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Estimation methods for the steel weight of inland tank ships

R. G. Hekkenberg and J. J. Hopman

In this paper, two methods to estimate the steel weight of inland coated tank ships during the earliest design stages are presented: the first is a set of simple functions that are valid for ships with common dimensions and length-to-beam ratios of European inland ships. The second is a single more elaborate function that covers a larger range of dimensions and length-to-beam ratios. Both methods are based on the calculated weights of a large series of computer-generated ship designs. To calculate these weights, a computer program was developed that generates ship structures on the basis of Lloyds Register's rules for inland ships and estimates the steel weight of those ship structures. The approach to generate the ship structures as well as a validation of their scantlings and steel weight are also discussed.

Keywords: Inland ships, Tankers, Ship design, Weight estimation

Introduction

In the last decades, the maximum dimensions of inland ships that sail on European inland waterways have increased significantly, while small ships are hardly built anymore. Thus far, the biggest increase in dimensions is observed for tank ships, the largest of which has a length of 147 m, a beam of 22.8 m and a draught of 5.4 m. This makes it the largest indivisible ship on European inland waterways. At the same time, the upward trend in draught of inland ships may have reached its limits: in 2011, the concern that the draught of inland ships is already too large was expressed in a document by the Dutch government (Rijkswaterstaat 2011, p. 13). This concern also exists in the ship design community, as is underlined by Thill (2009). He predicts the need for lighter and wider shallow draught vessels to cope with low water levels in the Rhine. As a result, it is likely that an increasing number of ships will be developed with dimensions, L/B ratios and B/T ratios that deviate significantly from common values. In the earliest development stages of such new ships, a lightweight estimate is required to assess their cargo carrying capacity and building cost. This in turn is essential input for the economic feasibility study that should precede the detailed design of a novel ship. However, for such unconventional ships, designers can no longer rely on the experience they obtained through the design of previous ships to estimate steel weight. At the same time, existing empirical steel weight estimation methods for inland ships become too unreliable since they are insensitive to changes in L/B and B/T ratios and do not cover vessels that are larger than existing ships, as is shown in the next section. In order to fill this gap, new methods are required that can provide more accurate steel weight predictions in the earliest conceptual design stages of inland ships. Two such methods are developed in this paper. They differ in form as well as the range of dimensions and L/B ratios that they can be applied to. After relevant background on existing methods is presented in the Background section, the Data creation section discusses the creation of the data underlying the new methods and the Data validation section treats the validation of the data. The Trends in steel weight section presents the trends in steel weight that are deduced from the dataset and the New estimation methods section discusses the development of the new methods.

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Background

Many analyses and optimisations of steel structures of ships can be found in scholarly literature. Many other papers describe the methods to perform these analyses and optimisations. Overviews of these studies may be found in e.g. Rigo (2003) and Sharma *et al.* (2012). However, analysis or optimisation of a ship's structure requires knowledge of that structure that is unavailable in the earliest design stages of a ship. During these earliest design stages, designers are interested in estimation of weight and centre of gravity rather than optimisation of the structure (Rigo and Caprace 2011). To estimate weight, they rely on data from reference ships or on one of the classic empirical methods of Watson and Gilfillan (1977), Kerlen (1981), Carstens (1970), Schneekluth (1968) or Puchstein (1961). These methods are poorly applicable to inland ships since they are based on regression of data from seagoing ships that have different L/B, B/T and D/T ratios from inland ships and are designed to withstand much larger wave loads. As an example, the method by Watson and Gilfillan leads to an overestimation of the steel weight by more than 35% for a common 110 m long and 11.4 m wide inland tanker. This underlines the large errors that may be result from the application of weight estimations for seagoing ships to inland ships.

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The few existing weight estimation methods for inland ships are based on dry cargo ships. Heuser (1986) provides a rough indication of the lightweight of inland dry cargo ships as a function of LBD (length × beam × depth), but does not identify which percentage of lightweight constitutes the ship's steel weight. Schellenberger (1978) treats length, beam and depth separately for the steel weight of the same ship type. More recently, Hekkenberg and Hopman (2015) developed new steel weight prediction methods for inland dry bulk ships. However, all three methods are based on dry cargo vessels and will, therefore, underestimate the weight when they are applied to tank ships. GL (Germanischer Lloyd 2006, Pt B, Ch 4, Sec 2, par 5.2) only states a steel weight of 0.15 × LBD for vessels with a depth of 3.7 m or less and 0.1 × LBD for vessels with a larger depth, which is too crude to serve as a reliable design estimate. From the above, it is concluded that neither the existing methods for steel weight predictions of seagoing ships, nor those for inland ships can reliably and accurately predict the weight of the desired range of inland tank ships. Therefore, new methods are required.

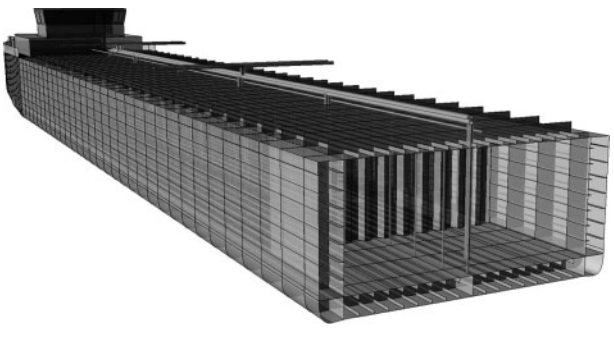
Data creation

The aim of the methods that are discussed in this paper is not only to predict the steel weight of inland tank ships with common main dimensions, but also to predict the steel weight for ships with main dimensions that deviate significantly from these main dimensions and have not been built yet, although they are anticipated. As a result, performing a regression analysis on known data is insufficient to develop this method, even if such data would be publicly available to a far greater extent than it is. Therefore, the missing data is generated by a large series of computer-generated ship designs. To obtain the weight data from these designs within a reasonable amount of time and with limited effort, a model that generates conceptual designs automatically is developed. This section discusses the way the designs are created, the way their structure is modelled the way their depth is calculated.

Creation of the designs

The designs are generated by a model that combines CAD program Rhinoceros 3D and Excel. Rhinoceros 3D is used for all geometry-related operations, while excel is used to calculate scantlings of all main structural members. This leads to a 3D representation of the design as shown in Fig. 1.

This model is used to generate a large series of designs with systematically varied length, beam and design draught. In this series, draught is varied from 1.5 to 4.5 m, length is varied from 40 to 185 m, beam is varied from 5 to 25 m and L/B ratio is bounded between 4 and 20. This leads to a matrix with 518 designs, as shown in Fig. 2.



1 Modelled ship (cut in half for illustration purposes)

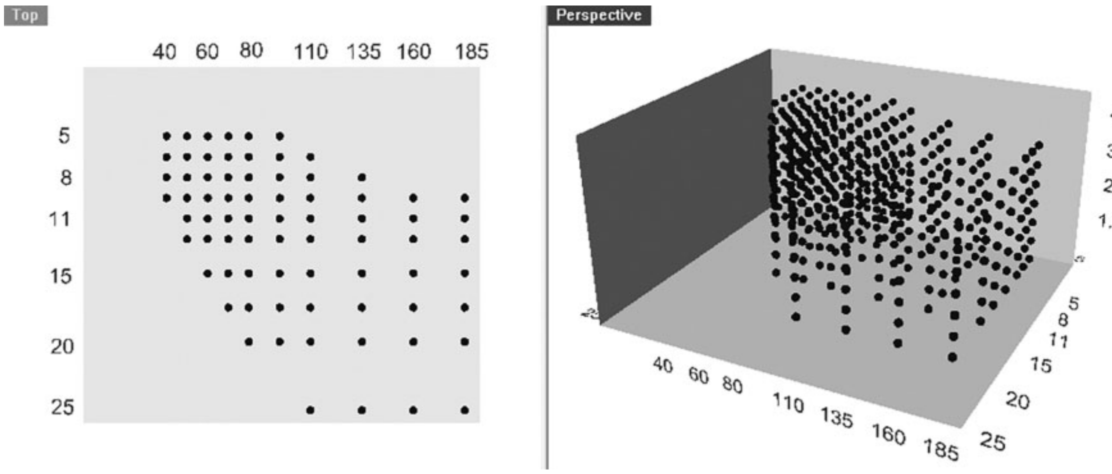
The lower limits of length and beam match the dimensions of the smallest commercially used inland cargo ships in Europe, while the upper limits represent the maximum practical size that inland ships can have on the river Rhine due to infrastructural restrictions. A significant part of the designs exceeds the regulatory length limit of 135 m as dictated by the Central Commission for Navigation on the Rhine (2010), thereby preparing the method for any future changes in the regulations.

Design of the steel structure

The scantlings of the steel structures of all designs are calculated according to the structural rules for inland ships by Lloyds Register (2008) for coated tankers that adhere to ADN rules (Economic Commission for Europe 2009). To ensure that global stresses are modelled correctly, the standard still water bending moments proposed by Lloyds Register are replaced by design-specific bending moment calculations that include an approximation of the ship's actual lightweight distribution and the loading conditions that normally lead to the highest bending moments: fully loaded, empty and with the aft 10, 15, 20 and 25% of the holds loaded.

The purpose of the methods to be developed is not to optimise the steel structure of inland ships, but to provide an acceptable weight estimation in the earliest design stages. Therefore the structural arrangement of the designs is fixed at values that are common in the sector, despite the fact that the model offers the freedom to change these values, e.g. for validation purposes. In all cases, the aftship and foreship are transversely framed, with a frame spacing of 500 mm and a webframe spacing of 3 m. The midship is longitudinally framed with a double bottom height of 0.7 m and double hull width of 0.8 m. The number of girders is selected such that their spacing is as close as possible to 5 m while ensuring that there are girders below the longitudinal bulkheads. Longitudinal spacing in the double bottom and sides is dependent on the girder spacing and height of the sides, but a maximum spacing of 600 mm is maintained. A detailed description of the generation of the general arrangement of the designs may be found in Hekkenberg (2013).

Despite the use of rules to calculate scantlings and the 3D representation of all main structural elements in the design model, the structural weight calculation requires several correction factors. A weight allowance of 10%, as proposed in Schneekluth's method (Schneekluth and Bertram 1998, p. 155), is applied to all structural elements to account for missing structural details, local strengthening etcetera. In the aftship, the weight allowance is increased to 15% to compensate for the simplification of the hullform and the absence of stern tunnels in the model. Lightening holes in non-watertight webframes, floors, girders and plate stringers are not modelled. To account for them, a 25% weight reduction is applied to these structural elements, based on an analysis of several webframes of inland ships. For plate frames in tanks, this reduction is increased to 30%, to



2 **Overview of design points in the systematic series**

account for the fact that they are typically wider than normal webframes, thereby leaving more room to cut out holes without compromising the structure's strength. It will be shown in the Data validation section that these assumptions lead to realistic steel weights.

Design of the ships' depth

For inland tank ships, depth of the ship is not determined by freeboard demands but by the need to match the volume of the tanks to the density of the cargo and the maximum cargo weight that the vessel can carry. Since there is an interaction between the volume of the tanks, vessel depth, lightweight and cargo weight, finding the right vessel depth is an iterative process.

The weight-to-volume ratio of the cargo tanks of common European inland tank ships is estimated at $0.86\ \mathrm{t\ m^{-3}}$, based on data of existing vessels recorded by Vereniging 'De Binnenvaart' (2007–2011). This value is used as the target value for the ratio between tank volume and deadweight. After two iterations, the tank volume to deadweight ratio of the designed ships closely matches this target value.

The need to increase depth to achieve the required tank volume leads to a relatively large increase in depth for short, narrow vessels and only a small increase for the long and wide vessels, as is shown in the example designs in Fig. 3.

Data validation

Validation of the steel structure and weight of the generated designs is done in three ways:

(1) Modelled midship scantlings are compared to scantlings of the midship sections of two existing ships.
(2) Calculated weights are compared to the weights of three existing ships.
(3) Calculated weights are compared to the weight estimated by Germanischer Lloyd (2006).

Further validation may be found in Hekkenberg and Hopman (2015), which shows good matches between modelled and actual scantlings of two dry bulk ships and between the modelled and actual steel weight of a dry bulk ship.

Validation of midship section scantlings

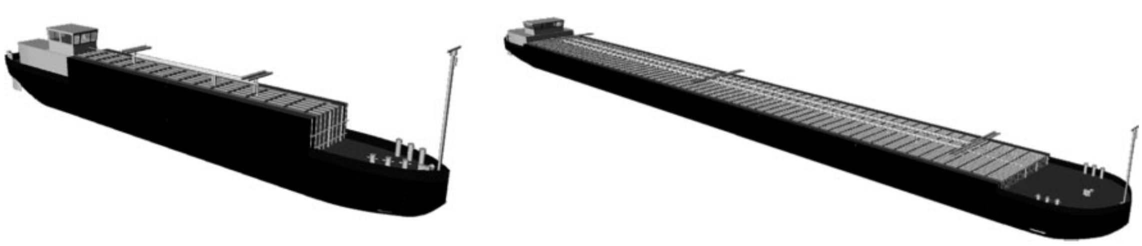
Validation of calculated scantlings is done through a comparison of modelled scantlings with those of the midship sections of two existing tank ships. The first is a stainless steel ship with a length of 110 m, a beam of 11.4 m, a draught of 3.35 m and a depth of 5.05 m, while the second is a coated tank ship with a length of 86 m, a beam of 10 m a scantling draught of 3.2 m and a depth of 4.85 m.

Ship 1:

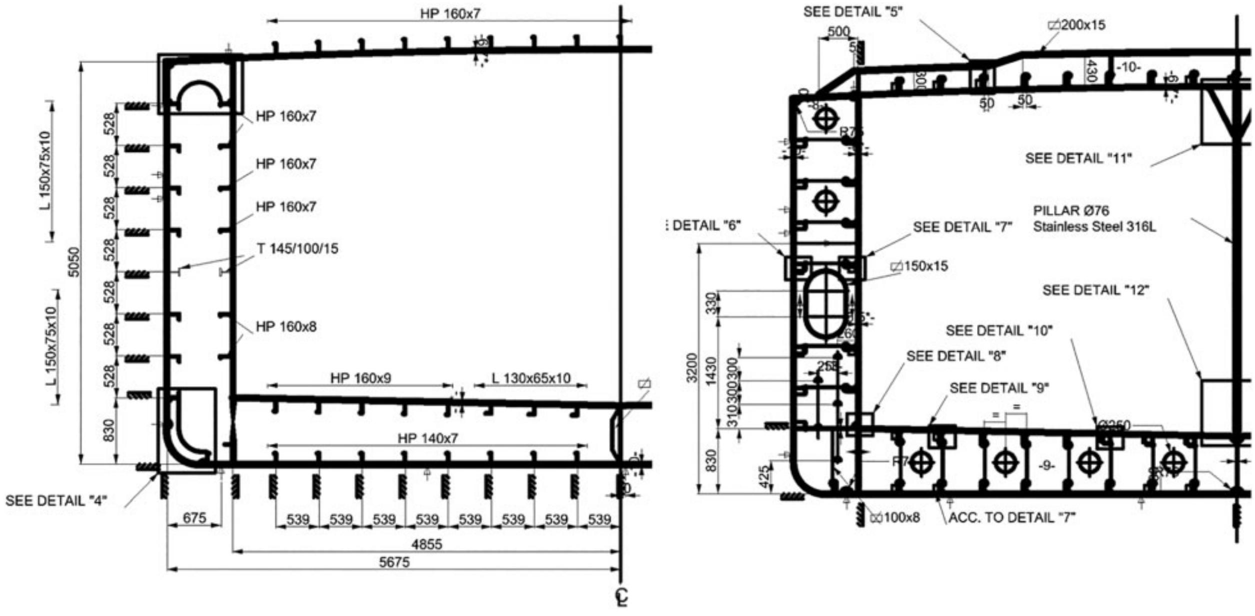
The structure of ship 1 has the following primary features: There are web frames every 1785 mm, the double bottom is sloped with a height between 730 and 830 mm and the double hull is 820 mm wide. Design pressure of the tanks is 50 kPa and design density of the cargo is $1.6\ \mathrm{T\ m^{-3}}$. Figure 4 shows a drawing of the relevant frames in the actual ship.

To validate the results from the model, Table 1 shows a comparison between the actual and modelled scantlings of the midship section of the ship.

Table 1 shows a close match between actual and modelled scantlings. The main deviation in this case is a slightly heavier/stronger bottom structure for the real ship. In practice, 9 mm is the smallest thickness that is commonly applied to bottom and sides of inland ships. This value is, therefore, also used as a minimum value in all subsequent designs generated with the model.



3 **Example designs of a small and large tank vessel**



4 Ordinary frame and webframe of ship 1. Drawings courtesy of Mercurius Shipping Group

Table 1 Validation of modelled scantlings of ship 1

	Real value	Model value
Bottom plating	10 mm	8.5 mm
Inner bottom plating	7 mm	7 mm
Bilge	13 mm	10.5 mm
DB floors	9 mm	8.5 mm
DB girders	Unknown	8.5 mm
Inner side plating	6.5 mm	6.5 mm
Corrugated bulkheads	6.5 mm	6.5 mm
Side plating	10 mm	9.5 mm
Deck plating	6.7 mm	7 mm
Inner bottom longitudinals	HP160 × 9/130 × 65 × 10	HP 180 × 8
Bottom longitudinals	HP120 × 7	HP120 × 7
Inner side longitudinals	HP160 × 8/HP160 × 7	HP160 × 9
Side longitudinals	150 × 75 × 10	150 × 75 × 10
Deck longitudinals	HP160 × 7	HP160 × 7
Deck beams	430 × 10 200 × 15 face plate	440 × 200 × 14
Pillars/tension rods	76 mm	75 mm

The heavier bottom of the real ship also explains its lighter inner bottom longitudinals, since the rules state that they may be made smaller than normally allowed if '*there is an appreciable excess in the midship section modulus*' (Lloyds Register 2008, Pt. 4 Ch. 6, Table 6.5.1), which is the case for this ship. The difference in the deck beams is explained by the fact that the model contains a limited number of beams with a large modulus and has selected the most appropriate one, which is indeed a close match with the modulus of the beams on the real ship.

Ship 2:

The structure of ship 2 has the following primary features: The sides are transversely framed with a frame spacing of 608 mm and web frames every 1824 mm. The double bottom and deck are longitudinally framed with a spacing of 495 mm between the longitudinals. The bottom is sloped with a height between 750 and 850 mm and the double hull is 1000 mm. The design cargo density is 1.0 T m^{-3} and the design pressure head is 50 kPa.

From Table 2, the general agreement between model and the actual ship is again visible. Again, the owner's preference for robustness over weight savings becomes clear from the slightly higher plate thicknesses. The fact that the side and inner side frames of the model are larger than those of the actual ship are explained by the thinner plating and by the fact that the real ship has support beams below the deck and bilge brackets that extend above the double bottom, thereby reducing the span of the frame.

Validation of overall steel weight

Validating the overall weight of the modelled steel structure of a ship is difficult because of the scarcity of available data and the impact of the many possible design choices in terms of frame spacing, double hull width, double bottom height, choice of framing system, vessel layout etc. However, based on a number of reference vessels a reasonable validation can be done. For the three chemical tankers in Table 3, weights are available but details about the structural arrangement as well as the length of fore and aftship are unknown. Vessel C is has stainless steel tanks, but for vessels A and B it is unknown if the tanks are coated or stainless steel.

Table 2 Validation of modelled scantlings of ship 2

	Real value	Model value
Bottom plating	10 mm	9 mm
Inner bottom plating	8 mm	7.5 mm
Bilge	12 mm	11 mm
DB floors	8 mm	8.5 mm
DB girders	10 mm	9.5 mm
Inner side plating	9 mm	8.5 mm
Corrugated bulkheads	8 mm	8.5 mm
Side plating	12/10 mm	9 mm
Deck plating	8 mm	7 mm
Inner bottom longitudinals	HP 180 × 8	HP160 × 7
Bottom longitudinals	HP 140 × 8	L 70 × 70 × 7
Inner side frames	HP 220 × 10	HP 260 × 11
Side frames	HP 180 × 8	HP 180 × 10
Deck longitudinals	HP 140 × 9	HP 160 × 7
Deck beams	400 × 8 with150 × 15 flange	350 × 200 × 14
Pillars/tension rods	90 mm	70 mm

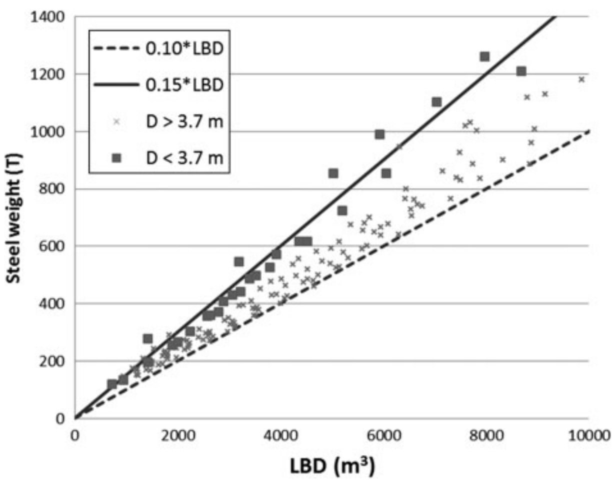
Table 3 Weight data of existing and modelled tank vessels

Ship	A	B	C
length × beam × depth (LBD)	86 × 9.6 × 3.75	85.9 × 11.4 × 5.05	110 × 11.40 × 5.4
Weight aftship	76 T	74 T	–
Weight midship	338 T	392 T	–
Weight foreship	53 T	45 T	–
Weight total	467 T	511 T	718 T
Modelled weight	390 T	517 T	717 T
Weight error	−16.5%	+1.2%	−0.1%

The weights of these ships are compared to the weight of designs generated using the approach of the Back ground section.

The modelled steel weight of ship C closely matches that of the actual ship. The same is valid for ship B, assuming it has stainless steel tanks. If it has coated tanks, the calculated weight is 20 t (3.9%) more. The weight difference for ship A is much larger. For this ship the weight difference between the stainless steel and coated versions is only 7 t, so this does not account for the difference. However, the design of this ship is derived from that of a dry cargo ship. This could mean that the ship is transversely framed and that the foreship and aftship have the same depth as the midship instead a lower depth, which is more common. When transverse framing is applied to the modelled ship and the depth is set at 3.75 m along the entire length, weight increases to 435 t. This reduces the discrepancy between actual and modelled weight to 6.9%.

The previous steps in the validation demonstrated two things. The first is that the model will properly calculate the scantlings of a ship, which ensures that the basis for the weight calculation is correct. The second is that calculated steel weight approximates the actual steel weight well, but that choices regarding the framing system, height of the bow and stern and material used for the tanks may have a considerable impact on the weight. Therefore, a final check on the validity of the generated data is done by comparing the weights of the modelled designs to the weight estimates by GL (Germanischer Lloyd 2006, Pt B, Ch 4, Sec 2, par 5.2). They state a steel weight of 0.15 × LBD for vessels with a depth of 3.7 m or less and 0.1 × LBD for vessels with a larger depth. Since Germanischer Lloyds' rules are applicable to common European inland ships, only ships with a length up to 135 m, a draught between 2 and 4 m an L/B ratio between 6 and 12 are selected from the dataset of designs. This captures the lengths, draughts and L/B ratios of the vast majority of European inland ships.

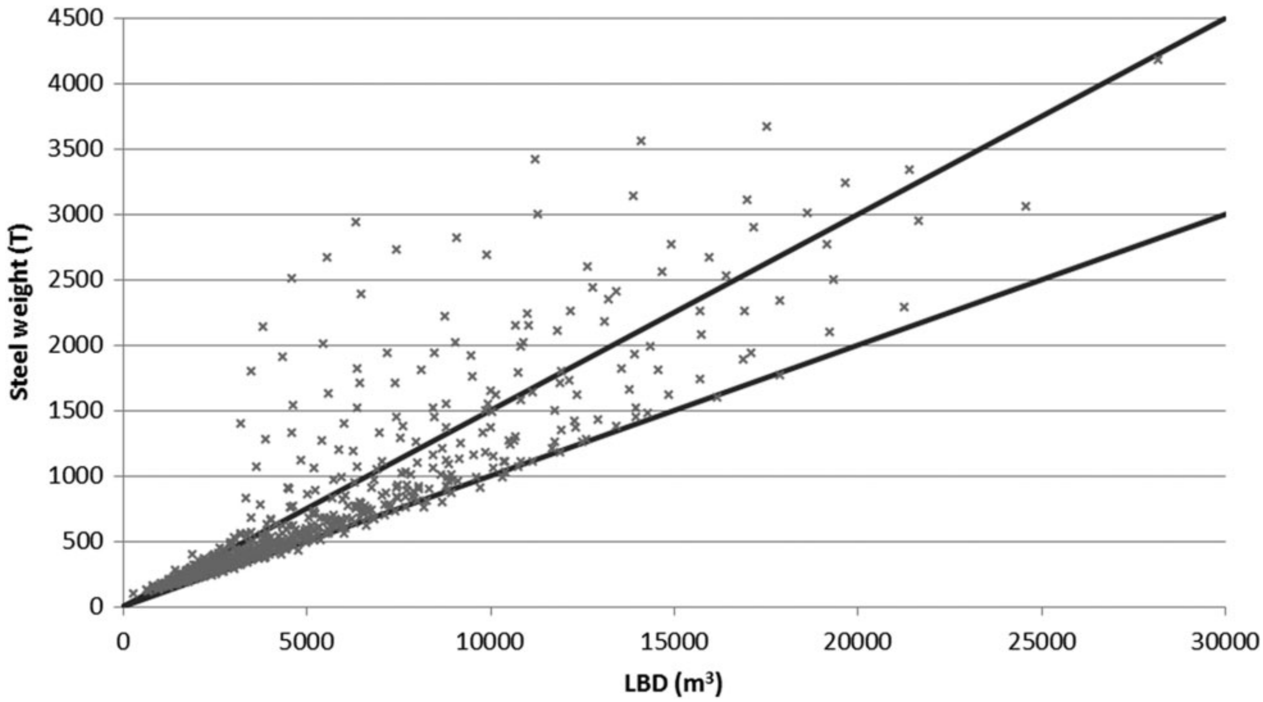


5 Steel weight versus length × beam × depth (LBD) – selected designs

Figure 5 shows that the designs with a depth below 3.7 m are close to the indicated value of 0.15 × LBD, while the lower bound of the weight of the vessels with a higher depth is very close to the value of 0.1 × LBD. This further increases confidence in the correctness of the calculations.

Trends in steel weight

The generated design data can be used to gain insight in the relation between ship dimensions and weight. In Fig. 6,



6 **Steel weight versus length × beam × depth (LBD) – all designs**

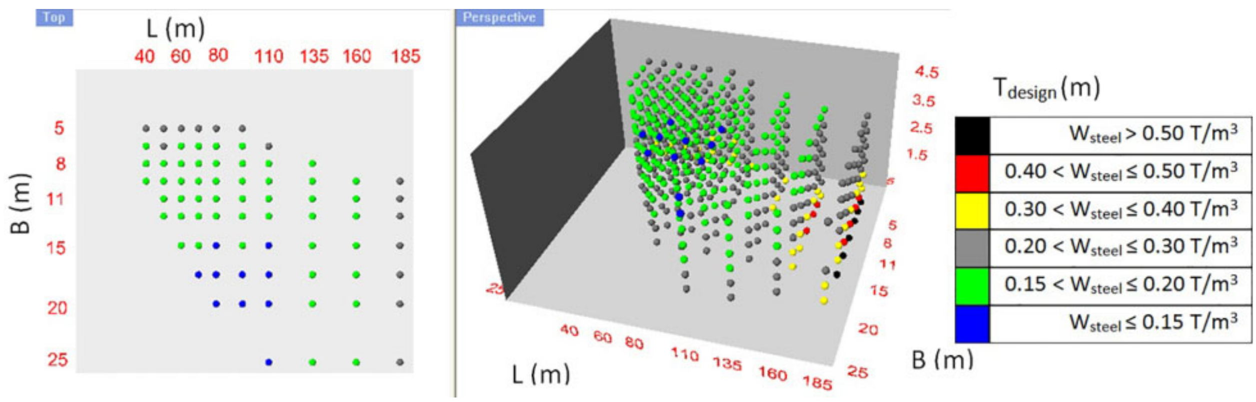
the steel weights of all generated designs are plotted against LBD. In this same figure, the weight estimates as provided by Germanischer Lloyd (2006), being 10 or 15% of LBD, are shown as continuous lines. What becomes apparent is that a number of ship designs are substantially heavier than these estimates. This underlines the limited validity of these estimates for non-standard ships and the need for alternative methods.

In the earliest design stages of inland tank ships, draught is a far more important design parameter than depth since draught is nearly always constrained by water depth. In practice the depth of inland tank ships depends only on the required tank volume, which is in turn determined by deadweight. A large depth is not required to meet stability regulations. This makes depth a derivative value of length, beam and draught. Therefore, in the remainder of this paper only length, beam and draught are used as parameters.

Steel weight of the modelled ships is plotted against length, beam and draught in Fig. 7. It shows that the lightest ships are relatively short and wide ships with a high draught. For these short ships, longitudinal bending moments are not yet high enough to increase plate thicknesses beyond the minimum commonly applied value of 9 mm for bottom and sides. Understandably long ships with a low draught will be relatively heavy due to the large bending moments and low distance between the extreme fibres of the structure.

The generated data can also be used to estimate what Watson and Gilfillan's well known K-factor (Watson and Gilfillan 1977) would be for inland tank ships. For *E*-numbers between 295 and 5700, *K*-values ranging from 0.020 to 0.048 are obtained. This is a much larger spread than for any other ship type in Watson and Gilfillan's method and severely reduces the accuracy of the method for this ship type. When limiting the dataset to ships that do not exceed the current maximum allowed length of 135 m, this spread in *K*-values is reduced only slightly to values between 0.020 and 0.044. This again underlines that existing weight estimation methods for seagoing ships are not suitable for the estimation of steel weight of inland tank ships.

The information in Figs. 6 and 7 provides significantly more insight into the weight of inland tank ships than



7 **Steel weight per cubic meters of LBT**

was available up till now, but is not yet very practical to use. Therefore, these data are also used to develop analytical estimation methods in the following sections.

New estimation methods

The weight data of the 518 modelled designs can be used as the basis for new empirical weight estimation methods that can be used in the earliest design stages of inland tank ships. The methods are not intended to predict the behaviour of the variables beyond the limits of the dataset, nor are they intended to be used in the optimisation of the ship's structure. This makes Ordinary Least Squares (OLS) regression, which is among the simplest methods for parameter estimation, a good approach to develop the estimation methods. Since OLS regression leads to good results, no alternative methods are explored.

The data points in Fig. 6 show a significant scatter, implying the need for a different function to approximate the data. However, most of the scatter is caused by vessels with an extreme L/B ratio, small draught or large length. This makes it possible to develop two estimation methods, a basic method that covers only a part of the dataset and a more generic one that covers the entire dataset.

The steel weight of ships with a length below 135 m, a constant draught and L/B values between 6 and 12 (i.e. more-or-less common European inland ships) can be approximated well by a simple second order polynomial with only LBT as a variable. Longer ships and ships with smaller and larger L/B ratios do not fit such polynomials well and need to be described by a more elaborate function.

Simple method

The simplest method consists of polynomials of the form of equation (1)

$$W_{\text{steel}} = c_1(\text{LBT})^2 + c_2\text{LBT} \quad (1)$$

The coefficients of this formula differ per draught. Table 4 displays coefficients $c1$ and $c2$ as well as the R^2 value for each draught

The high R^2 values demonstrate that the polynomial is a good approximation for the weight of the vessels in the dataset.

Generic method

The simplicity of the function of the simple estimation method could only be achieved by limiting the length

Table 4 Coefficients of the simple method

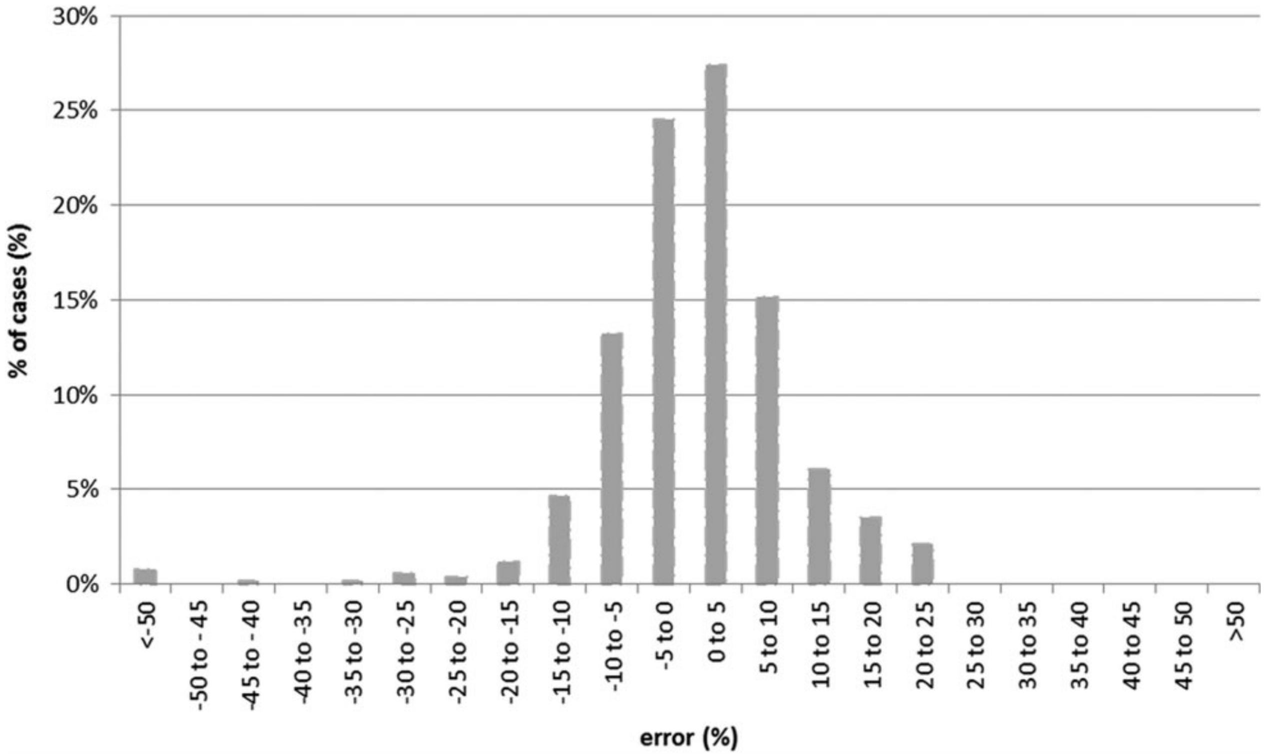
T (m)	*c*1	*c*2	R^2
1.5	6.70E−06	2.69E−01	0.993
2	−1.56E−07	2.33E−01	0.992
2.5	−1.24E−06	2.08E−01	0.990
3	−1.96E−06	1.97E−01	0.993
3.5	−1.61E−06	1.85E−01	0.991
4	−2.26E−06	1.82E−01	0.991
4.5	−1.99E−06	1.74E−01	0.990

Table 5 Coefficients of the generic method

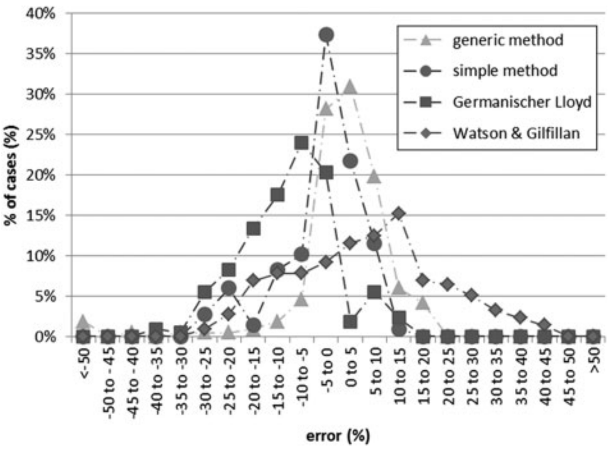
	Value	Std. error	Beta	*t*	Sig.
*c*1	4.220E + 02	1.600E + 01		26.372	0.000
*c*2	−7.694E−04	1.783E−04	−0.035	−4.314	0.000
*c*3	7.311E−02	1.939E−03	0.333	37.704	0.000
*c*4	1.157E−06	1.197E−08	0.679	96.688	0.000
*c*5	−7.922E+03	5.270E + 02	−0.095	−15.030	0.000

Table 6 R^2 value of the generic method

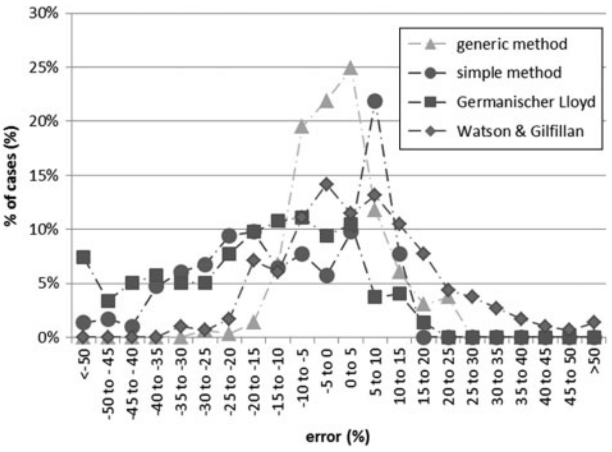
R	R^2	Adjusted R^2	Standard error
0.996	0.992	0.992	64.133



8 Steel weight error distribution for the generic method



9 Errors of various methods – conventional ships



10 Errors of various methods – unconventional ships

and L/B ratio of the vessels that are included and by setting different coefficients for each draught. A more generic function that covers the entire dataset should be able to deal with all extreme values in this dataset. It can be argued which parameters are relevant for this function. The simple estimation method already showed a strong correlation between LBT and steel weight, so this parameter should be included. Since the ratios between length, beam and draught vary widely in the dataset, the function should include variables that separate these elements. The combination of length and beam primarily influences the weight of the double bottom and main deck while the combination of length and draught primarily influences the weight of the double sides. Increasing length also leads to an increase in bending moments, which in turn leads to a heavier structure, especially in the double bottom and main deck. As a result, L^xB and L^yT are suitable parameters for the function. The exact values of x and y cannot be determined beforehand, so are varied systematically until good results are obtained. Values $x = 3.5$ and $y = 2$ lead to the best results. Since the use of these variables still leads to small systematic errors, a constant and a correction variable LBT^z are introduced. This leads to the function presented in equation (2)

$$W_{\text{steel}} = c_1 + c_2 L^2 T + c_3 LBT + L^{3.5}B + c_5 \frac{1}{(LBT)^{0.5}} \qquad (2)$$

The coefficients to be used with each of the variables from equation (2) are presented in Table 5. It shows the values of the coefficients but also reveals that all variables are significant and that LBT and $L^{3.5}B$ are the most influential variables. The R^2 values in Table 6 again show that the estimation method is a good predictor for the steel weights of the designs.

The error distribution in Fig. 8 shows that the error is less than $\pm 10\%$ in about 80% of all cases. However, there are a limited number of cases where the prediction deviates more than 25% from the original values. These cases represent the 5 m wide vessels with a draught of 1.5 m and/or a length of 40 m. In these cases the depth becomes excessive in order to accommodate the required tank volume, thus throwing off predictors that only incorporate L, B and T.

Analysis and conclusions

This paper discussed the development of new steel weight estimation methods for inland tank ships, to be used in the earliest design stages. It is demonstrated that the design model that is used leads to acceptable steel weight estimates and that the estimation methods that are derived from the generated designs lead to a good approximation of the original data. To prove the added value of the methods, their ability to accurately predict the steel weight of the modelled designs is compared to that of the previously discussed methods of Watson and Gilfillan for seagoing tankers and Germanischer Lloyd for inland ships.

For those designs that are within the validity range of the simple method, i.e. those resembling conventional European inland ships, results are presented in Fig. 9.

The figure shows that the new methods lead to a significantly higher number of cases with small errors than the other methods. It also shows that GL's method has a tendency to underpredict weight, while Watson & Gilfillan's method tends to overestimate weight. The simple method shows a small peak in the -15 to -30% error range. This peak is caused by the relatively poor prediction of the weight of 5 m wide ships because of their large depth.

The steel weight of the designs that are outside of the validity range of the simple method is predicted best by the generic method, as is shown in Fig. 10.

For these more unconventional ships, Watson and Gilfillan's method leads to a higher number of cases with large errors than the newly developed methods, while GL's tendency to underpredict weight increases further. It also becomes apparent that the accuracy of the simple method is greatly reduced outside its validity range.

The above demonstrates that in the earliest design stages, the newly developed methods can provide designers with a more accurate steel weight prediction than existing methods. For new designs with dimensions that lie within the dimension range of existing European inland ships, the simple method suffices, but for other designs, the generic method should be used.

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