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Feature-based estimation of preliminary costs in shipbuilding

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ABSTRACT

Accurate cost estimation is crucial for obtaining ship owners' orders in shipyards. The classic preliminary estimation methods of ship costs provide only rough estimates of the labor, materials, and equipment based on the overall ship parameters and do not reflect further specifications. This study develops an innovative cost estimation method called the feature-based estimation method that is based on the preliminary specifications to estimate ship costs, including the steel, other main materials, engine, power generator, other core equipment, and labor hours.

The method mainly establishes the topology of the relationships between the features by linking the general dimensional parameters and detailed features of the specifications of the designs and cost information to estimate the main cost items of the ship. The features are extracted and transformed into a quantifiable structure. The definitions of the features contains the core context using a small amount of information for the preliminary estimation.

Empirical formulas are derived based on the configured cost items in the preliminary design stage. The errors of the estimated total costs are less than ±7%. Hence, the estimation model is suitable for modern ships. The applications of the model may be more robust for new ships in a future study.

1. Introduction

The purpose of this research is to outline the preliminary stage of cost estimation of ships. Because the growing worldwide shipbuilding capacities, global crises, and overcapacity in shipping have led to significant decreases in construction prices, shipyards must decrease ship costs to respond to new orders with minimal profit margins and limited production time.

Accurate cost estimation is a crucial task. During the preliminary ship design phase, the design is temporary and subject to change based on variations in the ship owner's requirements. Rapid and flexible responses are important competitive advantages (Son et al., 2011). However, the specifications for a new design at the beginning of a project are typically incomplete and imprecise. Thus, the total costs are generally established through decisions made in the initial design phases (Fischer and Holbach, 2011).

Using the limited design parameters causes difficulty in developing an accurate budget. In this study, we take into account the preliminary design and preliminary cost estimation to improve the issue.

1.1. Discontinuous cost estimates at different stages

Cost estimates for the main items of merchant ships, including the labor, materials, and overhead costs of shipyards, typically evolve over three levels of detail, including the concept design, the ready preliminary design, and the completed contract design.

The top priority of the estimation process is to provide an approximate cost for the concept design before any details of the ship design and manufacturing processes are fully considered. The level estimations are developed based on the main parameters, such as ship's weight, principal dimensions, size and other general performance parameters. Most shipyards derive these cost estimates based on the costs per ton or man-hours per ton, which are typically obtained from records of recent construction projects (Watson, 2002). Thus, determining an accurate estimated weight is the first task. Additional details of weight estimation of preliminary cost items are presented in this study.

The next level is when a preliminary design has been prepared, and a system weight has been estimated to support the main estimation based on the owner's requirements (Lamb, 2004). The preliminary offer provides a basis to determine whether a project will continue until the contract negotiations between the shipyard and owner. In practice, the estimate is used to establish the cost by comparing critical factors in a

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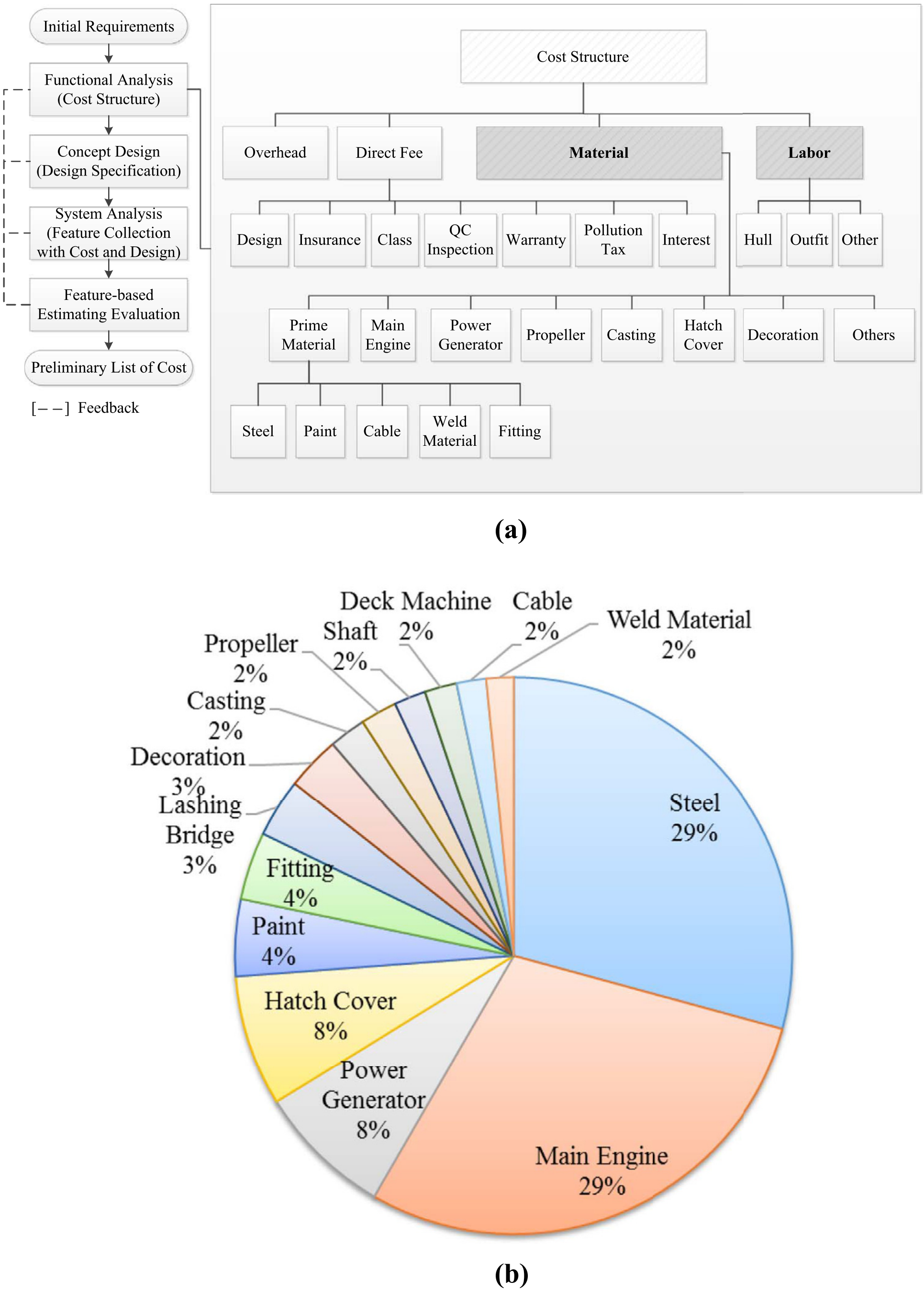


Fig. 1. **(a)** Cost structure. **(b)** Costs of the main materials and equipment.

new design with the characteristics of previously delivered vessels. It may take several weeks to obtain an accurate result because many design factors affect the cost. The owner prefers to acquire the estimate early to conduct a follow-up assessment and negotiation. Hence, rapid and flexible responses are critical during this phase. However, no existing systems support the shipbuilding tendering process due to the different design and engineering methods of ship construction. Although commercial software platforms for shipbuilding are available, the shipyard must identify the design parameters and cost items at different levels to support the cost estimation.

A more detailed estimate typically follows the completion of the contract design with a pricing process that operates within the work breakdown structure (WBS) format. The WBS provides a format by which a shipyard can collect, organize, and manage costs that can be used to estimate prices for new ships. The North Atlantic Treaty Organization (NATO) provides the Expanded Ship Work Breakdown Structure (ESWBS) that defines a hierarchy of the components of ships (NATO, 2006). Although the structure is based on the practical work of shipyards, it traditionally requires a list of common ship system components, including the hull structure, outfit, equipment, piping, electrical system, paint and furnishings, to support production. Thus, this study presents a list of preliminary critical cost items that are collected using the WBS database. The preliminary estimates that have the greatest impacts on the ship's total cost establish the base-line costs at different stages.

1.2. Relative methods

The major cost estimation methods in the literature are classified into

Table 1
Estimated items and feature parameters.

Item	Specification	Sub-items	*Principal Feature*	*Secondary Feature*
Steel	Weight	Fore, cargo hold, engine room, aft, others	L, B, D, d, C_B	*Segment Length, height, location, area*
	Cost			$C_{base\ price}$*, cutting loss, roportion of high-tensile*
Engine	P_{MCR}		$L, B, D, d, V, C_B, (\Delta, S)$	*Sea margin, energy-saving factor,* R_T
	Cost		P_{L1}	*Manufacturing region, exchange rate*
Generator	Power	Fore, cargo hold, engine room	$L, D, Qty_{reefer}, Qty_{teu}$	$P_{req}, P_{B/T}, P_{cargoFan}, P_{freezer}k_{ef}, P_{rate}, P_{MCR}$
Deck machinery	Load	Windlass, mooring winch	L, B, D, C_B	*GT, amount of outfitting equipment*
Hatch cover	Cost		L, B	*Unit weight,* $C_{base\ price}$
Lashing bridge	Cost		*Layers*	*Total weight,* $C_{base\ price}$
Accommodation	Cost		C_{crew}, l_{acc}	*Floor area,* $C_{base\ price}$
Castings and forgings	Weight	Propeller, shaft	P_{MCR}, P_{RPM}	$P_{shaftDiameter}$
		Rudder	d	
		Stern frame		$P_{shaftDiameter}$
		Bell mouth	L, B, D, C_B	*GT*
	Cost			$C_{base\ price}$
Paint	Solid volume	SPAF, general paint	L, B, D, C_B	*GT, thinner paint,* $C_{base\ price}$
Fitting	Weight	Deckhouse, engine room, hull	L, B, D	*Proportion for segment*
	Cost			$C_{base\ price}$ *for pipes, fittings, and valves*
Cable	Cost			*Generator power*

top-down, bottom-up, life-cycle, and feature-based methods (Caprace and Rigo, 2012). The main differences are the amounts and levels of detail of the available cost information (Shetelig, 2013). Different methods are used in the different design stages.

In top-down methods, the ship's cost is predicted from its higher level specifications instead of its detailed design, which may not be available at the time of the estimation (Caprace and Rigo, 2012). A parametric estimation procedure is utilized, which uses empirical relationships between the design parameters and costs (Benford, 1967; Carreyette, 1978). These methods are typically based on existing databases of similar ships or determine initial design parameters using the parametric design methods (Watson and Gilfillan, 1977). Because weight is an important parameter for estimating the main structure and systems, these methods are commonly referred to as weight-based estimations. Empirical formulas in which indices are allotted to the ship's main parameters, such as the ship type, dimensions, size, hull weight, block coefficient, area, and complexity, are used (Geiger and Dilts, 1996). Rreference data are then selected to estimate the weights of the important items by regression analysis.

A parametric estimating system can be continuously refined and recalibrated. The relationships between the cost and global parameters are determined by evaluating previous ships (Barentine, 1996). Thus, top-down methods are more applicable if the considered design is similar to those of previous ships. For example, a new ship with a slightly greater depth may be based on a recent ship with the same design and equipment.

Cost reductions that result from newly adopted and developing shipbuilding technologies and production methods cannot be directly reflected in existing historically based cost estimation techniques (Christensen et al., 1992). Weight-based assessment approaches do not reflect improvements in the production process. Some designs have no impact on the weight, in which case the cost assessment will not change (Carreyette, 1978). In practice, these methods require considerable expert judgment to determine a reasonable cost for a novel feature of a new ship. The accuracy of the method is dependent on experts identifying changes in the important costs. Thus, early-developed methods have limited applicability in modern designs. More representative data should be included in the database and analyzed to obtain the features (Mulligan, 2008). Kaluzny et al. (2011) applied the M5 model tree to distinguish different conditions that correspond to the appropriate relation.

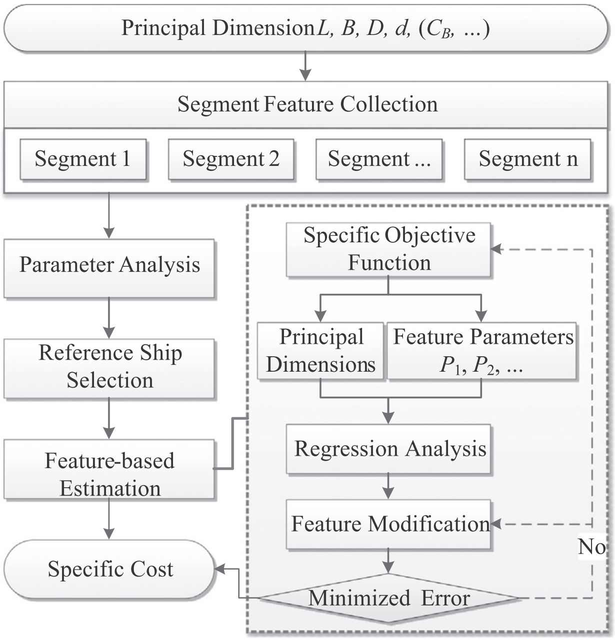
The second type of method, the bottom-up approach, is an alternative to the top-down approach. The bottom-up approach depends on an engineering analysis to reflect changes in cost by breaking the cost down into smaller units. Thus, bottom-up estimation is based on drawings, bills of materials (BOMs), historical vendor costs, and existing quotes. Ross (2004) described a three-tier method based on the ship work breakdown structure (SWBS). However, the validity of the approach is highly dependent on the integrity of the design and engineering systems. This method considers the actual cost of the project, which can be applied to the costs of analogs by analyzing the costs of association, and can obtain similar ship cost items on a contract basis. However, it is difficult to use dozens of parameters in the early design of a new ship. Further analysis of features is possible based on feature-based estimation methods, such as data mining and artificial intelligence.

The third type of method is the life-cycle approach, which is based on advanced computer-aided design (CAD) and product life-cycle management (PLM). Integration with an enterprise resource planning (ERP) database of the shipyards is necessary. Based on this background, a preliminary cost estimation method is applied using the BOM, 3D computer-aided manufacturing (CAM) tools, and a computerized expert system approach. The method computes estimates for each configured segment, which can be duplicated from similar parts of previously built ships (Son et al., 2011).

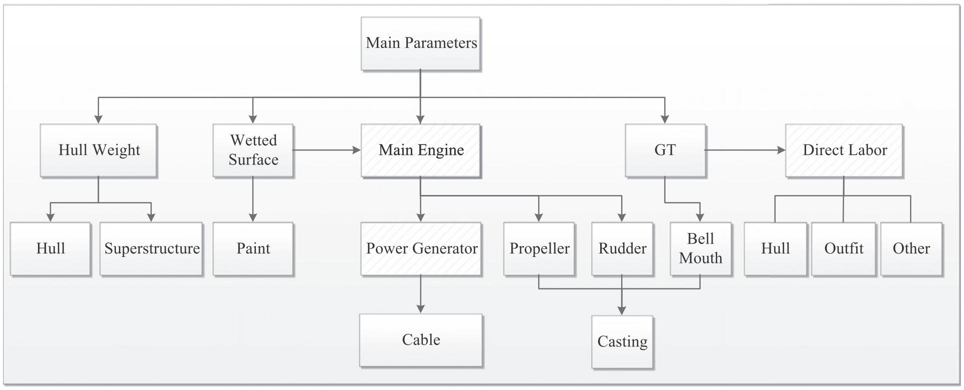
This style, which applies the actuarial valuation to the BOM of the materials, is still the most complete historical reference source from shipyards and is commonly used in practice. Therefore, Son et al. (2011) proposed a hybrid method based on the BOM combined with the case-based and feature-based methods from the preliminary stage. The method defines several feature types and does not include further specifications, parameters and cost estimation relationships (CERs). Hence, the method addresses the gaps of the preliminary application.

The fourth type of method is the feature-based approach. Some information in more detailed layers cannot be directly obtained from general parameters but is meaningful for the estimation. Geometric information has been widely used as simplification criteria in previous studies (Lee, 2005), and only a few conducted studies have considered non-geometric information. Sufficient design details may rule out this approach in the earliest stages of design (Bole, 2007).

The reasonable division of ships is a popular methodology in shipbuilding. A segment framework is applied to estimate the costs of the structures of ships (Son et al., 2011). This methodology is mainly applied in the replacement of existing designs and to determine the work for the weight and labor hours of a structure. (Caprace and Rigo, 2011) considered qualitative complexity criteria to estimate six segments of a ship in the conceptual design stage, and (Caprace and Rigo, 2012) developed a feature-based cost model of ships for cost-effectiveness measurements based on the elementary parts of a ship's structure. This method is mainly used for construction, with no further description of the equipment. In the field of computer-aided engineering (CAE), the feature-based method collects features that are more important and



(a)



(b)

Fig. 2. **(a)** Process of principal feature estimation method. **(b)** Feature structure.

meaningful modeling units than dots, lines, and faces by simplifying and reducing 3D CAD data (Kwon et al., 2015).

In this study, we simplify 3D CAD data of built ships under the specific segment framework of ships to analyze and mine features of the hull that are not only geometric (Lin and Shaw, 2015b). This domain of analysis considers the cost, design specifications, and principal parameters. The features of the relationships between the hull segments and the estimated items are then considered and applied to estimate the cost items.

1.3. Scope of the preliminary estimation

For a new ship, the function cost analysis is the first stage in which the initial top-level requirements are analyzed and divided into the main cost items based on the required or assumed design specifications (Fig. 1 (a)). The relative methods are the second layer of the cost structure, which evolves from the labor, construction materials, overhead, and other direct fees in the shipyards. Although shipyards roughly estimate the required labor, materials, and equipment based on overall ship parameters, this estimate does not reflect additional cost factors, including design, material, construction, exchange rate, and marketing costs.

In this study, we include a more detailed level to determine additional features and costs items based on the statistical analysis using the database of modern container ships. The database based on the structure of the level is constructed to provide a different level of estimates. Thus, the specific estimate for each top level can be summarized from the detailed items.

The typical cost structure for a container ship is shown in Fig. 1(a). Although all cost items are complicated, material and labor costs account for the largest proportion (approximately 75–80%) of general merchant ships (Celik et al., 2013). The material costs are the main item and commonly represent more than 60% of the total cost of large container ships. The proportion of material costs increases with increasing ship tonnage, and the proportion of labor has the opposite trend. The variable costs of the materials and labor leads to the variations in cost of container ships.

The scope of this study is to estimate the main cost items in the preliminary stage based on Table 1. The related features of ships are used to develop the preliminary estimation method. These items have the greatest impact on the ship's total cost, including the hull, propulsion plant, material, major equipment, and direct manufacturing costs. In the database, container ships that were designed or delivered since 2000 are divided into four major categories: Feeder, Feedermax, Panamax, and

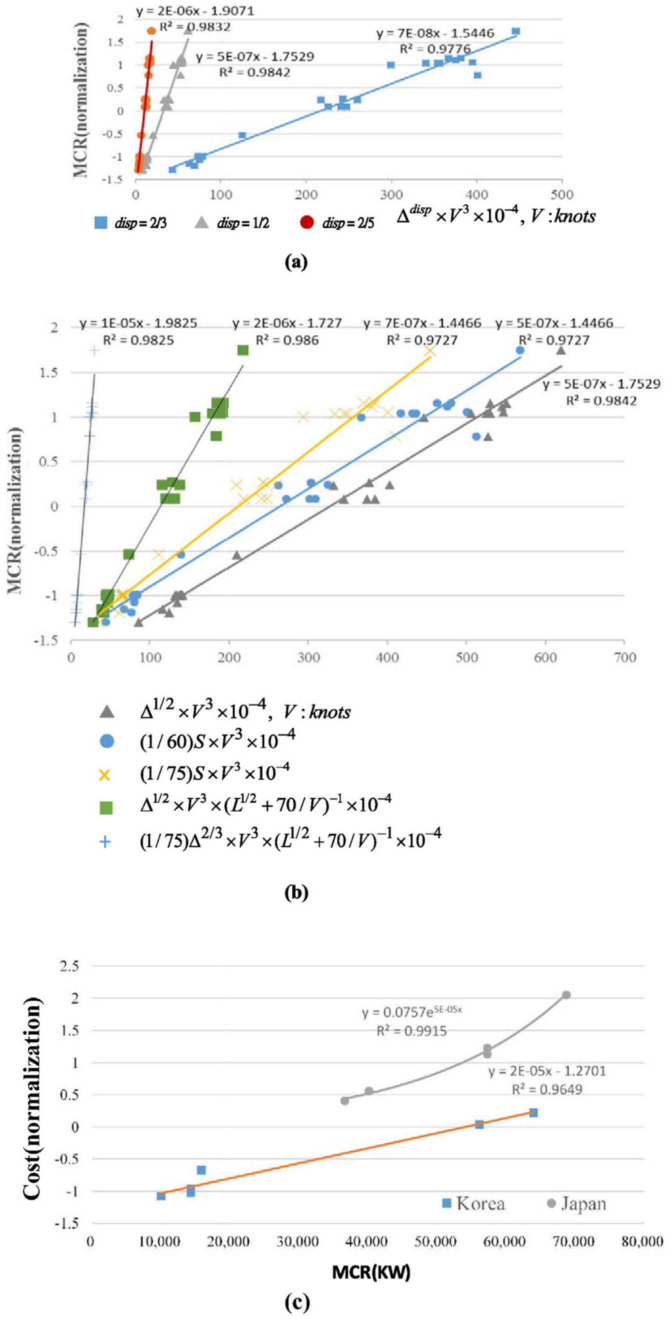


Fig. 3. **(a)** MCR vs. displacement and speed. **(b)** MCR vs. wetted surface area, displacement, and speed. **(c)** Cost vs. MCR.

Post-Panamax. Fig. 1(b) shows a list of the main estimated materials, which includes the equipment. This list includes the average ranking based on the 38 types of container ships at the collaborative shipyard.

These items can be estimated based on the preliminary parameters, detailed design parameters, or actual cost records. Thus, the method supports the cost management in the different stages.

1.4. Outline

In this paper, we propose an innovative estimation method, called feature-based estimation (FBE), for use in the preliminary design phase of a ship tendering process. FBE, requires only a few parameters, including additional detailed information, and it is more powerful than other parametric estimation methods that rely on the characteristics of the entire ship to derive regression formulas and do not consider the specific features of the ship's configuration. The method is faster and simpler than other present methods that require more detailed designs.

To estimate each specification, the relationships between the important features are determined from the preliminary design parameters, significant specifications, and cost structures based on a reasonable division of the estimated item. Regression analysis is used to develop the estimation method, and corrections are used to identify ship features that are neglected by the regression analysis. The less quantifiable

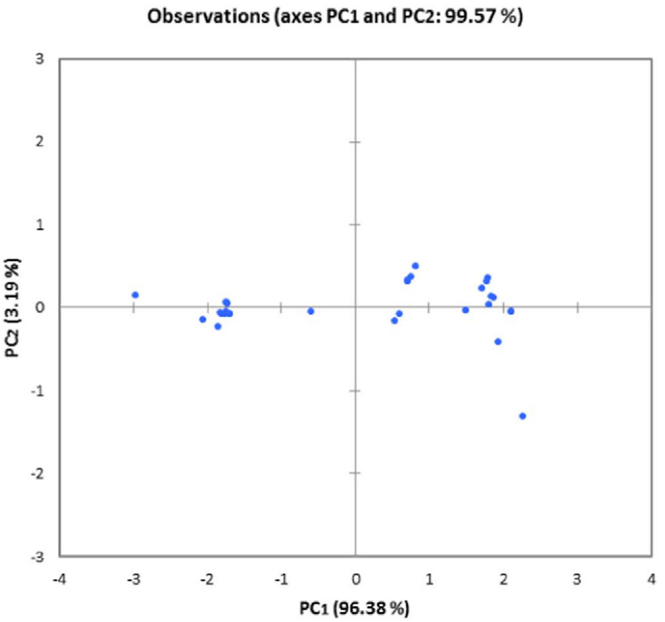


Fig. 4. PCA diagram.

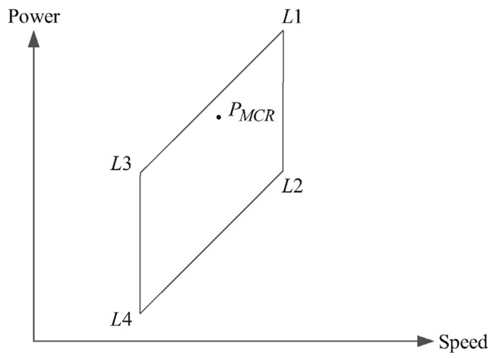


Fig. 5. Power diagram.

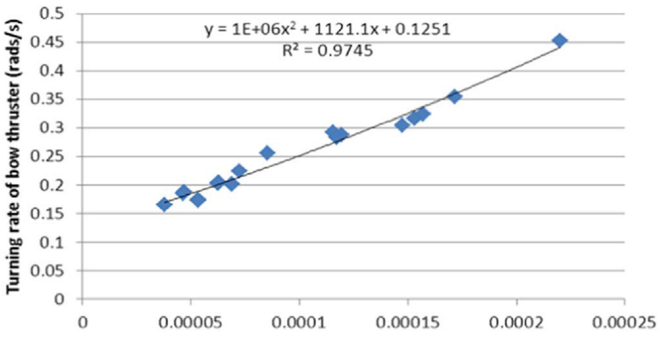


Fig. 6. Turning rate vs. $1/sqrt(L^3 \times d)$.

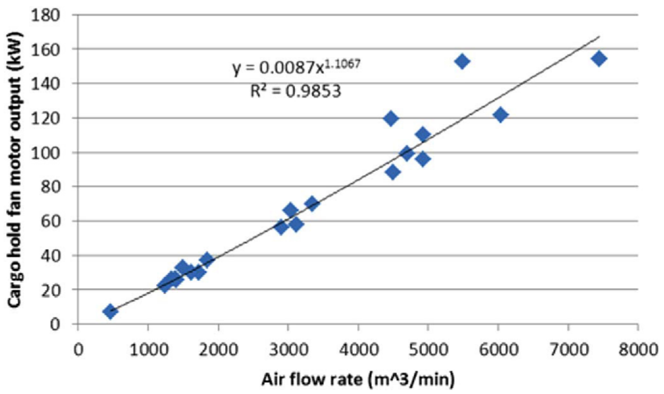


Fig. 7. Cargo hold fan motor vs. air flow rate..

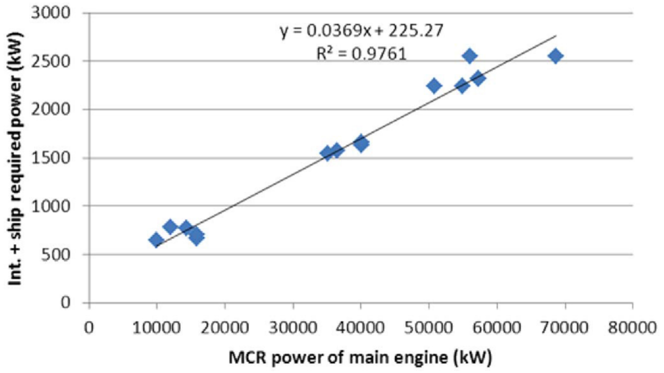


Fig. 8. P_{req} vs. MCR.

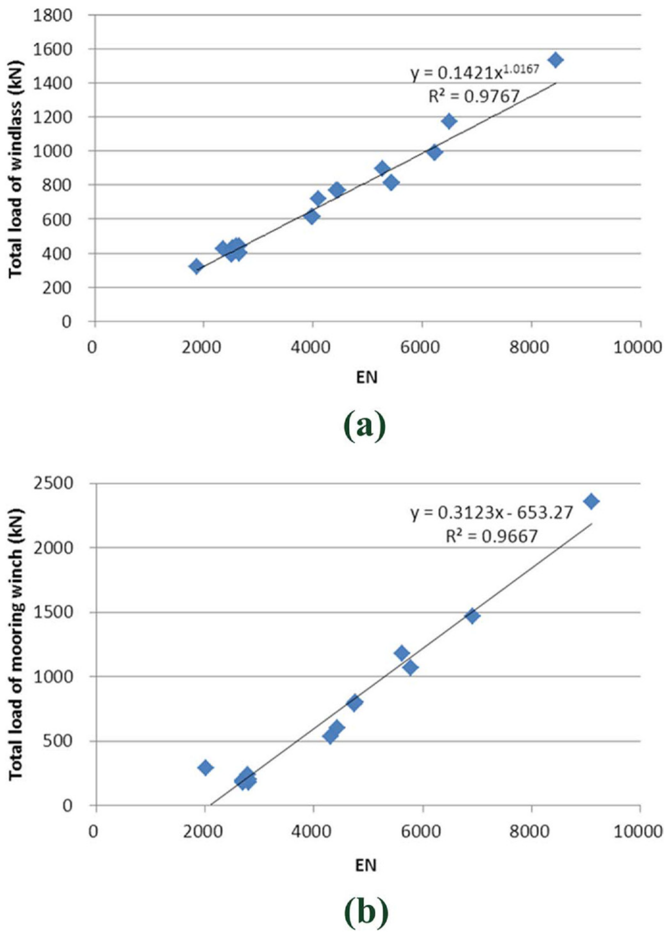


Fig. 9. Load of the windlass and mooring winch.

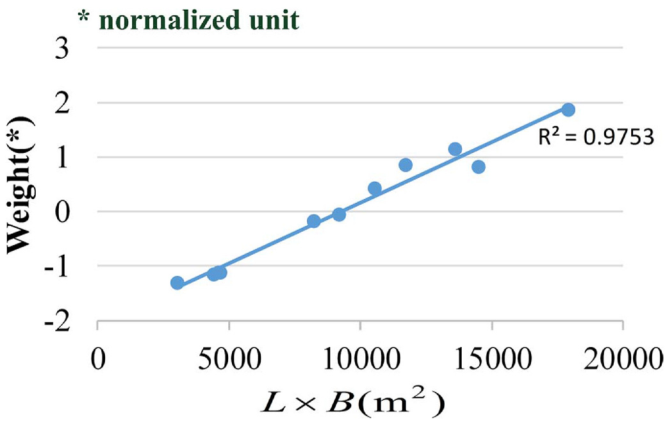


Fig. 10. Weight vs. $L \times B$.

characteristics of the design are referenced to similar specifications of the reference ship to reflect the actual costs. The development of FBE is described in Section 2, including the features of ships and the derivation of the general estimation. We describe the method of estimating the main cost items in Section 3 and demonstrate the practicality and effectiveness of the method in Section 4. In Section 5, we provide conclusions and describe future work.

2. Development of the feature-based estimation method

FBE was developed to estimate important cost items. Table 1 lists all estimated items and sub-items with their feature parameters. FBE mainly establishes the topology of the relationships between the features by linking the principal dimensional parameters and detailed features of the design specifications and cost information to estimate the main specifications of ships. The method is sufficiently detailed for the design, production and marketing of these cost items to improve the estimates.

The concept is divided into three parts. First, the parameters and relations of the design and cost of ships are mined for their principal features based the design and cost analysis. The principal features are analyzed based on the general design parameters, and the secondary features are collected based on a reasonable division of the estimated item. The sub-items of the estimated items are defined to extract the features. Second, we transform the features into a quantifiable structure between the features and within individual features. The principal features, which are general parameters that use the parameter combinations, contain the core context with few parameters. The estimation, which is based on a combination of several principal features, can account for most of the actual value. Third, the estimate may be adjusted for various characteristics based on the secondary features using special treatments.

Fig. 2(a) shows the process of the method. In the first step, the preliminary principal dimensions and basic parameters based on the requirements of a ship can be used to derive specific feature parameters to estimate a specific item. In the second step, which considers the estimated factors with the design and cost, each estimated item is related to several principal features. We collect the features of the important sub-items for the top-level item shown in Fig. 2(b). The feature collection combines the estimation of the design and cost based on the analysis of a series of ship features.

In the third step, which considers the application of the features, the parameter analysis used Principal component analysis (PCA) and a general empirical equation to select the estimated independent parameters

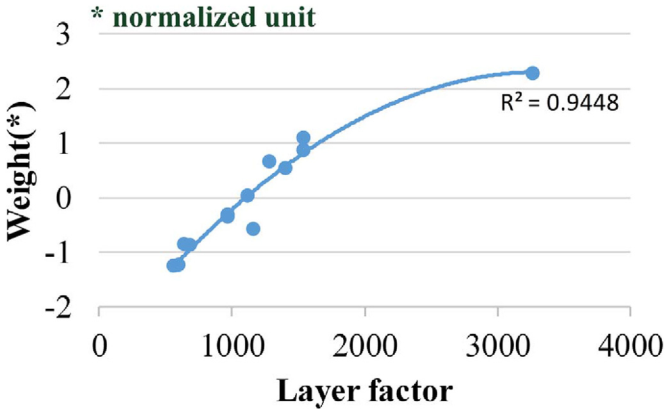


Fig. 11. Lashing bridge weight vs. layer factor.

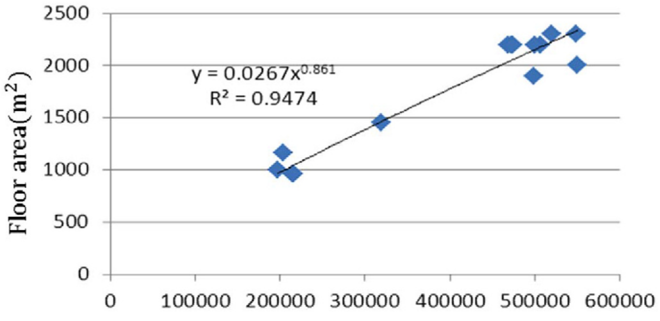


Fig. 12. Floor area of the decorated rooms.

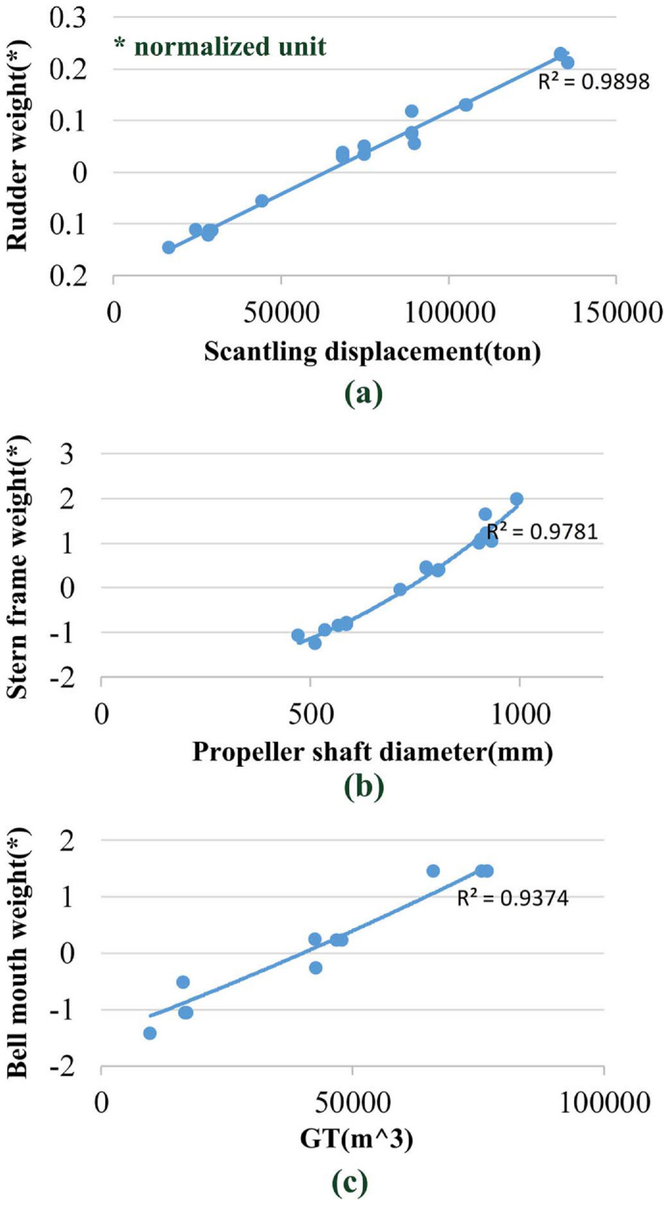


Fig. 13. **(a)** Rudder weight vs. scantling displacement. **(b)** Stern frame weight vs. propeller shaft diameter. **(c)** Bell mouth weight vs. GT.

for the regression analysis. In the fourth step, the reference ships are selected to develop a fitting database for the regression analysis. In the fifth step, the feature-based estimation model to estimate the specific item is developed by regression analysis; this is described next.

2.1. Feature definition

FBE extracts the detailed features from different datasets (Fig. 2(b)). The form of the detailed features is then transformed into a quantifiable structure using the associated parameter combinations. Finally, the most significant parameters of the inputs are defined, including the relationships between the input parameters of the principal dimensions, the specifications of the ships, and the estimated cost items, using the important design features and costs in the shipbuilding process.

2.1.1. Database and feature parameters

The features are classified by the principal and secondary variables. The principal variables are global and consist of the principal dimensions and coefficients, major design features and the layouts of the ships, whereas the secondary variables usually refer to a part or detail of local segment variables.

After reviewing the database of the containers for the major equipment, material, labor and other valuation parameters, we aggregate the design parameters of the 18 usable parameters, including length L, breadth B, depth D, design and scantling draft d, C_B at scantling draft, displacement Δ at design and scantling draft, maximum speed V, maximum continuous rating power (MCR), revolution per minute (RPM), thickness of the self-polish antifouling (SPAF), which is the primary ship-bottom paint, deckhouse height, layers of the lashing bridge, number of reefer containers, number of crew, dollar exchange rate, and proportion of indirect costs. The indirect costs include general activities that are repeated and support the maintenance in a particular shipyard and do not include the direct costs of a specific project.

In addition to these parameters, which depend on the design, the unit costs of the estimated items, which are quoted from previous estimates, are also important reference parameters, including the steel, engine, power generation, SPAF and other paint, hatch cover, outfit materials, lashing bridge, accommodation, casting, propeller, deck machinery and mooring system, cable, weld materials, direct labor and overhead. Using these parameters, FBE can be applied to the cost structure, including the specifications and characteristics of the main materials and equipment.

2.1.2. Features of ship types

First, 38 containerships from the initial database were distinguished into four major size categories: Feeder, Feedermax, Panamax, and Post-Panamax. Because the only New-Panamax type is still under construction, estimats of the man-hours and paint for this type of ship were omitted, but those for the other items were included. Reference ships with the same specifications can influence the results of the regression results; ships with the same parameters were omitted from estimating the relative items.

For containerships of a shipping line with the same main dimensions,

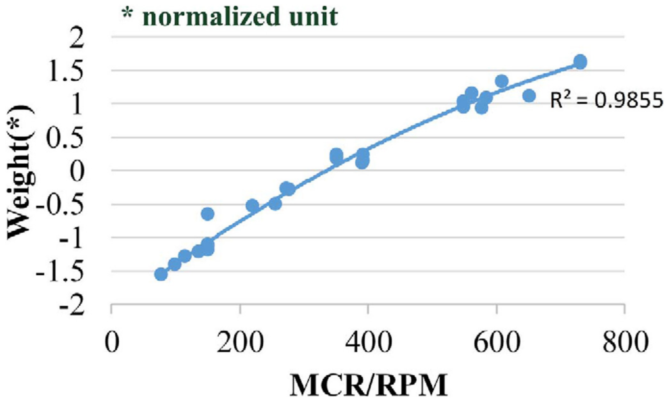


Fig. 14. Propeller weight distribution.

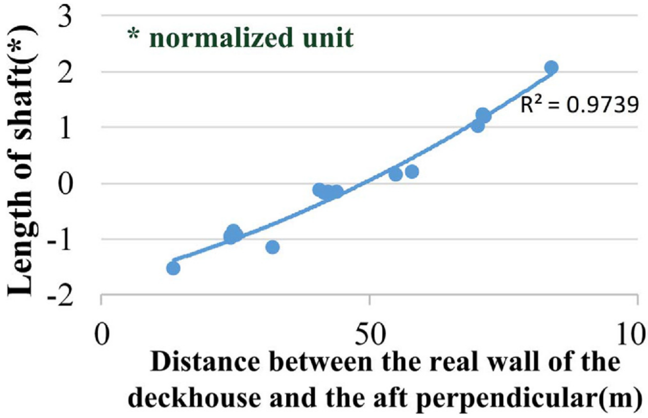


Fig. 15. Length distribution of the shaft.

the shipyard will continue to modify the hull in order to meet regulations and increase performance. Therefore, only the latest design is used with the general conditions. We found it necessary to filter the old information to estimate the structural weight. However, series of ships with different equipment were used in the other estimated items.

Second, to reduce the estimation errors, we used a single design source with a similar topology to a hull in a shipyard. We also found that the foreign designs belong to the older design. Some ships were omitted because their drawings were incomplete. The representative types of these ships were selected, and others with consistent, special, or obsolete designs were omitted. We thus selected the most recent design types to obtain representative data. We assumed that these categories must be satisfied by the various general designs.

2.2. Principles of feature-based estimation

2.2.1. Analysis of principal parameters

PCA is a commonly-used mining analysis technique for shipbuilding costs (Hart et al., 2012; It, 2002; Kaluzny et al., 2011). PCA can identify the most important factors among a set of parameters of ships with the highest correlations to the cost (Hart et al., 2012). PCA can screen for sensitivity parameters, multivariate conversion into a single variable, simplified regression analysis to identify the cost-related patterns. Thus, this study adopted PCA to develop the estimated models. The standard steps are described as follows:

The input matrix X consists of a physical parameter data set given as

$$x_{(i)} = [x_1, \cdots, x_m]_{(i)}, \quad i = 1 \cdots n, \tag{1a}$$

where each i of the n rows represents data for a different ship, and each element of the m columns gives a particular type of parameters. If the input data for each kind of parameter have different units, they should be pretreated to a normalized unit with a mean of 0 and a standard deviation of 1. The matrix X is expressed as

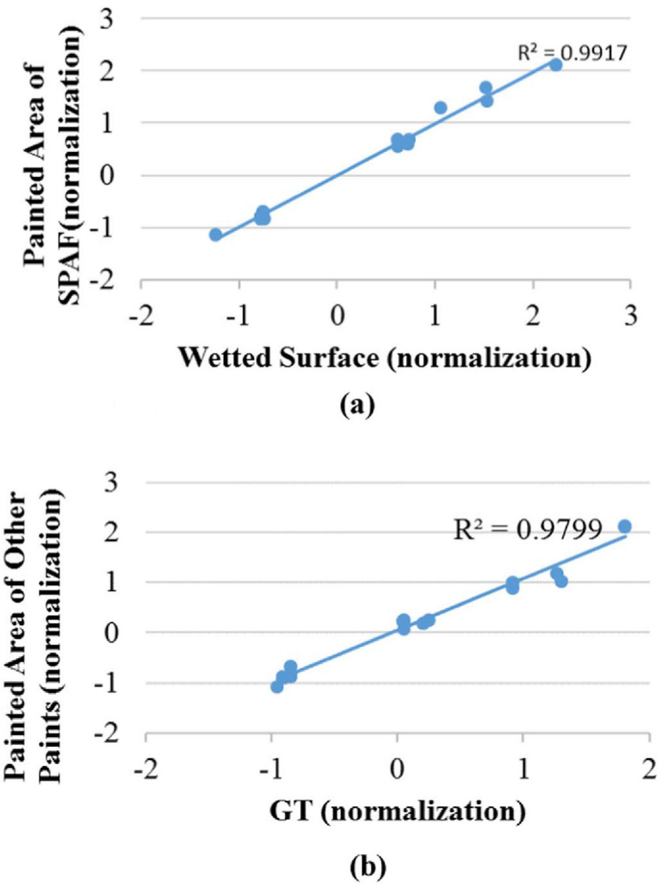


Fig. 16. **(a)** Painted area of SPAF vs. wetted surface. **(b)** Painted area of the other paints vs. GT.

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix}. \tag{1b}$$

The full principal components (PCs) decomposition of X using PCA is

$$Q = A \cdot X. \tag{2}$$

where A is an m-by-m matrix whose columns are the eigenvectors of $X^t X$ and X^t is the transposed matrix of X.

The matrix Q inherits the maximum possible variance from X, and the matrix A contains the weights or loadings of X. The matrix A consists of

$$a_{(p)} = [a_1, \cdots, a_m]_{(p)}, \ p = 1 \cdots m, \tag{3}$$

where $a_{(p)}$ is constrained as a unit vector, and p indexes the weights of the combined parameters with different dimensions. Each item of $a_{(p)}$ is treated as a weighting factor for the corresponding physical parameter.

$a_{(p)}$ maps each row vector $x_{(i)}$ of X to a new vector of the PC scores

$$q_{(i)} = [q_1, \cdots, q_p]_{(i)}, \tag{4a}$$

where

$$q_{p(i)} = a_{(p)} \cdot x^t_{(i)}, \tag{4b}$$

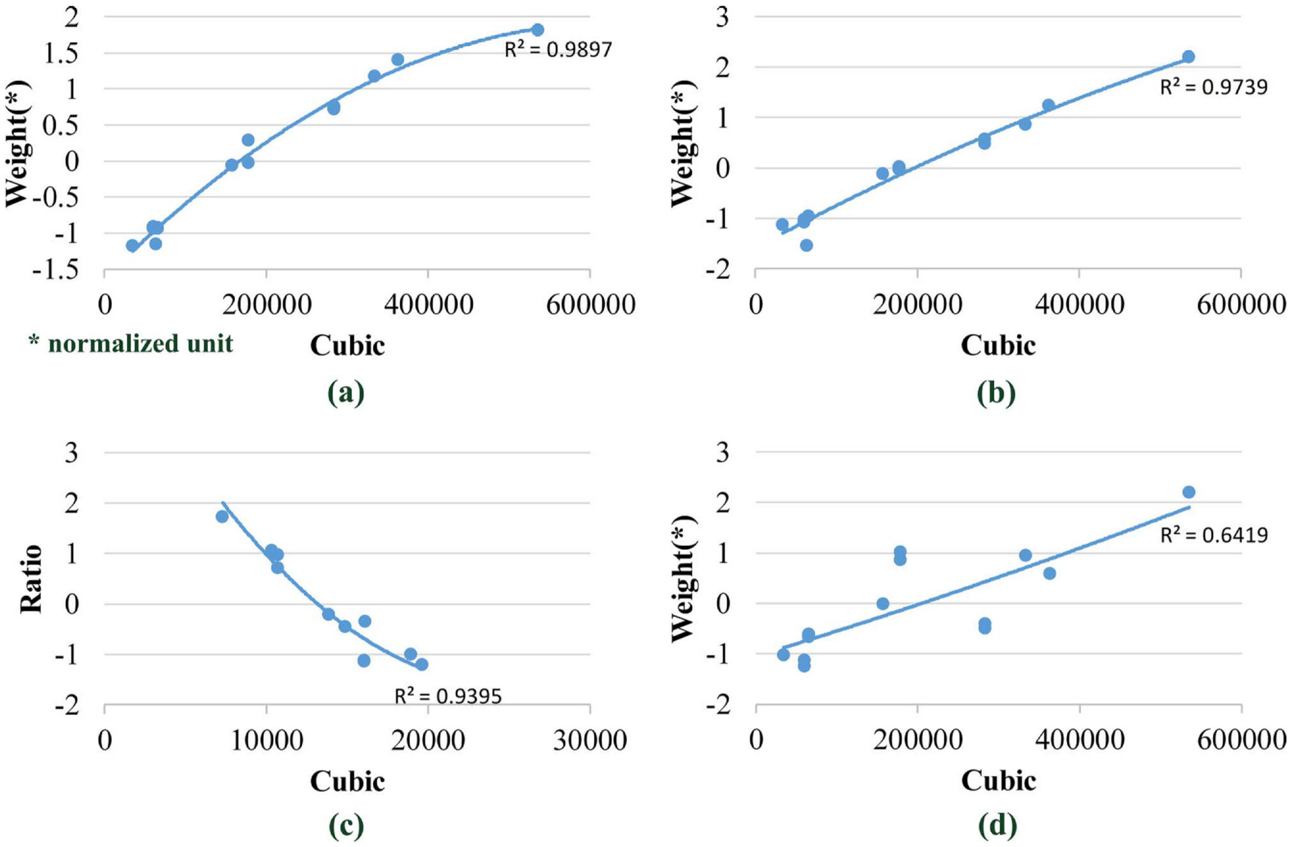


Fig. 17. **(a)** Weight of outfit materials of the engine room vs. cubic dimensions of the entire ship. **(b)** Weight of outfit materials of the hull vs. cubic dimensions of the entire ship. **(c)** Ratio of the weight of the deckhouse to the total weight of the engine room and hull for outfit materials vs. cubic dimensions of the deckhouse. **(d)** Weight of outfit materials of the deckhouse vs. Cubic dimensions of the entire ship.

$$q_{p(i)} = (a_1x_1 + a_2x_2 + \ldots + a_mx_m)_{(i)}. \tag{4c}$$

The matrix Q inherits the maximum possible variance from X, and each loading vector $a_{(p)}$ is constrained as a unit vector. The first loading vector $a_{(1)}$ satisfies

$$a_{(1)} = \arg\max\left\{\sum_i (x_{(i)}\cdot a_{(p)})^2\right\}. \tag{5}$$

A standard result of a symmetric matrix, such as X^tX, is that the quotient's maximum possible value is the largest eigenvalue of the matrix, which occurs if $a_{(1)}$ is the corresponding eigenvector.

We can then analyze the influence of each parameter in $a_{(1)}$ to select the principal parameters. The largest eigenvector is aligned in the direction of the greatest variation in the data, which calculates the first PC as

$$PC = a_{(1)}x^t_{(i)}, \tag{6a}$$

$$PC = (a_1x_1 + a_2x_2 + \ldots + a_mx_m)_{(i)}. \tag{6b}$$

2.2.2. Estimation model

Considering the principal parameters of the features, we choose the most important parameters which have large weights from the PCA. The selected parameters of the *PC* obtain the greatest influences (greater than 80%) of the PC through Eq. (4).

For more independent variables, PCA is applied to combinations of variables that are linear, logarithmic, or natural logarithmic based on the data distribution of variables or the relative physical meaning. For example, the combination of the variables is defined as

$$PC = a_1P_1 + a_2P_2 + \ldots + a_nP_n, \text{ or} \tag{7a}$$

$$\ln PC = a_1 \ln P_1 + a_2 \ln P_2 + \ldots + a_n \ln P_n, \tag{7b}$$

where PC is the first principal component, P_1–P_n are the specific parameters of the features, and a_1~a_n are calculated using Eq. (4). Eq. (7b) can be written as

$$PC = P_1^{a_1}\cdot P_2^{a_2}\cdot P_3^{a_3}\cdot \ldots \cdot P_n^{a_n}. \tag{8}$$

where the data are converted from a natural logarithmic scale to a linear scale. *PC* represents an independent variable that is a predictor for estimating a specific item E_d. The estimating functions are then derived for the empirical equation using numerical methods, such as linear or nonlinear regression.

We use *PC* and E_d in PCA again. PCA builds a linear regression model between the parameters *PC* and the actual value E_d as

$$PC_{reg} = a_1PC + a_2E_d, \tag{9}$$

where a_1 and a_2 are calculated using Eq. (4).

If the first PC of PC_{reg} represents all of weight factors, the second PC is equal to zero. The second PC of Eq. (9) is expressed as

$$0 = a_1PC + a_2E_d. \tag{10}$$

The equation may be written as

$$E \sim E_d, \quad \text{where} \quad E_d = \frac{-a_1}{a_2}PC. \tag{11}$$

E is the estimate of E_d. Eq. (11) provides only the best-fitting curve in

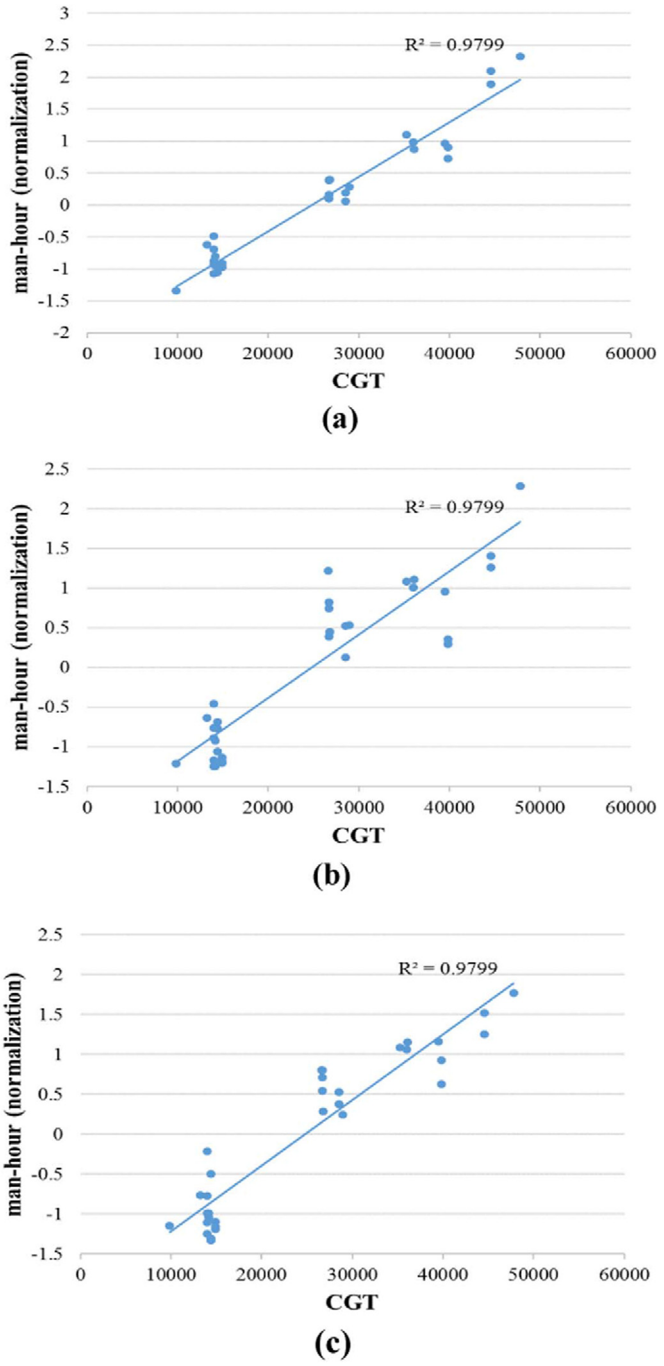


Fig. 18. **(a)** Hull man-hours vs. CGT. **(b)**Outfit man-hours vs. CGT. **(c)** Others man-hours vs. CGT.

the equation that accounts for most of the actual value. We can then consider the influence of the feature c on the specific item to modify the error of the first estimation by multiplication i.e., $f(c)\cdot E$.

3. Feature-based estimation method for ship costs

3.1. Steel estimation

First, we sum up all estimated weights to obtain the total weight W_{tot} based on the feature-based method (Lin and Shaw, 2015a). Then, we consider the related cost features. The materials of the steel are divided into two categories, the angle bars and plates. Each category contains several grades based on the tensile strength of steel. For example, the raw plates for shipbuilding include grade EH32, EH36, EH40, and EH47 by DNV-GL. Some high tensile steel, such as grade EH47, is more than 1.5 times the price of general marine steel. Thus, we need to consider the base price of each material separately. The base price of each type of material is mainly influenced by the steel market, the exchange rate and the freight procurement. Considering the average cutting loss k_{loss} and the proportion k_{rate} of the angle bar and plate of W_{tot} in a specific built yard, the purchasing weight W_{steel} is defined as

$$W_{steel(i)} = W_{tot} \times k_{rate(i)} \times k_{loss(i)}, \tag{12}$$

where i represents various materials including the angle bar and plate.

The CER for the cost of the steel is defined as

$$CE_{steel(i)} = C_{base\ price(i)} \times W_{steel(i)} \times k_{shipment(i)} \times k_{grade(i)}, \text{ and} \tag{13}$$

$$k_{grade(i)} = \sum_j \frac{Price_{tensile(j)_{Ref\ ship}}}{Price_{base_{Ref\ ship}}} \times \frac{W_{tensile(j)_{Ref\ ship}}}{W_{steel_{Ref\ ship}}}, \tag{14}$$

where $C_{base\ price}$ is the only input parameter and includes the base price of the angle bar or plate, and the others are nearly constant based on the results of the analysis of the database of the configuration of the reference ship. The parameter $k_{shipment}$ is the shipment rate based on the distance from the steel factory to the shipyard. k_{grade} is the correction coefficient of the high tensile steel, j represents various grades, including several varieties of tensile steel, and k_{grade} establishes a relationship between $C_{base\ price}$ and the price of each type of tensile steel. $Price_{tensile(j)_{Ref\ ship}}$ is the base price of the specific tensile steel, $\frac{Price_{tensile(j)_{Ref\ ship}}}{Price_{base_{Ref\ ship}}}$ is the price ratio between a type of tensile steel and typical steel, which represents the impact of price changes in the market, $W_{steel_{Ref\ ship}}$ is the weight of the reference ship, and $\frac{W_{tensile(j)_{Ref\ ship}}}{W_{steel_{Ref\ ship}}}$ is the rate of the specific material. When the steel market is the same as the reference ship of the same design, k_{grade} will be equal to 1.

3.2. Main engine and machines

3.2.1. Main engine

According to recent trends, the overall efficiency of a ship is quantified by the Energy Efficiency Design Index (EEDI), where a lower EEDI indicates that the ship is more environmentally and socially efficient (International Maritime Organization, 2011). Furthermore, ships with greater power requirements require more fuel for each voyage. Our database shows that in recent years, slow cruising speed has become an efficient method to counter the effects of the maritime recession; thus, diesel propulsion is preferred in many cargo ships, including bulk carriers, oil tankers, and container ships.

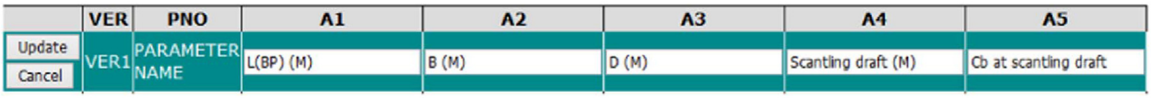
In general, the resistance is the most important factor in estimating the required power. Resistance increases because of the sea, wind and current. The resistance is proportional to the wetted surface area S and the square of the speed V, but the wave resistance increases more rapidly at higher speeds and represents a greater proportion, a greater proportion of the total resistance. The general relation is:

$$R_T = \frac{1}{2} \times C_T \times \rho \times S \times V^2\ . \tag{15}$$

where ρ is the seawater density and C_T is the coefficient of the total resistance. S may be replaced by the displacement Δ. The equation may be rewritten as

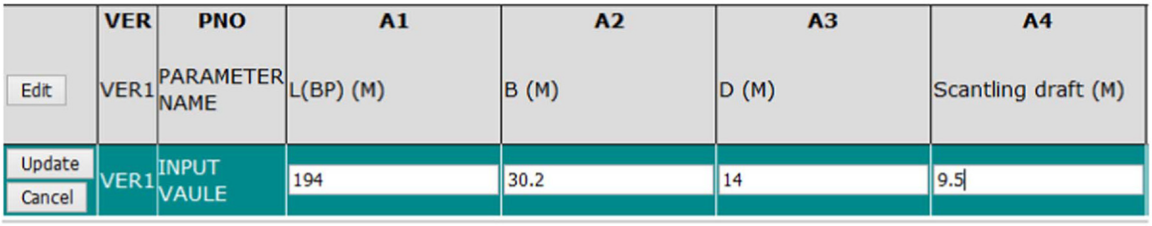
$$\frac{R_T}{\frac{1}{2} \times \rho \times S \times V^2} \sim \frac{R_T}{\frac{1}{2} \times \rho \times \Delta^{2/3} \times V^2} \sim \frac{V}{\sqrt{gL}}\ . \tag{16}$$

The Admiralty coefficient A_c, which is a constant that is valid for a



VER	PNO	A1	A2	A3	A4	A5
VER1	PARAMETER NAME	L(BP) (M)	B (M)	D (M)	Scantling draft (M)	Cb at scantling draft

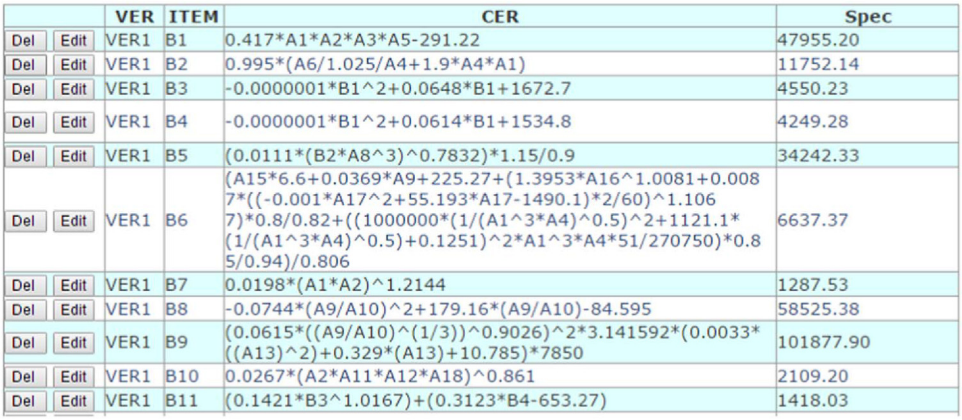
(a) Function of definition interface parameters



VER	PNO	A1	A2	A3	A4
VER1	PARAMETER NAME	L(BP) (M)	B (M)	D (M)	Scantling draft (M)
VER1	INPUT VAULE	194	30.2	14	9.5

(b) Function of input interface of parameters

Fig. 19. Estimation parameters.



VER	ITEM	CER	Spec
VER1	B1	0.417*A1*A2*A3*A5-291.22	47955.20
VER1	B2	0.995*(A6/1.025/A4+1.9*A4*A1)	11752.14
VER1	B3	-0.0000001*B1^2+0.0648*B1+1672.7	4550.23
VER1	B4	-0.0000001*B1^2+0.0614*B1+1534.8	4249.28
VER1	B5	(0.0111*(B2*A8^3)^0.7832)*1.15/0.9	34242.33
VER1	B6	(A15*6.6+0.0369*A9+225.27+(1.3953*A16^1.0081+0.0087*((-0.001*A17^2+55.193*A17-1490.1)*2/60)^1.1067)*0.8/0.82+((1000000*(1/(A1^3*A4)^0.5)^2+1121.1*(1/(A1^3*A4)^0.5)+0.1251)^2*A1^3*A4*51/270750)*0.85/0.94)/0.806	6637.37
VER1	B7	0.0198*(A1*A2)^1.2144	1287.53
VER1	B8	-0.0744*(A9/A10)^2+179.16*(A9/A10)-84.595	58525.38
VER1	B9	(0.0615*((A9/A10)^(1/3))^0.9026)^2*3.141592*(0.0033*((A13)^2)+0.329*(A13)+10.785)*7850	101877.90
VER1	B10	0.0267*(A2*A11*A12*A18)^0.861	2109.20
VER1	B11	(0.1421*B3^1.0167)+(0.3123*B4-653.27)	1418.03

Fig. 20. Models of design specifications.

given ship, is also useful for simple ship estimations; it uses approximate relationships between the propulsion power P, the cube of the speed and the displacement (Turbo, 2011). The constant A_c is defined as

$$A_c = \frac{\Delta^{2/3} \times V^3}{P}\ . \tag{17}$$

Therefore, Δ, V, and S have the greatest impacts.

Considering the ship owners' requirements, we use Δ and V to explore the relationship with MCR, which is the maximum continuous rating of the engine based on the different displacement indexes, shown as Fig. 3(a). The R-squared values of these models are greater than 0.97, which indicates that the regression models are appropriate. There are three main errors. First, a large displacement indicates that the power is overestimated. Thus, the index of the displacement must be decreased to fit the distribution of the power curve. Second, ships that use energy-saving technology have recently led to overestimates of power. Third, a ship design may be unique in terms of the need for an ultra-high speed.

Increasing the wetted area S leads to greater frictional resistance. At low speeds, this increase is typically greater than the reductions in resistance caused by other factors. The factor S is defined as

$$S = k \times L \times d + \frac{\Delta}{d}\ \text{or} \tag{18}$$

$$S = k \times L \times d + C_b \times L \times B, \tag{19}$$

where k=1.7 according to Denny Mumford (Molland et al., 2011), and k=1.8 for modern warships (Bertram and Schneekluth, 1998). The coefficient k should increase slightly when it is applied to modern container ships. The power is also primarily a function of S and V. The power can be estimated by regression analysis as shown in Fig. 3(b).

Because (S, V) and (Δ, V) have similar distributions (Fig. 3(b)), Δ and V are identified as having the greatest impacts on power estimation, and Δ can also be determined by the principal dimensions and C_b. The parameter $(L^{1/2} + 70/V)$ is the correction coefficient (Celik et al., 2013). However, the magnitude of this correction is insufficient for modern ships, such as 8,000 twenty-foot equivalent unit (TEU) and larger ships; the maximum estimated error exceeds 15%. These larger, more modern ships are located in the fourth quadrant of Fig. 4. These modern ships have a different trend in the second PC because the values on the Y-axis have greater variations due to the energy-saving technologies applied.

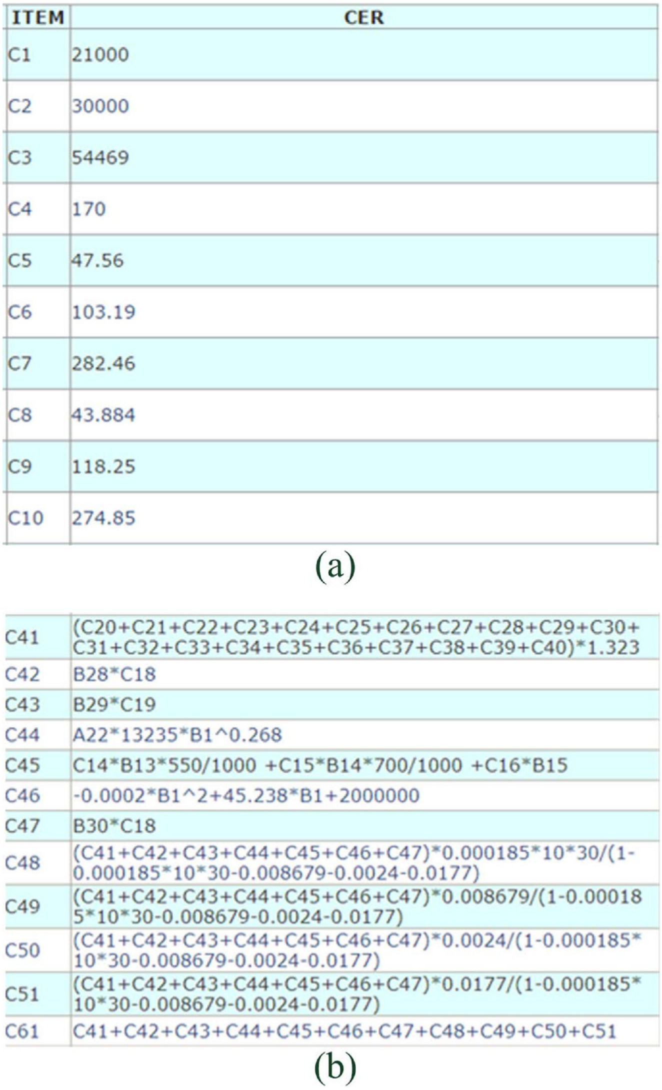
P_{MCR} represents the power during service considering the specified sea margin and the running factor of the propeller (i.e., heavy or light). For general conditions, we use an MCR of 90% and a sea margin of 15% to estimate the required power P_{MCR}:

$$P_{MCR} = P_D \times 1.15/0.9,\ \text{and} \tag{20}$$

$$P_{MCR} = PC(\Delta, V^3), \tag{21}$$

where P_D is the delivered power.

We obtain the standard estimation through PCA and regression analysis. We can then modify the estimation using the energy-saving factor Es by multiplying $P_{MCR} \cdot f(Es)$ and the speed factor by $P_{MCR} \cdot f(V)$. To minimize hull resistance and increase propulsion efficiency, the hull form (lines), fore, and aft must be optimized. The main items include the



ITEM	CER
C1	21000
C2	30000
C3	54469
C4	170
C5	47.56
C6	103.19
C7	282.46
C8	43.884
C9	118.25
C10	274.85

(a)

C41	(C20+C21+C22+C23+C24+C25+C26+C27+C28+C29+C30+C31+C32+C33+C34+C35+C36+C37+C38+C39+C40)*1.323
C42	B28*C18
C43	B29*C19
C44	A22*13235*B1^0.268
C45	C14*B13*550/1000 +C15*B14*700/1000 +C16*B15
C46	-0.0002*B1^2+45.238*B1+2000000
C47	B30*C18
C48	(C41+C42+C43+C44+C45+C46+C47)*0.000185*10*30/(1-0.000185*10*30-0.008679-0.0024-0.0177)
C49	(C41+C42+C43+C44+C45+C46+C47)*0.008679/(1-0.000185*10*30-0.008679-0.0024-0.0177)
C50	(C41+C42+C43+C44+C45+C46+C47)*0.0024/(1-0.000185*10*30-0.008679-0.0024-0.0177)
C51	(C41+C42+C43+C44+C45+C46+C47)*0.0177/(1-0.000185*10*30-0.008679-0.0024-0.0177)
C61	C41+C42+C43+C44+C45+C46+C47+C48+C49+C50+C51

(b)

Fig. 21. **(a)** Models of configuration unit costs. **(b)** Models of cost estimation.

Table 2
Comparison of the estimation results.

SHIP	A	B	C
Type	Feeder	Panamax	New Panamax
LBP (m)	169	246.4	352
Breadth (m)	27	37	51
Error (%) of Total Cost	0.84	−2.63	6.90
Error (%) of Material Cost	7.30	−8.44	11.72
Error (%) of Labor Cost	0.61	2.95	−25.70
Error (%) of Overhead Cost	−6.38	−2.55	27.31

The error differences are calculated as follows:
(the estimated cost−the real cost)/the real cost×100%.

sea-sword bow, vortex generator, propeller boss cap fin, rudder bulb, rudder skeg, rudder fin, and contracted and loaded tip propeller in the database. Contra-rotating propellers have been applied in small ships. The total efficiency of the energy saving is in the range of 5–10% and is higher in slow vessels. Thus, in the fourth quadrant of Fig. 4, the ships with energy-saving technologies have different trends; the values of the second *PC* (Y-axis) have greater variations.

An engine's layout is limited by two constant mean effective pressure lines, *L*1–*L*3 and *L*2–*L*4, and two constant engine speed lines, *L*1–*L*2 and *L*3–*L*4, as shown in Fig. 5 (Turbo, 2011; Woodyard, 2009). The power P_{L1} refers to the engine's nominal maximum continuous output the *L*1 point of the engine and is an actual unit of measurement. Designers must consider specifications from the manufacturer at the owner's request to identify the corresponding P_{L1} based on the estimated power. P_{MCR} must be inside the limitation lines of the layout diagram; otherwise, the propeller speed must be changed or another main engine type must be chosen. The cost of the engine *CE* can be estimated by regression analysis, as shown in Fig. 3(c). and can be defined as

$$CE = c_i P_{L1} + c_j. \tag{22}$$

The engine prices are mainly affected by three factors. First, larger engines have lower prices in KW/tons. Second, the prices are affected by market conditions. Third, the manufacturing cost of the engines are affected by the manufacturing countries. We use data generated since the financial crisis of 2008 to reduce the effects of the market. The manufacturing region is divided into two groups: Japan and South Korea.

3.2.2. Power generator

Because ship service generators must be sufficient in number and size to provide power consistent for the mission of the ship, the estimated items are divided into the ship's required power, intermittent power, cargo hold fans, reefers, and bow thruster.

3.2.2.1. Bow thruster. The required thrust of the bow thruster is directly related to $P_{rate}^2 \times L^3 \times d$ (Beveridge, 1971), where P_{rate} is the turning rate, *L* is the ship's length, and *d* is the ship's draft. This relation was derived using flat-plate theory by (Hawkins et al., 1965). The theory represents the ship as a flat plate with underwater dimensions of *L* and *d*. Thus, the general equation for estimating the capacity of the bow thruster is simplified and defined as

$$P_{B/T} = k_{ef} \times P_{rate}^2 \times L^3 \times d, \tag{23}$$

where k_{ef} is the average efficiency of the bow thruster.

The equation may be written as

$$\frac{P_{rate}}{\sqrt{P_{B/T}}} = \frac{1}{\sqrt{k_{ef} \times L^3 \times d}}. \tag{24}$$

The regression formula for the capacity of the bow thruster that is used to estimate the turning rate is shown in Fig. 6. Hence, the parameters *L* and *d* can be obtained to estimate the turning rate P_{rate}. The estimated function is derived for P_{rate} using linear regression as

$$P_{rate} = PC(L^3, d). \tag{25}$$

Fig. 6 shows this linear relationship. The load factor (L.F.) and efficiency (Eff.) are determined from the average values of historical equipment, and k_{ef} is determined by applying the ratio (L.F./Eff).

3.2.2.2. Cargo hold fan. The cargo load is divided into two cases: with and without reefers installed. Based on the reefer demands of the owner, the demand is set as an input parameter.

For the no-reefer case, we can only estimate the ventilation load based on using the volume of the cargo by following the general standard, such as two times the air change per hour. The equation is defined as

$$P_{cargoFan} = k_{lf} \times (c_i Qt_{teu} + c_j) \times 2/60, \tag{26}$$

where k_{lf} is the load factor of the cargo fan, and Qt_{teu} is the number of containers. The linear relationship is shown in Fig. 7.

For the reefer case, the load is the sum of the load of the cargo hold and all reefer fans. Because each reefer has a power of 11 kW and the number of reefers Qt_{reefer} is known, the required power can be estimated directly as

$$P_{freezer} = k_{ef} \times 11 \times Qt_{reefer}, \tag{27}$$

3.2.2.3. Required continuous operation and intermittent power. The required continuous operation and intermittent power is estimated by P_{MCR}. The relationship is shown in Fig. 8.

$$P_{req} = c_i P_{MCR} + c_j. \tag{28}$$

3.2.2.4. Total capacity and cost estimation. The total capacity is expressed as

$$P_{tot} = L.F._{generator}\left(P_{req.} + P_{B/T} + P_{cargoFan} + P_{freezer}\right). \tag{29}$$

The cost of the generator *CE* can be estimated by regression analysis and is expressed as

$$CE = c_i P_{tot}^{c_j}. \tag{30}$$

3.3. Deck machinery and Mooring system

To simplify the estimation process, only the total load of the anchor windlass and mooring winch are estimated. The general arrangement is set as one machine with two dual wheels to allow two anchors on double rollers to be serviced. According to the class rules, the outfitting equipment number (EN) is the reference input parameter for the total load of the windlass and mooring winch (Fig. 9). Because the EN is related to the GT, we can use the GT to estimate the EN and then estimate the loads of the windlass and mooring winch.

3.4. Superstructure

3.4.1. Hatch cover

The average unit price per ton of the hatch cover is quite stable. Hence, the only required information for the entire hatch cover is the weight, including the outfitting and paint coating. We can use the area of hatch cover to estimate the weight, as shown in Fig. 10. The cost is estimated as

$$CE = C_{base\ price} \times L \times B. \tag{31}$$

3.4.2. Lashing bridge

The components of the lashing bridge are applied to larger-sized containers, which have capacities greater than 4,000 TEU. Designs have been gradually becoming more lightweight, particularly for larger ships. The curve of the weights of lashing bridges indicates a logarithmic relationship. The main input parameter is the sum of the layers of the lashing bridges. This parameter is then multiplied by the breadth to yield the relationship with the weight of the lashing bridge (Fig. 11). The cost is multiplied by the weight and the recent unit cost.

3.4.3. Accommodation

The floor area is the main basis of the decoration cost of the accommodation. The number of inner compartments of the room is related to the number of crew members C_{crew}. Therefore, we estimate roughly the decorated floor area by the sum of the floor volumes of all layers l_{acc} and the number of crew members C_{crew} (Fig. 12) and we define the CER as

$$CE = C_{base\ price} \times PC(l_{acc}, C_{crew}), \tag{32}$$

where $C_{base\ price}$ is an optional input parameter that includes the base price. $C_{base\ price}$ is generally fixed, but special needs of the owner may be incorporated using a coefficient of increase.

3.5. Castings and forgings

3.5.1. Rudder and bell mouth

The category of special metal components is divided into three groups of items, including the rudder casting with the stock and sleeve, the stern frame casting, and the bell mouth casting. The weight of the rudder casting is relative to the scanting draft, as shown in Fig. 13(a). The weight of the stern frame casting is relative to the propeller shaft diameter $P_{shaftDiameter}$, as shown in Fig. 13(b). Following the general design rule, the parameter can be calculated as

$$P_{shaftDiameter} = \left(k \times P_{MCR}/P_{RPM}\right)^{1/3}. \tag{33}$$

The weight of the bell mouth is related to the GT, as shown in Fig. 13(c). We use the total weight $P_{totWeight}$ which is the sum of the estimated items to estimate the cost with the linear function $C_{base\ price} \times PC$.

3.5.2. Propeller

The main relevant information is the MCR power, RPM, and propeller weight (Fig. 14). The estimated cost is based on the weight, which is determined by the power function:

$$P_{proWeight} = c_i\left(P_{MCR}/P_{RPM}\right)^{c_j}. \tag{34}$$

3.5.3. Shaft

The cost of the shaft is calculated by estimating the weight, which is calculated using the general equation

$$P_{shaftWeight} = k \times \pi \times P_{radius}^2 \times P_{length}. \tag{35}$$

The main relevant information is the radius and length of the shaft, as shown in Fig. 15. The estimated cost is based on the weight of the shaft using a linear function.

3.6. Other materials

3.6.1. Welding materials

The ratio of the welding material to the weight of the steel is relatively constant at approximately 1–2% based on the historical data. The proportion is slightly lower in larger ships with a large-scale segmented design. We estimate the cost based on the average price of the delivered ships. The average unit price is approximately \$1,800-2,000/ton. The equation is as follows:

$$CE = C_{base\ price} \times c_i \times P_{steelWeight}. \tag{36}$$

3.6.2. Paint

Considering the main differences of the unit prices of different types of paints, the print specifications are divided into three categories: SPAF paint, general paint and thinner paint. Considering the average painting loss k_{loss} , dry film thickness *Dft* and estimated painted area for the different types of ships, the quantity of the painted solid volume *Pt* is defined as

$$Pt_{(i)} = Dft_{(i)} \times Area_{(i)} \times k_{loss(i)}, \tag{37}$$

where *i* represents the various paint types (i.e., SPAF paint, general paint, or thinner paint).

SPAF, which uses a hydrolysable polymer rosin to form self polishing antifouling coating, is the most expensive type of paint in shipbuilding. SPAF is applied below the waterline and on the bottom shell; the painted area of SPAF relative to the wetted surface is shown in Fig. 16(a). Because GT is dimensionless index relative to a ship's overall internal volume, the painted area of the general paint is also related to the GT (Fig. 16(b)). According to the database in this study, thinner paint accounts for 10–15% of the total amount of paint. The maximum quantity of thinner paint is defined as

$$Pt_{Thinner} = \left(Pt_{SPAF} + Pt_{General}\right) \times 0.15, \tag{38}$$

The CER of the cost is defined as

$$CE_{(i)} = C_{base\ price(i)} \times C_{year(i)} \times Pt_{(i)}, \tag{39}$$

where $C_{base\ price}$ is the only input parameter and includes the base price of SPAF or general paint, and C_{year} is the years of warranty.

3.6.3. Fitting (pipes, fittings, and valves)

The outfitting materials mainly include the pipes, fittings, and valves. The outfit zone of a ship can be divided into three parts: the engine room, hull, and deckhouse. Because different quantities of these materials are used in these zones, they should be estimated separately. We first estimate the outfit weight of the engine room and the hull (Fig. 17(a–b)):

$$P_{outfitWeight} = C_i(PC(L, B, D))^{C_j}, \tag{40}$$

The weight of the deckhouse can be estimated from the ratio of the weight of the deckhouse to the total weight of the engine room and hull. The estimates that use the ratio parameter are more constant, as shown in Fig. 17(c–d).

Second, the proportion of the individual materials of a specific zone (*i*) can be determined by referring to the average statistical values of the database $C_{weightRatio}$. Then, the cost can be obtained according to each item multiplied by the respective average unit cost $C_{base\ price}$:

$$CE_{(i,j)} = C_{base\ price(i,j)} \times C_{weightRatio(i,j)} \times P_{outfitWeight(i)}, \tag{41}$$

where i includes the engine room, general hull, and deckhouse, and j includes the pipes, fittings, and valves. $C_{weightRatio}$ of the valves is the key item. The ratio of the engine room is approximately 10%, the ratio of the deckhouse is approximately 4%, and the ratio of the general hull is less than 2%. The value of $C_{base\ price(i,j)}$ is determined by the market.

3.6.4. Cable

The total weight of the cable has a more significant linear relationship with the power load (Eq. 29) than with the total length. The CER is defined as

$$CE = C_{base\ price} \times c_i \times E.F._{\cdot generator} \times P_{\text{tot}}. \tag{42}$$

The average unit price is based on the average market price of the previous year; since 2000, it has typically been approximately \$5–6/kg.

3.7. Labor and overhead

3.7.1. Labor

The wage rate and man-hours are the main factors of labor in construction shipyards. The estimated items are divided into the hull, the outfit, and others because of differences in the unit prices and working ratios. The data were collected from two shipyards. The built area is not distinguished because only one type is built concurrently in the two shipyards, and there is a 0.5% efficiency gap (equal to 1.5% of the total working hours). The major difference is the other items. In large shipyards, the man-hours of the supporting work will be diluted, which results in fewer average working hours. The estimated parameter is the Compensated Gross Tonnage (CGT), which is an international indicator of the amount of work necessary to build a given ship and is calculated by multiplying the tonnage of a ship by a coefficient. The OECD revised the formula used to calculate CGT in 2007. The estimated gross tonnage (GT) can be directly converted into the CGT.

$$CGT = c_i GT^{c_j}, \tag{43}$$

where $c_i = 19, c_j = 0.68$. The relationships are defined as

$$P_{man-hour} = C_{base\ price} \times (c_i \times CGT + c_j), \tag{44}$$

where n the estimated category includes the hull, outfit and other items. The relationship is shown in Fig. 18(a)–(c). With increaseing tonnage, the relationships in Fig. 18(a)–(c) should generally exhibit linear increases. Because the production equipment limits the production efficiency, the largest ship leads to the exponential growth trends in the left parts of the figures.

3.7.2. Overhead

The overhead is not an onboard factor and is determined by the construction shipyard. The two shipyards with databases have significant differences; the cost ratio is approximately 3:2. Thus, the wage rates and estimated total man-hours are the main factors in the shipyard. The overhead *CE* isdefined as

$$CE = C_{base\ price} \times k_{ef} \times P_{totalMan-hours}, \tag{45}$$

where $C_{base\ price}$ is the average wage rate, and k_{ef} is the efficiency factor.

4. Preliminary estimation of containerships

Shipyards generally aim to offer ship owners attractive projects and focus on decreasing the labor and material costs to build ships with lower construction costs. The preliminary estimated cost is a standard for cost savings. The estimated and final costs are usually some what different.

In this study, we focus on the development of an agile preliminary estimating system that incorporates the presented method with reasonable cost estimates. The estimation system is developed in Microsoft Visual Studio.Net 2012. We verify the results using Microsoft Excel 2010. The results from both programs are consistent; the differences are less than 0.001 and are mainly due to differences in the decimal digits of precision. The estimation steps are as follows:

1. Define the principal parameters A*i*, such as A1 and A2 (Fig. 19(a)) and input the value of the defined parameters (Fig. 19(b)).
2. The system calculates the estimates of the design specifications B*i*, such as B1 and B2, based on the presented equation of CERs using the input parameters (Fig. 20).
3. Define the unit cost of the main estimation items C*i*, such as C1 and C2, based on the reference-configured estimates of the database (Fig. 21(a)). These items are optional inputs based on changes in the market.
4. The system calculates the cost estimates based on the presented equation of CERs, including the relevant features such as the design, specifications, building, and market factors, using the combined estimations (Fig. 21(b)).

We sum all estimated items of the main material and equipment to the cost of the direct material C41 as shown in Line 1 of Fig. 21(b). Then, C41 is multiplied by the ratio of the other material components. The direct labor C42 is multiplied by the wage rate as shown in Line 2. The other direct fees C51 contain the design fee, the class inspection fee, the quality control inspection fee, the air pollution charge, and the overhead cost. Because the contributions of these items are extremely low, the accuracy of these cost estimates is not as critical, and reasonable values will suffice. The proportion of costs of these items is approximately constant and is not in the scope of this study. The main coefficients are the premium ratio, the interest payment ratio, the warranty cost ratio, and the ratio of operating expenses. We can then calculate the total cost C61.

Most estimates of the cost items in this database have highly linear correlations with errors of less than±15%. However, most samples are within the four categories. Additional samples of vessels that are larger than Panamax are needed to validate this method.

Table 2 shows a comparison of the main cost items. Ship A (Feeder), which was delivered in 2015–2016, Ship B (Panamax), which was delivered in 2014–2015, and Ship C (New Panamax), which was delivered in 2016, are examples of recently built ships. Ship A and B are excluded from the database. The cost structures for these ships are mainly the material, labor, and overhead costs. We set the exchange rate and wage rate based on the initial values of the orders. Based on a comparison with the actual costs, the errors of the total costs are nearly 0.84% for Ship A, −2.63% for Ship B, and 6.90% for Ship C. Hence, the maximum error of the estimated total cost is less than±7%.

The errors of the material costs which include the equipment costs, are nearly 7.3% for Ship A, −8% for Ship B, and 11.72% for Ship C. Because the shipyards attempt to avoid losses, the cost overruns of a project can be reduced by reducing the material costs, as shown in Ships A and C. Thus, an appropriate overestimation of the material cost is a reasonable situation. The main error for Ship B was in the material costs because of the estimate for the main engine. We find that the price of the engine is greatly affected by the exchange rate. In future studies, changes of the exchange rate and market prices for various cost items should be considered in detail.

5. Conclusions

1. FBE was proposed to estimate the important ship costs in the preliminary design phase.
2. A database of container ships for the feature analysis was developed by using 3D CAD tools. An innovative framework was defined to collect the component features based on the preliminary parameters.
3. PCA was used to identify the principal parameters from the overall dimensions and components of the ship. A regression analysis was then used to derive a general equation to estimate the main cost items rather than the cost of the entire ship.
4. Most estimates of the cost items have highly linear correlations and errors of less than±15%. The errors of the estimated total costs are less than±7%.
5. The results show that the FBE method clearly provides cost profiles for many configurations. Hence, the model may be more robust for new ships or outliers. The estimated model is better for cost management in the preliminary stage.
6. Future work will develop FBE for other types of ships. In the results, the configured feature framework is the most important foundation for the success of the method. A framework that is not appropriate will lead to accumulated errors in the results. We examined have looked at the main cost items of merchant ships, such as bulk carriers and tankers. The main cost items are similar in the three merchant ships, but the lashing bridge of the container ship is a unique item. Further consideration of whether to add specific items with the estimated features is needed. This method provides new possibilities to observe and estimate features of ships. In the future, by utilizing the synergies between 3D CAD tools and the BOM, we intend to research other components, the requirements of the materials and the cost at various stages of system engineering using the FBE concept.

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