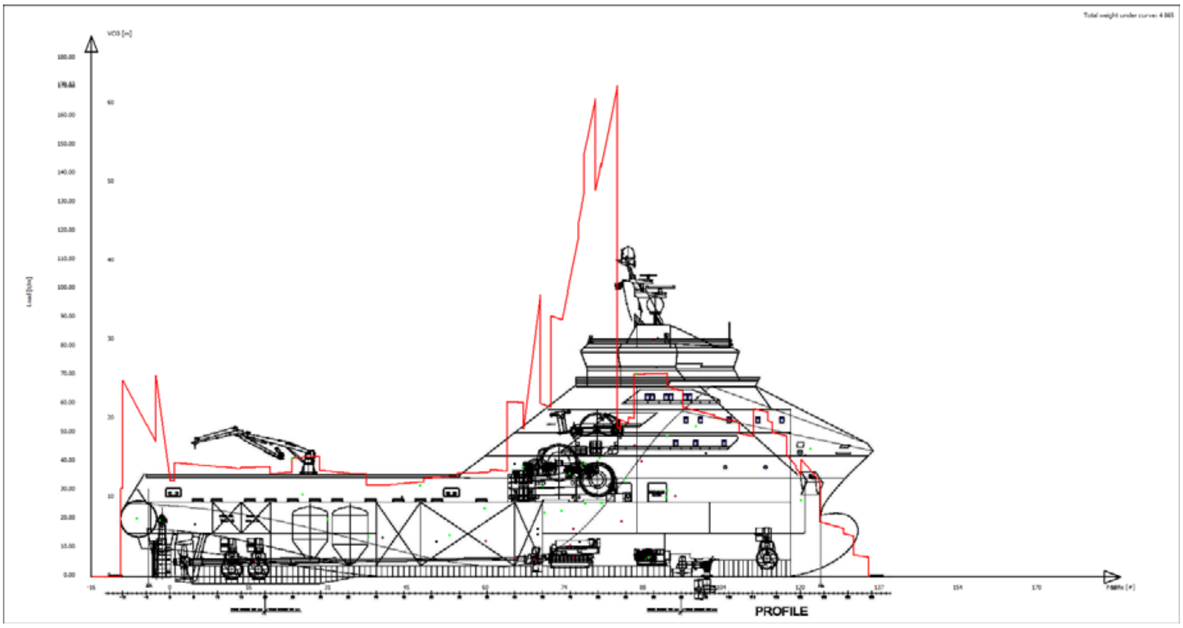
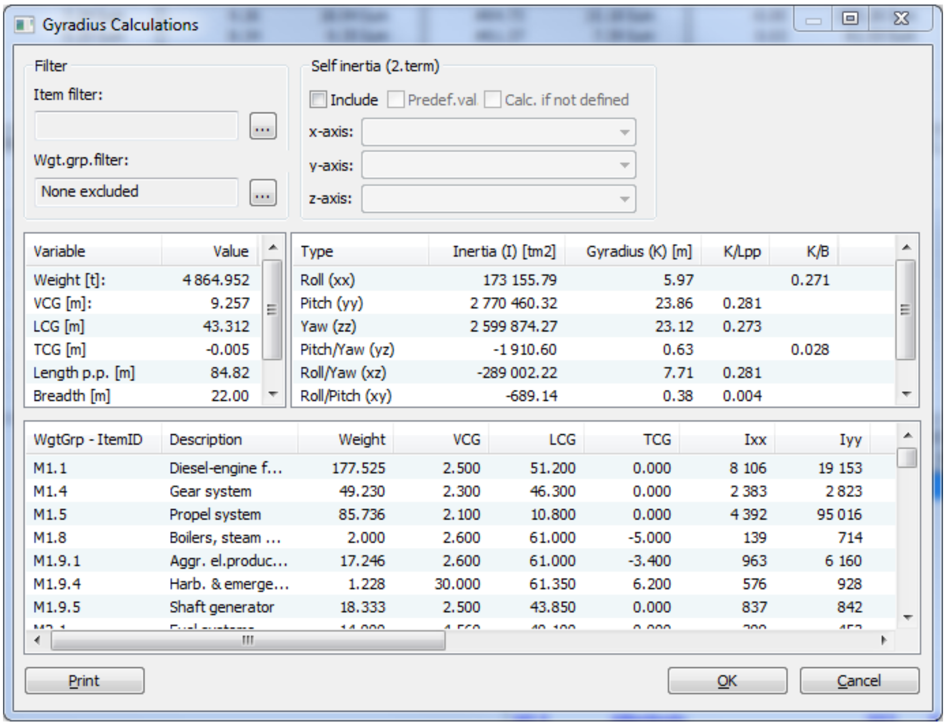


Figure 8: Weight Distribution curve based on parametric weight estimation for AHT

Besides the graphical curve, the values for the curve in specific table formats are exported so that the weight distribution curve can be imported to hydrostatic software for calculation of hogging and sagging moment.

9.3 Moment of Inertia and Gyration

Moment of Inertia and gyration figures can also be calculated based upon the weight and CoG estimation results and this is a necessary input for seakeeping software to calculate the behavior of the vessel at sea.



Picture 1: Screenshot from ShipWeight showing calculated figures for moment of inertia and gyration

9.4 Weight of Modules, Towing, and Sea Launching

If the estimates are executed at a sufficient level of detail it will be possible to calculate the weight and CoG for modules in an early phase. It is quite common that the main hull and some outfitting (e.g. piping and foundation) are completed by a subcontractor and then towed to the main contractor for final outfitting and completion. In such cases there is a need for a good estimate of the half-finished hull to plan launching/undocking and towing. Sub-estimates according to hull areas as shown in Figure 7 are a good starting point to make such calculations.

There may also be reviews of how much of the superstructure / deckhouses / wheelhouse that can be put together prior to a lift onto the main hull, in order not to exceed the maximum lifting capacity on the shipyard. Level of outfitting will also be a consideration in connection with the planning of this type of lifts.

10 Design Changes and Re-estimation

10.1 The Need of Re-estimation

In the design phase there will be continuous changes to the vessel's design and characteristics toward entering the contract. Because of this there will be a continuous need of re-estimation of the weight of the ship. Due to the often limited amount of resources dedicated to carry out these tasks, re-estimation is only done when there are major design changes or close to contract signing.

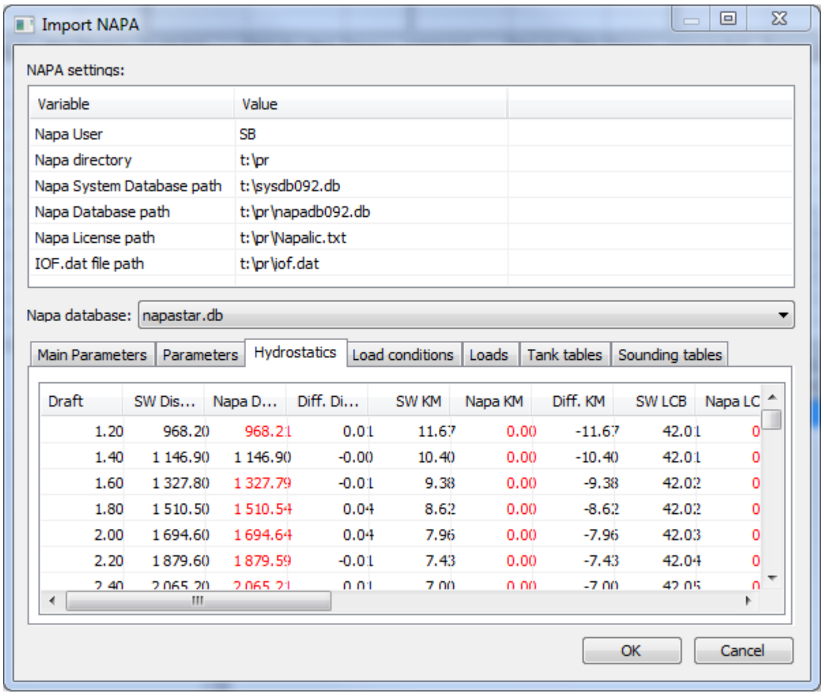
Unfortunately, it turns out that one often waits too long before doing a re-estimation of a project and even enters a contract based upon weight estimates carried out on outdated assumptions.

In the next chapters we will look into what is needed to update the weight estimate in an easier and more efficient way than is commonly done today.

10.2 Import of Parameters

Because most of the estimates are based on various parameters describing the size and power of the vessel, it is essential that the transfer of this type of information can be carried out as efficiently as possible from other design systems into the weight estimation system. This applies to parameters like ship length, beam, depth and draft, but also the number of main engines and their associated systems. Areas and volumes are also key variables in weight estimation. See definition of estimation methods in Table 15.

Table 16 shows the parameters used in the estimation of the most important weight groups, and as specified in the table, information sources are the General Arrangement (GA), outline (building) specification, and ship models for hydrostatic calculations. It has been proved possible to implement import procedures in the weight estimation system making it possible to retrieve information from design product models seamlessly without the use of intermediate files or manual input, by the use of an application programming interface (API).

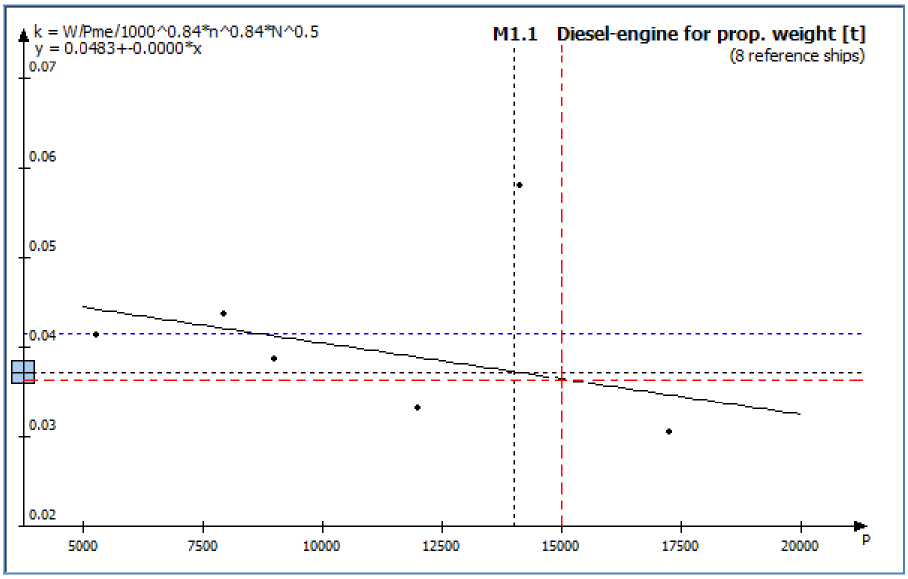


Picture 2: Screenshot from ShipWeight showing parameter import from a product design model

10.3 The Consequence of Changing Parameters and Re-estimation

When a parameter used in estimation of weight or CoG has been changed, the system should alert for the need of re-estimation. It should also be possible for the system to automatically re-calculate the affected groups based on those selections and regression curves generated in the initial estimate.

The example below shows a re-estimate for weight of main engines when the number of engines is reduced from 4 to 3 and the power has increased from 14 000 kW to 15 000 kW.



Graph 10: Plot of reference ships and regression line for weight of main engines

	k	P_{me}	n_{me}	N_{me}	Weight
Estimate	0.037	14000	750	4	178
Re-estimate	0.036	15000	750	3	158

Table 17: Re-estimate of weight for main engines

11 Conclusion

Parametric estimation of weight and center of gravity is an effective way of generating a weight budget all the way through the design phase. In the last 10 years we have used this methodology for estimation of several new designs for a large variation of ship types and offshore constructions.

The assumptions that must be fulfilled to carry out parametric estimation are:

- An efficient estimation system;
- Reference ship data systemized according to a fixed breakdown structure;
- A skilled weight estimator; the system is not a black box solution!

The most significant disadvantages with the methodology are:

- Many people are skeptical to the methodology, mainly because of limited understanding of the theories behind it;
- The method is based on use of systemized as-built data that may be hard to collect or generate, because it’s not necessarily the same people, departments, or companies doing estimates and weight monitoring;
- Re-estimation is not very efficient in many systems available today, and it’s not possible to have real-time updated weight estimates when changing the design.