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Feature-based estimation of steel weight in shipbuilding

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ABSTRACT

An innovative and accurate method for estimating the steel weight and center of gravity (COG) of a ship in the preliminary design phase, named feature-based segment estimation (FSE), is presented. The method is based on principal component analysis (PCA) and includes corrections to capture ship features that are neglected by PCA. The feature analysis is based on three-dimensional (3D) computer-aided design (CAD) tools, which are used to build a framework of the ship components, deriving the general steel weight formulas and developing correction methods.

The method uses PCA to identify the principal parameters from a set of the ship's parameters and the main structural components, or segments, and to derive general equations for estimating the steel weight. Then, the estimated weight is adjusted using least squares regression based on the features of each structural segment. We demonstrate the practicality and effectiveness of the proposed method by applying 10 modern designs ranging from 1000 to 8500 twenty-foot equivalent units (TEU). The estimated results are presented and compared with those of the standard method, which consists of estimating the weight of the entire ship.

1. Introduction

1.1. Early stage steel weight and center of gravity estimation

Estimating the weight and center of gravity (COG) is an essential task in the design phase of a vessel. Accurate estimates are important for obtaining a light ship weight, and the quality of the estimate is crucial for the success of a project, affecting not only the ship design but also contract negotiations. The light ship weight estimate, which can be obtained using various methods, typically consists of the structural, outfit and machinery weights. However, the structural weight is the main factor in weight control because it has a significant influence on large merchant ships (Aasen and Bjorhovde, 2010; Watson, 2002). According to this research, the structural weight accounts for more than 70% of the total **light weight** of large container ships with a capacity of at least 8000 twenty-foot equivalent units (TEU) (CSBC Corporation, 2011). Although the structural weight in merchant ships includes all of the steel or other structural materials required for construction, including any filler metal in the welds, preliminary estimates typically include only the weight of the steel, which is obtained from a suitable empirical formula (Barrass, 2004) and then corrected for lesser items based on practice. Hence, we focus on methods that provide fast and accurate preliminary estimates of the steel weight.

From the beginning of the conceptual design to the contract stage, weight estimation is a challenging task if the new ship differs even slightly from previously built ships (Aasen and Bjorhovde, 2010). There are insufficient data to support accurate computations because a complete three-dimensional (3D) computer-aided design (CAD) model of the new ship is not available, and only an approximate arrangement plan exists. The lack of systematic empirical data, the limited project time and the considerable uncertainty of the results hinder the estimation task. However, the estimation results may be the deciding factor for success in winning a contract for designing or constructing the vessel. The estimate will affect the load capacity, speed, stability, seaworthiness, and delivery of the completed vessel, as well as the financial outcome of the project (Aasen and Bjorhovde, 2010).

Most estimation methods consider the weights of the hull and superstructure separately. There are 4 types of method. The first type is based on the ship's characteristics, where the weights are assumed to be functions of the main characteristics of the hull. Systematically varied container ship forms and sizes have been evaluated while considering the dimensional constraints, structure, form, speed, and propulsion (Bertram and Schneekluth, 1998). Many formulas have been derived with different constraints for container ships (Bertram and Schneekluth, 1998; Kerlen, 1985; Miller, 1968; Watson and Gilfillan, 1976). This type is also appropriate for optimization of the

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main dimensions (Kuniyasu, 1968; Lyon and Mistree, 1985; Nowacki, 2010).

The second type is based on data from existing ships. However, the data may be not satisfactory for the new types of ships. To obtain more precise estimates, the second method is typically combined with elements of the first method and appropriate regression analysis with data compiled from existing ships. This traditional estimation procedure is referred to as parametric estimation. An empirical formula in which indices are allotted to the ship's main dimensions, such as the length L, breadth B, depth D, and block coefficient (C_B), is used. Reference ship data are selected for use with the estimation formula and regression analysis (Watson, 2002). Two models of the regression-based parametric estimation, which use the cubic number $C_n = (L \times B \times D/100)$ or the area variable $L \times (B+D)$ as the independent variable, are more general in the early stages of design (Kazuhiko, 1998; Lamb, 2004). In addition, C_B may be an optional corrected parameter in these models. The models are still generally applied using commercial design software, such as Shipweight, Costfact, or Spar. The length of the superstructures and the ratio L/D can be used to correct the estimated result and then add the extra estimated weight (Benford, 1969). However, the parametric estimation method mainly uses overall ship parameters; it does not reflect local design features, such as a parallel midship section, the bow type, or the forecastle geometry. Most methods use fixed values or provide an empirical range for the coefficients of the main parameters. Therefore, the method provides only a rough estimate of the total weight and no estimate of the weight distribution. Although the method can be easily applied, choosing the appropriate formula and coefficients of the main parameters to precisely fit a ship design can be difficult in practice because of design changes. For example, a bulk carrier applying for the Common Structural Rules will have an increased hull weight (Zakki, 2013), but the hull weight can be reduced using high-strength steel (Løseth et al., 1994).

The third method is based on surfaces of the hull form. Due to the demand for faster and more efficient development of hull forms, designers face the challenge of quickly determining the hull form (Zhang et al., 2008). Because the method requires more information, including the thicknesses of the hull and the bulkheads for calculating the weight, it can be used when the general arrangement and the subdivisions are already approximately known.

The fourth method is based on the midship section modulus and is widely used by classification societies (AS, 2011). The weight and COG can be calculated by designing the scantlings of the midship section and estimating the weight distribution. Although CAD systems have emerged as powerful tools for calculating the structural limits and bending moments, human intervention is typically required to determine the midship section and weight distribution. For more precise estimates and to analyze the structure, the surface information and general arrangement used in the third method can be included using the CAD tools. If major changes are made to the design or a special configuration is used, the ship can be divided into sections that are considered separately. However, this process is slower, and it is difficult to respond quickly and flexibly to variations in requirements in the early design stage.

1.2. Feature-based method

In the field of computer-aided engineering (CAE), feature-based approaches collect features that are more important and meaningful modeling units than dots, lines, and faces by simplifying and reducing 3D CAD data (Kwon et al., 2015). In previous studies (Lee, 2005), geometric information was widely used as simplification criteria. Only a few conducted studies have considered non-geometric information. Sufficient design detail may rule out this approach in the earliest stages of design (Bole, 2007). A reasonable division of ships is a popular methodology in ship design. A segment framework is applied to analyze the parts of the structures of the ship (Son et al., 2011). The qualitative complexity criteria were considered for estimating six segments of a ship in the concept design stage (Caprace and Rigo, 2011). A feature-based cost model of ships for cost effectiveness measurements was developed based on the elementary parts of a ship's structure (Caprace and Rigo, 2012). In this study, we simplify the 3D CAD data of the built ships under the specific segment framework of ships to analyze and mine the features of weight that are not only geometric. Then, the features of the relationships between these hull segments are considered and applied to estimate the weight and to correct the results of the segment estimations.

1.3. Related research

The proposed method uses the configuration segment concept and principal component analysis (PCA) to build segment frameworks and thereby obtain estimates for parts of the ship in addition to the entire ship, regardless of the differences between the new design and previous designs. The segment concept originates from the research of Son et al., which established a preliminary cost estimation method for ships using the bill of materials (BOM), 3D computer-aided manufacturing (CAM) tools and a computerized expert-system approach. Rather than computing an estimate for the entire ship, the method computes estimates for each configuration segment, which can be duplicated from similar parts of previously built ships (Son et al., 2011).

PCA, a multivariate analysis method, is used as the basis of the method to enable the accommodation of completely new designs. The earliest descriptions of PCA were given by Pearson (1901) and Hotelling (1933) and were subsequently combined by Atchley and Bryant (1975). In many physical and statistical investigations, it is desirable to represent a system of points in a plane or a higher dimensioned space using the “best-fitting” straight line or plane. Analytically this consists of taking $y = a_0 + a_1x_1 + a_2x_2 + \ldots + a_nx_n$, where $y, x_1, x_2, \ldots, x_n$ are variables, and determining the “best” values for the constants $a_0, a_1, a_2, \ldots, a_n$ in relation to the observed corresponding values of the variables. Pearson was concerned with finding lines and planes that best fit a set of points in n-dimensional space, and the geometric optimization problems that he considered led to principal components (PCs). PCA can use an orthogonal transformation that is determined by the eigenvector and eigenvalues to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called PCs. This transformation is defined in such a way that the first PC has the largest possible variance and each succeeding component in turn has the highest variance possible under the constraint that it be orthogonal to the preceding components.

Pearson's comments regarding the computations, given over 50 years before the widespread availability of computers, are interesting. He stated that his methods can be easily applied to numerical problems of four or more variables (Jolliffe, 2002). In this study, his observations are true in the domain of the ship weight estimation. PCA can also be used to identify the most important factors among a set of parameters. We follow the approach of Hart et al. (2012), who applied PCA to identify the physical parameters of ships with the highest correlations to the cost. However, we propose new parameters that are relevant to the weight of the structure.

Aasen et al. proposed a system for estimating weights and the COG early in the design stage through the use of parametric estimation formulas obtained from regression analysis of historical data (Aasen and Bjorhovde, 2010). This study provided the basic concept for our research. We combine the configuration segment concept with PCA to create a segmented estimation method to assess the effects of various ship segment parameters. The new method produces estimates of various ship segments using the most recent design data. This approach is based on Pearson's analysis, which finds a straight line that best fits the data (Pearson, 1901), to form standard weight formulas that depend on only a few parameters combined with the local and overall structural factors. Then, we apply the numerical analysis methods of linear and nonlinear approximation to correct the weights for discrepancies between the new design and standard weight estimation formulas, thereby achieving accurate estimates of the weight of the steel and the COG.

1.4. Outline

In this paper, we propose an innovative estimation method, named feature-based segment estimation (FSE), that can be used in the preliminary design phase of a ship tendering process. Accurate and efficient estimates of the weight of the steel and the COG are possible for a new design. The method is based on PCA and feature corrections for containerships of various sizes. The feature corrections account for differences that are not captured by PCA. The feature analysis relies on 3D CAD tools for building the segment framework, deriving the general steel weight formulas and the corrections.

FSE is more powerful than other parametric estimation methods, which rely only on the characteristics of the entire ship to derive regression formulas and do not consider the specific features of the ship's configuration. Only a few main features are required when using FSE, and the method is faster and simpler than structural analysis methods, which require detailed structural information and the selection of additional coefficients.

In Section 2, the FSE model is derived by dividing the ship into various segments (e.g., forepeak, cargo, engine room, aft peak, forecastle and deck house). *The database is based on 10 modern vessels, which were selected from 31 vessels.* In Section 3, we describe the proposed FSE method. PCA is used to identify each segment's correlative parameters, including the principal parameters of the entire ship and local characteristic values. Then, the basic equation for estimating the standard steel weight is derived. In Section 4, we demonstrate the use of FSE to adjust the standard weight using the main structure and design factors of each segment. In Section 5, we demonstrate the method and its practicality and effectiveness. The segment estimation results are presented and compared with those of a method that uses only overall ship parameters. Finally, in Section 6, we provide conclusions and describe future work.

2. Feature-based segment model

The segment model is based on 10 vessels, which were selected from 31 vessels separated into 10 categories by size. Then, 10 more modern designs with sizes in the range from 1000 to 8500 TEU were used to obtain the representative data. We selected the latest design types of various sizes and omitted the older designs to avoid similarities that would influence the accuracy of the regression. Then, we analyzed the general arrangements of the 10 vessels to establish a general model for structural weight estimation.

The hull is generally divided into subgroups that are estimated separately rather than estimating the complete hull. Based on the general components, or segments, of the structure, the configuration model is defined as shown in Fig. 1 and described in Table 1. Fig. 1 illustrates the segments of the ship, and Table 1 lists the definitions of the segments and their characteristic parameters. The selection of these parameters was constantly evaluated to obtain the most significant estimation results with the minimum number of parameters while satisfying the PCA limitation requiring the number of arguments to be less than the quantity of ship data. The use of these parameters and the method for estimating the weights of the individual segments will be described in the next section.

3. Feature-based segment estimation

FSE is based on two concepts. First, FSE uses PCA to reduce a set of variables to a new set called PCs to derive the standard weight formula. Second, the standard weight may be adjusted for various physical characteristics using linear regression or nonlinear regression with the power function or higher-order polynomials.

3.1. Standard weight estimation based on PCA

PCA is a method used to transform a set of correlated variables into a smaller set of new variables while preserving the most important information of the original data set. In previous research (Chen et al., 2013), PCA was applied to filter various factors to identify the variables that were highly correlated with the hull steel weight. Then, PCA was applied to calculate the combinations of these variables, known as the PCs. We assume that the hull weight of a ship is primarily a function of the principal dimensions of length L, breadth B, depth D and one or two local factors. For example, the combination of variables for the cargo segment is defined as

$$PC_1 = a_1\left(\ln L - \overline{\ln L}\right) + a_2\left(\ln B - \overline{\ln B}\right) + a_3\left(\ln D - \overline{\ln D}\right) + a_4\left(\ln l - \overline{\ln l}\right) \quad (1)$$

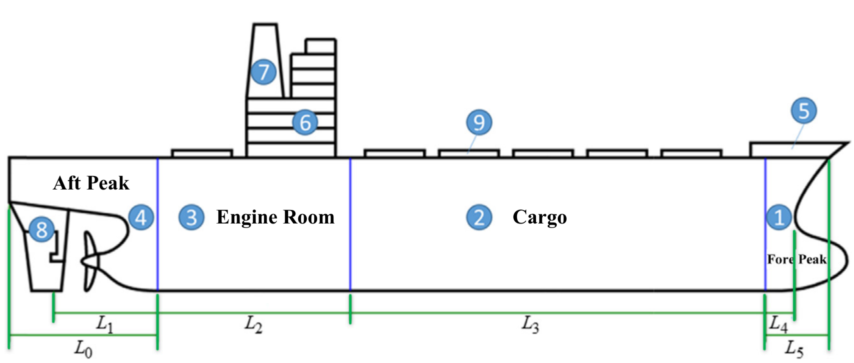

Fig. 1. FSE configuration segments.

Table 1
Segment details for FSE.

Category	Segment	Structure	Region key factor	Feature
Hull	**1. Forepeak**	The fore structure from the forepeak bulkhead, including the bulbous bow.	• L_4: Length between the forward perpendicular and the forepeak bulkhead • L_5: Upper deck length between the bow (the foreside of the stem) and the forepeak bulkhead.	• Deck area • Form variation • Segment size • C_B
	2. Cargo	The structure between the engine room and forward segment.	• L_3: Cargo length • $0.5L_3+L_4$: Length from the forward perpendicular to the cargo segment center	• Structure type • Segment size and location • Section weight distribution for various ship sizes • C_B
	3. Engine room	The structure from the first bulkhead of the engine room to the aft peak bulkhead, including the engine head, shaft tank, and rear cargo area up to the shaft tank.	• L_2: Engine room length • $L_1+0.5L_2$: Length from the after perpendicular to the engine room segment center	• Structure type • Segment size and location • Section weight distribution for various ship sizes • C_B
	4. Aft peak	The rear structure from the aft peak bulkhead.	• L_0: Upper deck length of the aft segment	• Segment size • Section weight distribution for various ship sizes • C_B
Super structure and other elements	**5 Forecastle**	The structure above the upper deck, including the forecastle deck.	• Forecastle length • Forecastle height	• Segment size
	6 Deck house	The structure for all decks in the deck house.	• The length of each deck	• Segment size • Decks and lengths
	7. Funnel	Trapezoidal form	• Bottom length • Upper length • Funnel height	• Segment size • Form variation
	8. Rudder	Rudder and rudderpost	• Bottom length • Top length • Rudder height	• Segment size • Form variation
	9. Hatch coaming	The structure around the perimeter of each hatch, totaled over all hatches	• Hatch perimeters • Number of hatches	• Segment size

where l is the length of the cargo segment and the overbar signifies the average value of the parameters.

Eq. (1) may be written as

$$PC_1 = \ln PC - \overline{\ln PC} \tag{2}$$

where

$$\ln PC = a_1 \ln L + a_2 \ln B + a_3 \ln D + a_4 \ln l, \tag{3a}$$

and

$$\overline{\ln PC} = a_1 \overline{\ln L} + a_2 \overline{\ln B} + a_3 \overline{\ln D} + a_4 \overline{\ln l}. \tag{3b}$$

Eq. (3a) is equivalent to

$$PC = L^{a_1} B^{a_2} D^{a_3} l^{a_4}. \tag{4}$$

PC represents an independent variable, and hull steel weight represents a dependent variable for establishing a simple linear regression model. The first *PC* describes major trends for the hull steel weight. The first eigenvector or *PC* aligns with the direction of the greatest variation in the data, and the second *PC* aligns with the greatest variation that is orthogonal to the first *PC*.

Generally, data can be adequately described using far fewer PCs than original variables. In this study, we apply a new strategy in which we assume that a PCA model includes all of the factors in the standard weight. PCA is applied to ln*PC* and ln*W* to obtain the first and second PCs. Because the first *PC* represents all weight factors, the second *PC* is equal to zero. Then, the weight estimation equation is defined as

$$b_1\left(\ln PC - \overline{\ln PC}\right) + b_2\left(\ln W - \overline{\ln W}\right) = 0. \tag{5}$$

Eq. (5) may be written as

$$\ln W = \frac{-b_2}{b_1}\left(\ln PC - \overline{\ln PC}\right) + \overline{\ln W}. \tag{6}$$

Hence, Eq. (6) may be rewritten in exponential form to obtain the standard weight equation

$$W = C \cdot PC^{b'} \tag{7}$$

where

$$C = e^{\overline{\ln W} + b' \ln PC},\ b' = \frac{-b_2}{b_1}.$$

3.2. Standard weight modification

The variation described by the *PC* does not completely reflect the difference in the actual weight due to specific physical factors. Therefore, to address this problem, we analyze combinations of PCs. Then, the effect of each *PC* on the weight estimate is determined.

In the linear regression for the steel weight, it is assumed that the first *PC* is a function of every factor (i.e., the overall ship dimensions), and the second *PC* is equal to 0. Therefore, each factor of the standard ship may be defined as

$$\frac{\ln Ls - \overline{\ln L}}{a_1} = \frac{\ln Bs - \overline{\ln B}}{a_1} = \ldots = t \tag{8}$$

where L_S, B_S and Ds are the standard ship parameters.

Eq. (8) may be written as

$$\ln Ls - \overline{\ln L} = a_1 t,\ \ln Bs - \overline{\ln B} = a_2 t, \ldots \tag{9}$$

Second, we obtain the standard ship parameters. We substitute Eq. (9) into Eq. (2) to obtain PC_1 in terms of the standard ship dimensions. The *PC* of the standard ship dimensions is obtained from

$$PC_1 = ({a_1}^2 + {a_2}^2 + {a_3}^2 + {a_4}^2)t \tag{10}$$

Each factor coefficient is a component of the unit vector for PC_1; thus, Eq. (10) can be written as

$$PC_1 = t. \tag{11}$$

because the sum of the squares of the components of a unit vector is equal to 1.

PC_1 may be calculated from the principal dimensions of the design ship, *L*, *B*, and *D*. We let the *PC* of the principal dimension of the design ship equal the *PC* of the principal dimensions of the standard ship, i.e.,

$$a_1\left(\ln L - \overline{\ln L}\right) + a_2\left(\ln B - \overline{\ln B}\right) + a_3\left(\ln D - \overline{\ln D}\right) = ({a_1}^2 + {a_2}^2 + {a_3}^2)PC_1. \tag{12}$$

where the terms on the left side of the equation are the principal dimensions of the design ship.

Eq. (5) may be written as

$$PC_1 = \frac{a_1\left(\ln L - \overline{\ln L}\right) + a_2\left(\ln B - \overline{\ln B}\right) + a_3\left(\ln D - \overline{\ln D}\right)}{{a_1}^2 + {a_2}^2 + {a_3}^2}. \tag{13}$$

We replace *t* in Eq. (9) with PC_1 from Eq. (13) such that Eq. (9) may be written as

$$\ln Ls - \overline{lnL} = a_1 PC_1,\ \ln Bs - \overline{\ln B} = a_2 PC_1, \ldots. \tag{14}$$

Hence, Eq. (12) may be rewritten in exponential form to obtain the standard ship parameters, e.g.,

$$Ls = e^{a_1 PC_1 + \overline{\ln L}}, \tag{15}$$

and the other parameters B_S, Ds, and l_S are obtained in the same manner.

We can consider the influence of each parameter on the steel weight by applying the ratios L/Ls, B/Bs, D/Ds, and l/ls. We take the length factor as an example. The weight *W* is given by Eq. (6) using the standard ship parameters in Eq. (15). W/Ls represents the weight per unit length. Then, to account for differences in the weight distribution, we can modify the weight by multiplying, i.e., $W \cdot f(L/Ls)$. The modified functions are derived for the physical structure factors using numerical methods, such as linear regression or nonlinear regression with power functions or polynomials. These modified functions will be described in the next section.

4. Application of feature-based segment estimation

In this study, the *PC* of the standard weight estimation accounts for approximately 85% of the actual weight in the hull using the principal parameters, but the actual steel weight of a specific ship will not lie exactly on the curve. Because each segment has different physical characteristics, the unit length of the weight distribution is not exactly the same. We consider the structural properties by observing the unit weight distribution characteristics of the segments.

4.1. Cargo segment weight estimate

4.1.1. Structure factor

First, we consider the structure factors for analyzing the weight distribution in the largest component of a freighter. We treat the hull as a simple beam, mainly because the strength requirements are one of the main considerations.

To analyze the factors that influence the mean weight per unit length for the cargo segment, we treat the segment as a cylindrical shell, or tube, where the radius of the shell is *R* and the equivalent thickness of the shell is *T*. Then, the weight per unit length is equivalent to $2\pi RT$, which is obtained by expanding the shell. Therefore, a two-stage correction is included for *R* and *T*.

Because the ship's breadth has a greater effect on the use of materials (the decks contribute more than the hull), we let $R = 0.5D + B$ to obtain the first correction coefficient,

$$C_1 = \frac{(0.5D + B)L_4}{(0.5Ds + Bs)Ls_4}, \tag{16}$$

which is used to estimate the effect of the volume with the linear function $W \cdot C_1$.

From the maximum bending moment, the stress can be obtained as

$$\sigma = \frac{My}{I} \tag{17}$$

where I/y is the modulus of the effective structural section.

Next, let $y = R$ and define the moment of inertia as $I = \pi R^3 T$ according to the structural properties of a thin-walled tube. Substituting into Eq. (17) yields

$$\sigma = \frac{M}{\pi R^2 T}. \tag{18}$$

As the ship length decreases, *R* increases (the ship' master aspect ratio B/L becomes larger) and *M* decreases (the bending moment becomes smaller). Eq. (18) indicates that *T* must decrease. Hence, the equivalent thickness *T* decreases with the ship length. The second correction coefficient is

$$C_2 = \frac{L}{Ls}, \tag{19}$$

which is used to estimate the effect of length with the exponential function $W \cdot e^{C_2}$.

4.1.2. Form factor

Because the shape of the hull is not uniform, we use the block coefficient C_B to modify the weight estimate to account for the effect of the form factor. We then observe the weight change of the segment to obtain correction coefficients. The relationship between C_B and the draft *d* is also found to have a significant effect on the weight. The block coefficient expresses the fineness of the bow and the stern relative to the middle body below the waterline and affects the amount of steel used; however, the height above the waterline (freeboard) also affects the amount of steel used. Therefore, we adjust C_B to include the effect of freeboard and then define the modified block coefficient $C_B{}'$ to reflect the effect of the shape above and below the waterline, as follows:

$$C_B{}' = \frac{LB(D-d)C_W + LBdC_B}{LBD}, \tag{20}$$

where the value of C_W/C_B is 1.25. We define the correction coefficient as

$$C_3 = \left(1.25 - 0.25\frac{d}{D}\right)C_B, \tag{21}$$

which is used to estimate the effect of length with the exponential function $W \cdot e^{C_3}$.

The cargo weight distribution as a function of the local form factor is indicated in Fig. 2. The section of the structure below the waterline may be gradually reduced using a linear design, which would cause the weight to be concentrated in the aft portion of the segment. The section weight becomes lighter as the cargo segment becomes closer to the bow. Thus, to correct for the position, we define the fourth correction coefficient as the distance between the center of the cargo segment and the bow, i.e.,

$$C_4 = L_4 + 0.5L_3, \tag{22}$$

which is used to estimate the effect of length with the exponential function $W \cdot e^{C_4}$.

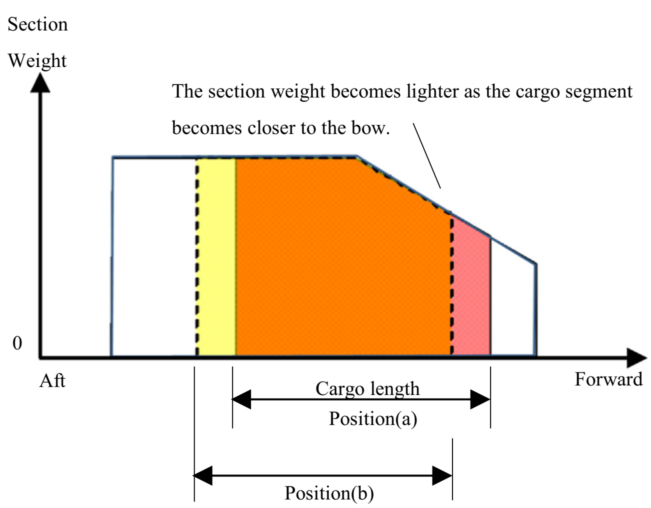

Fig. 2. Cargo weight distribution.

Fig. 3(a) shows the calculated average weight per unit length. Because the major changes in the cargo segment are in the aft section, the average weight per unit length will be underestimated in the aft end if the length of the cargo segment is greater than the standard cargo segment length, as shown in Fig. 3(b). Conversely, the average weight per unit length is overestimated in the aft end if the length of the cargo segment is less than that of the standard cargo segment, as shown in Fig. 3(c). When the length is greater, as indicated by the green block in Fig. 3(b), the linear correction given byC_2 is insufficient. The gray block in Fig. 3(c) indicates the amount of over-correction given by C_2.

Therefore, the weight estimate must be corrected for the segment length. The correction factor is defined using the ratio of the design segment length to the standard segment length, i.e.,

$$C_5 = \frac{l}{ls}, \tag{23}$$

which is used to estimate the effect of the cargo segment length with the exponential function $W \cdot e^{C_5}$.

4.2. Engine room segment weight ESTIMATe

The engine room segment has two possible configurations, one that includes cargo space and one that does not. To estimate the segment weight for smaller container vessels, the steps are similar to those for the cargo segment. In larger vessels, however, the engine room segment also contains cargo space, and thus, special treatment is required.

Fig. 4 illustrates the weight distribution in the case where the engine room segment includes the rear cargo space. The yellow rectangle represents the standard average weight per unit length, which is less than the engine segment weight and greater than the rear cargo space weight. The length adjustment of the engine room segment partially depends on the rear cargo space. The increase in the estimate will be higher for greater lengths, as

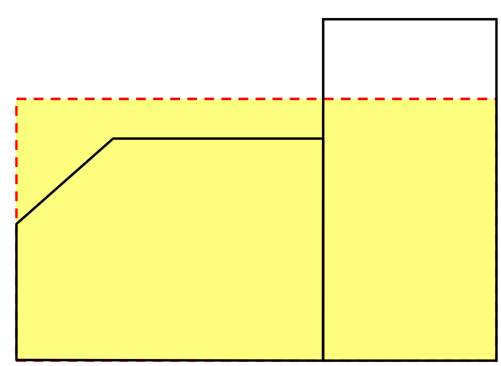

Fig. 4. Engine room segment weight distribution.

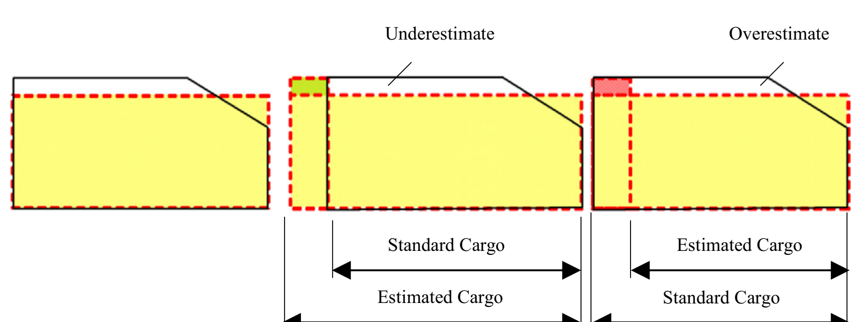

Fig. 3. Cargo segment weight estimate for various segment lengths. (a) Correct estimate: the design cargo segment length equals the standard cargo segment length. (b) Low estimate: the design cargo segment length is longer than the standard cargo segment length. (c) High estimate: the design cargo segment length is shorter than the standard cargo segment length.

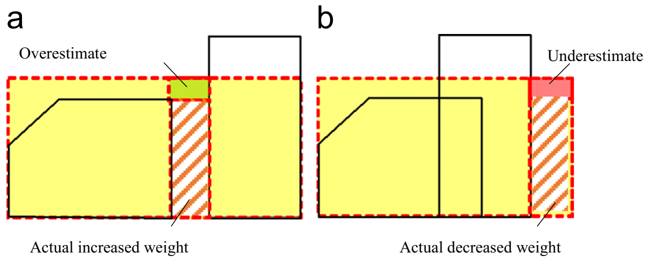

Fig. 5. Engine room segment weight estimates for two lengths.(a) The design engine room segment is longer than the standard engine room segment. (b) The design engine room segment is shorter than the standard engine room segment.

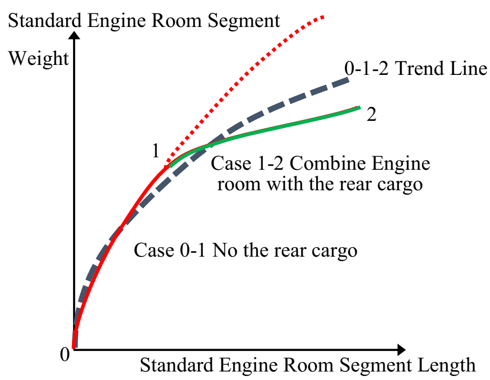

Fig. 6. Engine room segment weight distribution.

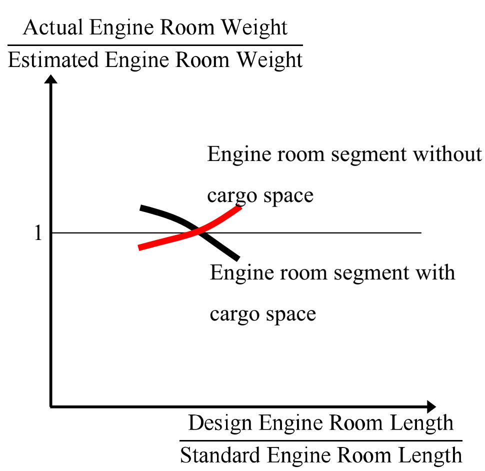

Fig. 7. Engine room segment weight distribution.

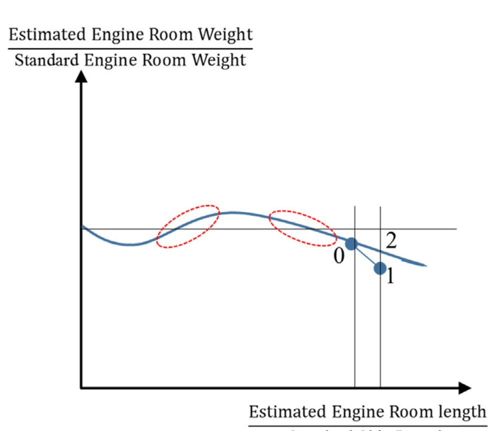

Fig. 8. Exponential weight relationship.

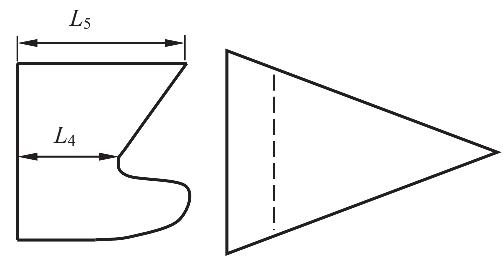

Fig. 9. Areas of the forward segment.

indicated by the green block in Fig. 5(a), and lower for shorter lengths, as indicated by the pink block in Fig. 5(b).

The segment weight vs. length functions are combined for the two cases, as shown in Fig. 6. The solid red line from 0 to 1 is used for shorter segment lengths, where the growth rate is higher because there is no rear cargo, and the green line from 1 to 2 is used for longer segment lengths. The blue line represents the two combined trends.

Because the ratio $(\text{ActualEngineRoomweight}/\text{EstimatedEngine Roomweight})$ is approximately constant at 1 with variations in the ratio $(E\text{stimated segmentlength}/\mathit{Standard}\text{ segmentlength})$, regardless of the cargo space (see Fig. 7), we use the ratio $(E\text{stimated segmentlength } L_2/\mathit{Standard}\text{ segmentlength } Ls)$ to adjust the weight with the correction factor

$$C_6 = \frac{L_2}{Ls}, \tag{24}$$

which is used to estimate the effect of the cargo space with a 3rd-order polynomial *f*, i.e., $W \cdot f(C_6)$.

The data may converge in one of the two regions shown in Fig. 8; segments without cargo space fall in the region on the left on the increasing part of the curve, and the others fall in the region on the right on the decreasing part of the curve. In summary, we use C_1–C_4 to correct the general factors, C_6 to adjust for the cargo space factor, and C_5 to correct for the effect of the engine room segment length, which creates the error between the 0–2 estimated line and the 0–1 trend line.

4.3. Forepeak segment weight estimation

We assume that the standard area of the forepeak segment is A at the waterline, which is where L_4 is measured. The design area is $A(L_4/Ls_4)^2$ at the waterline, and the area is $A(L_5/L_4)^2$ at the main deck, which is where L_5 is measured, as shown in Fig. 9. The dashed line in the figure shows the difference between the minimum and maximum areas. The average rate of increase between the waterline and main deck is used to define the correction coefficient as

$$C_7 = \frac{A\left(\frac{L_4}{Ls_4}\right)^2 + A\left(\frac{L_5}{Ls_4}\right)^2}{A + A\left(\frac{Ls_5}{Ls_4}\right)^2} = \frac{\left(\frac{L_4}{Ls_4}\right)^2 + \left(\frac{L_5}{Ls_4}\right)^2}{1 + \left(\frac{Ls_5}{Ls_4}\right)^2}, \tag{25}$$

which is used to estimate the effect of area with the exponential function $W \cdot e^{C_7}$.

In summary, we use C_7 and C_3, which was defined in Eq. (21) of Section 4.1.2, to correct for the form factors.

4.4. Aft peak, deck house and forecastle segment weight estimates

Because the weight contributions of these segments are extremely low, the accuracy of the weight estimates is not as critical, and reasonable values will suffice. For the deck house segment, we sum all of the deck lengths to obtain the segment length l. We assume a rectangular shape for the decks. We modify Eq. (16) to obtain the correction coefficient C_8 for the form factors as

$$C_8 = \frac{(D+B)l}{(Ds+Bs)ls}, \quad (26)$$

which is used to estimate the effect of the volume with the linear function $W \cdot C_8$.

4.5. Funnel and rudder weight estimation

The approach is similar to that in the previous section. The difference is that two local parameters, the length l_1 and height l_2, are introduced. We modify Eq. (16) to obtain the correction coefficient C_9 to correct the form factors as

$$C_9 = \frac{(D+B)L}{(Ds+Bs)Ls} \cdot \frac{l_1}{ls_1} \cdot \frac{l_2}{ls_2}, \quad (27)$$

which is used to estimate the effect of the volume with the linear function $W \cdot C_9$.

4.6. Hatch coaming weight estimation

The hatch coamings are part of the cargo segment. To obtain the correction coefficient, we use the hatch coaming length in place of the cargo segment length and then use C_1 and C_2 to estimate the weight.

COG estimation

Using the segment weight estimates, we can estimate the COG of each segment by finding a reference point for the coordinates of the COG position correction for each segment. The COG is determined by estimating the moment of the segment. We take LCG as an example. First, the value of the moment M of the segment can be calculated as

$$M = W \times X_{LCG}, \quad (28)$$

where W is the weight of the segment and X_{LCG} is the length between the after perpendicular to the COG of the segment in the longitudinal axis for all referred ships.

Then, the moment of each segment $M_{estimation}$ is estimated using FSE. Finally, the estimated X_{LCG} is determined as $(M_{estimation}/W_{estimation})$.

The estimation method is similar to that for the weight estimates, although factors that are not related to the COG, such as C_B, the length correction, and the segment location correction, are excluded.

5. Comparative study

5.1. Segment-based weight estimation

Table 2 and Fig. 10 present a comparison of six methods for estimating the structural weight based on the selected 10 ships. Method (a1) is FSE, which divides the ship into 9 segments. The maximum error is approximately 2.33%, and the standard deviation is approximately 1.31. Method (a2) presents the test for estimating each ship using the other 9 ships as the training population to validate the usefulness of the method. The maximum error is approximately 3.2%, and the standard deviation is approximately 1.64. The experimental results also show that the average error is minimized and approximately $\pm 0.5\%$. Hence, the model may be more robust for new ships or outliers.

The following four methods are compared with Method (a1). These methods determine the coefficient k using linear regression analysis of the same 10 ships. The R-squared value of each of these models is also greater than 0.99, which indicates that the regression models are proper. Method (b1) uses the standard cubic number method $k(L \times B \times D)$; the maximum error is approximately -15.91%, and the standard deviation is approximately 6.75. Method (b2) makes the general correction for C_b based on $k(L \times B \times D \times {C_b}^{0.5})$(Aasen and Bjorhovde, 2010); the maximum error is approximately -15.33%, and the standard deviation is approximately 5.82. Method (c1) makes an extended correction of the L/D ratio based on $k(L \times B \times D)^{0.9} \times (0.675 + 0.5C_b) \times 0.006(\frac{L}{D} - 8.3)^{1.8}$(Miller, 1968); the maximum error is approximately -7.34%, and the standard deviation is approximately 4.51. Method (c2) is the correction of Method (c1), where the equation from Method (c1) is multiplied by the length of the superstructure

Table 2
Comparison of the estimation results.

Ship no.	A	B	C	D	E	F	G	H	I	J
TEU	1040	2226	2200	3237	4680	4200	6000	6600	8500	8626
LBP (m)	136.1	187.1	187.6	232.4	246.4	256	263.8	293.16	317	318.2
Breadth (m)	22.5	30.2	30.2	32.2	37.3	32.2	40	40	45.8	42.8
Depth (m)	11.2	17.5	16.6	19.5	19.4	19.1	24.2	24.2	25	24.5
Length of superstructure (m)	29.7	49.9	48.9	34.7	60.8	35.2	36.4	40.4	53.6	40
Error in Method (a1)	−0.77% SD = 1.31%	−1.33%	−0.95%	−0.69%	−0.83%	0.88%	−1.87%	2.33%	1.77%	0.10%
Error in method (a2)	−1.17% SD = 1.64%	−1.65%	−1.27%	0.01%	−1.45%	−1.17%	[a]	3.2%	2.25%	−0.37%
Error in method (b1)	−15.91% SD = 6.75%	4.05%	4.02%	3.24%	2.10%	3.37%	−9.98%	−5.21%	1.01%	4.83%
Error in method (b2)	−15.33% SD = 5.82%	3.25%	3.10%	2.34%	3.13%	2.58%	−6.23%	−4.45%	0.42%	3.06%
Error in method (c1)	−7.34% SD = 4.51%	6.34%	5.14%	2.46%	−0.72%	−2.10%	−6.17%	−4.41%	1.33%	3.65%
Error in method (c2)	−3.25% SD = 3.67%	4.72%	3.78%	3.50%	−3.26%	−0.86%	−5.47%	−3.89%	0.54%	4.34%

SD = Standard deviation.

[a] Because the engine room of Ship G is indispensable for the model of the cubic polynomial estimation, the ship is not estimated.

L_{sup} defined as $(1+0.36(L_{sup}/L))$ (Benford, 1969); the maximum error is approximately -5.47%, and the standard deviation is approximately 3.67. The overall error using FSE is considerably lower than the others. Hence, the estimated model is better for these modern target ships.

Table 3 shows the segment estimations based on Method (a1). Fig. 11 shows that the two main segments, the cargo and the engine room, account for almost 70% of the total weight and yield accurate estimation results. Figs 12 and 13 illustrate that the standard weight estimation accounts for approximately 85% of the actual weight in the main segments. The major error in ship H occurs because of the estimation of the engine room. Thus, it would be beneficial to further analyze the features of the engine room. For the forepeak, aft peak and deck house, the average performances have errors with standard deviations of 7.04%, 10.58% and 6.19%, respectively. The results are suitable for the accurate segment estimation. Additional characteristics of the customizations and specifications should be considered for optimal estimation. For the forecastle, funnel, and rudder, we quickly obtain rough estimates; more research is required to build feature-based models.

5.2. COG estimation

Using the established estimation model, FSE is applied to estimate the COG of the structural mass. Fig. 14 shows the distribution of the weight and the COG and can provide distribution data of weight per unit length. The distribution and LCG for each segment are given in the form of a trapezoid. Table 4 presents the main segments, which account for more than 90% of the total weight. The errors in the COG estimates are provided in Table 4. The maximum error in the LCG (Fig. 15) and KG (Fig. 16) are less than 1 m, except for the LCG of the deck house segment for Ship E and the KG of the deck house segment for Ship I. The two cases can be studied to explore the characteristics of the other parameters in a follow-up study.

6. Conclusions

FSE was proposed to estimate the steel weight and COG in the preliminary design phase of a vessel. A database of container ships for the segment feature analysis was obtained using 3D CAD tools. An innovative segment framework was defined to correct for segment features and characteristic parameters.

FSE combines PCA and structural feature corrections. PCA is used to identify the principal parameters from the overall ship dimensions and segment features and derive a general equation for estimating the weight of each segment rather than the entire ship. Feature corrections were applied to adjust the estimates for factors that the PCA does not include, such as parameter modifications, structural factors, and variations in the weight, area, and location across a segment. Based on the segment features, the estimated weight was obtained using linear regression. To demonstrate the practicality and effectiveness of the proposed method, we analyzed data from 10 modern design vessels selected from 31 vessels placed into 10 categories by size ranging from 1000 to 8500 TEU. We present the test results from estimating each ship using the other 9 ships as the training population to validate the usefulness of the new estimated ship model. The estimates of the steel weight had a maximum error of 3.2% and a standard deviation of 1.64% using FSE. The overall error using FSE is considerably lower than those of the other methods. Hence, the estimated model is better for these modern target ships. The model may be more robust for new ships or outliers.

This method is distinct from the traditional process, in which the engineer assigns the weights to the main structural segments and rapidly estimates the total ship weight in the early design

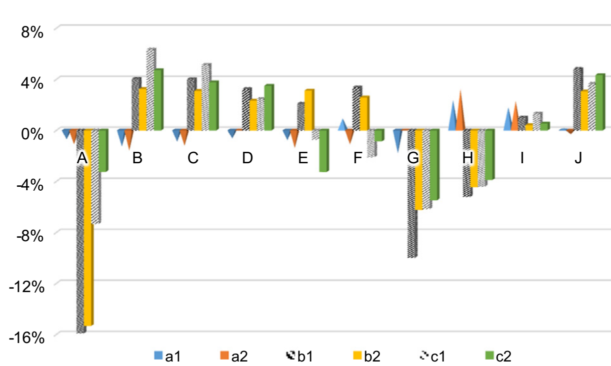

Fig. 10. Comparison of the estimation results.

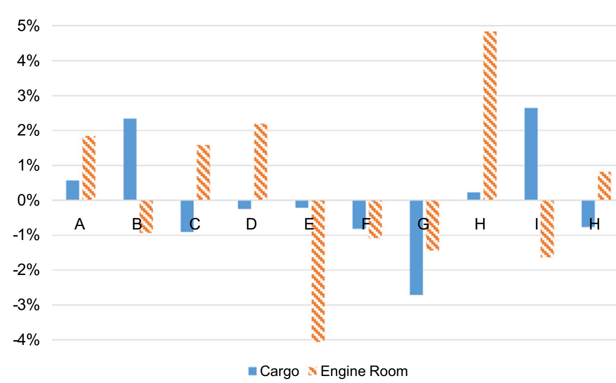

Fig. 11. Estimation error for the cargo and engine room segments.

Table 3
Estimation error of the segments.

Ship no.	A	B	C	D	E	F	G	H	I	J	SD[a]
Forepeak	−7.14%	−4.29%	7.24%	−4.66	−4.72	4.58%	−9.71%	9.96%	10.79%	0.51%	7.04%
Cargo	0.57%	2.34%	−0.91%	−0.25%	−0.22%	−0.81%	−2.71%	0.22	2.64%	−0.76%	1.49%
Engine Room	1.84%	−0.93%	1.58%	2.19	−4.06	−1.09%	−1.43%	4.83%	−1.64%	0.81%	2.40%
Aft Peak	13.46%	−16.43%	−14.39%	−2.58%	−5.90%	−2.71%	1.73%	5.95%	16.92%	9.47%	10.58%
Forecastle	−15.00%	−27.49%	−6.08%	1.95%	53.92%	5.92%	11.94%	13.07%	−3.66%	−10.75%	20.86%
Deck House	−10.21%	10.86%	−3.64%	3.73%	−3.07%	6.26%	3.53%	0.86%	−8.27%	1.86%	6.19%
Funnel	[b]	18.75%	−12.50%	−9.52%	0.00%	−13.64%	−2.44%	7.69%	−14.81%	37.50%	16.54%
Rudder	−7.14%	−9.68%	[b]	−75.83%	11.43%	14.71%	[b]	14.29%	−18.31%	−1.75%	27.68%
Hatch Coaming	−8.42%	−20.54%	15.71%	2.02%	−12.82%	31.52%	−7.07%	2.12%	7.97%	−1.26%	14.19%

[a] SD = Standard deviation.
[b] Source data cannot be distinguished from the segment weight.

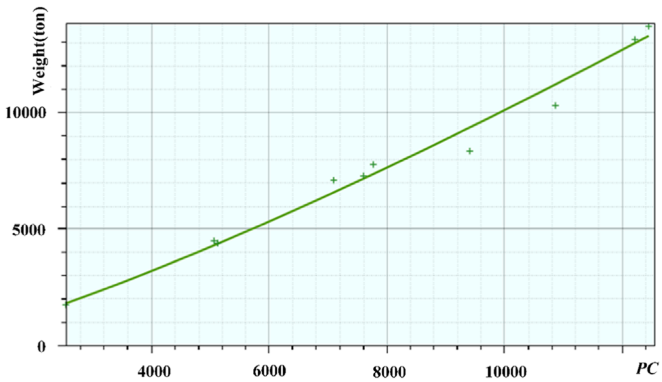

Fig. 12. Cargo segment standard weight vs. ship size.

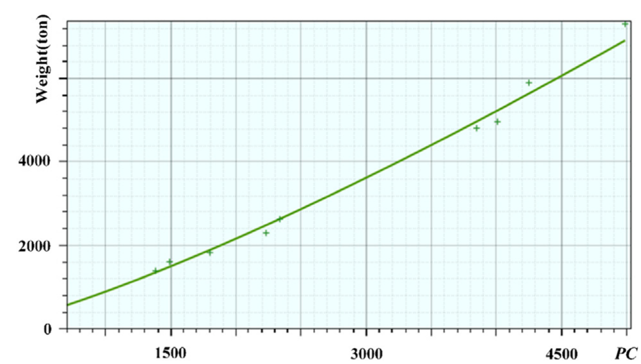

Fig. 13. Engine room segment standard weight vs. ship size.

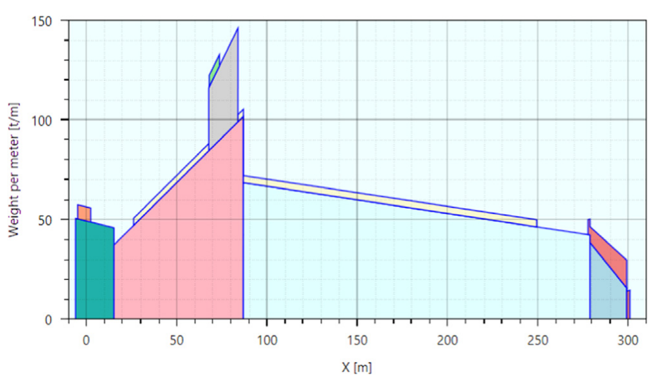

Fig. 14. Distribution of the weight and LCG.

Table 4
Estimation error of the COG.

Ship no.		E	F	H	I	J
Forepeak	LCG error	0.683	−0.89	−0.13	0.162	0.249
	KG error	−0.297	0.414	−0.665	−0.219	−0.061
Cargo	LCG error	−0.432	0.077	0.657	0.452	0.073
	KG error	0.591	0.151	−0.121	−0.707	−0.31
Engine room	LCG error	−0.096	0.402	−0.135	0.207	−0.291
	KG error	−0.068	−0.397	0.128	−0.438	0.653
Aft peak	LCG error	0.15	0.797	−0.564	0.161	−0.768
	KG error	−0.459	−0.537	0.143	−0.812	0.081
Deck house	LCG error	1.806	0.579	−0.207	0.716	0.472
	KG error	0.354	−0.352	1.265	−1.477	0.275

Units: meters.

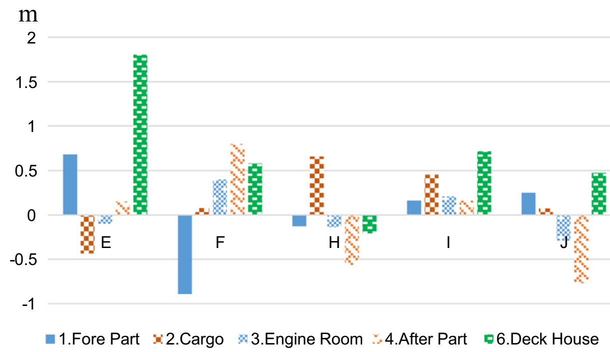

Fig. 15. Estimation error of the LCG.

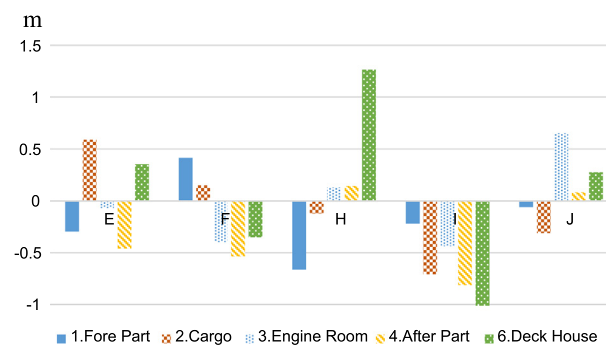

Fig. 16. Estimation error of the KG.

stages. In this study, we analyzed the characteristics of the weight variations for each segment. This method provides new possibilities to observe and estimate features for ships. In the future, by utilizing synergies between 3D CAD tools and BOM, we intend to research the fitting weight and other components of the light-ship weight, the materials requirements and the cost at various stages of system engineering using the FSE concept.

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