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Shipyard Mathematics: A Comprehensive Mathematical Model for Estimating Manhours in Ship Repair

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ABSTRACT

The process of ship repair involves the restoration and maintenance of vessels to ensure their operational efficiency and safety. The term "man-hour" refers to the amount of labor required for a ship to undergo maintenance services in a dockyard. The process of docking ships for maintenance and repair is a complex undertaking that requires advanced planning and techniques. Additionally, it is a labor-intensive task that must be completed under strict time limitations. This study presents the development of a mathematical model utilizing multiple linear regression modeling techniques, specifically employing the least square method, to estimate the repair man-hour of cargo ships. This study aims to examine the interdependence among various characteristics related to the estimation of man-hours required for ship repair. In this model, the ship repair man-hour is determined by various factors, including structural steel works, pipework, displacement, hull cleaning and painting, general service, underwater fitting, and ship draft. The findings of this study indicate that certain independent variables, such as the number of plate works, exert a greater influence or dominance compared to other variables, such as the beam of the ship, in influencing the man-hours required for ship repairs. This model is hypothesized to potentially enhance shipyard and dockyard management by facilitating the estimation of labor man-hours required for repairs and the associated costs and time needed for initial quotations.

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1. Introduction.

Optimizing repair costs and maximizing sales (revenue increase) are two crucial considerations for both dry-docks and shipyards. The amount of sales generated is not solely determined by the organizations themselves but rather influenced by market competition and various factors that differ from one dockyard or shipyard to another.

Each organization maintains its own tariff chart for individual repair and maintenance tasks. The authorities of dry-docks and shipyards aim to increase revenue while minimizing costs associated with man-hours and other expenditures. Conversely, customers seek services at competitive prices while maintaining quality. These two objectives often need to be revised. Ship repair expenses fall under the purview of the dockyard and shipyard authorities, encompassing material costs, consumable items, and man-hour expenses. The majority of repair and maintenance work in shipyards heavily relies on man-hours and consumable items. Many consumable items are sourced from local shipbreaking industries (Abdullah et al., 2020). Thus, accurately estimating work plans in terms of man-hours is a significant undertaking for any docking ship undergoing maintenance. Dockyards and shipyards employ various methods to reduce man-hours during operations, tailored to their specific infrastructure and management systems. Table 1 categorizes repair and maintenance tasks based on man-hour requirements, including tasks solely performed by man-hours and those combining man-hours and machine-hours. After a ship

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is docked, various jobs are undertaken within main categories such as docking/undocking, plating and welding, rudder and propeller work, valves and piping, sandblasting and painting, transport and general services, mechanical work, electrical work, and more. The table further delineates subcategories within these main categories, distinguishing tasks accomplished solely by man-hours and those completed using a combination of man-hours and machine-hours.

Table 1: Different types of work involved with man and machinery.

	Types of work related to Man-Hour only	Types of work related to Man, and Machine Hour
Docking/Undocking	Docking Plan	Berth Preparation
	Chain Locker clean	Operation of Docking
	Under water fitting works.	Dock Cleaning
	Sea chest and grating works	Anchor and Chain Works
	Manhole cover opening work	Block Shifting Work
Plate and Welding works	Plate Visual inspection	Plate gauging works
	Hull template preparation	Hull plate cutting works
		Hull structure preparation
	Welding visual inspection	Hull structure fitting work
	Bottom plug checking	Hull structure welding
	Zinc anode checking	NDT test for welding
Rudder and Propeller works	Rudder Shaft clearance checking	Rudder unship and refitting works
	Rudder oil Change	Associated rudder item dismantles work.
	Zinc anode checking	Propeller dismantle work
	Propeller Shaft clearance checking	Tail and intermediate shaft withdrawal work.
	Bush checking	Calibration work
	Different seal checking	Simplex seal renewal
	Deep sea seal check	Chrome liner machining work
Valves and piping works	Valves opening works	Valve overhauling work
	Valves refitting works	Valve housing pressure test work
	Pipe line checking works	Pipe opening and refitting works
	Pipe line visual inspection	Pipe welding work, if required
Sandblasting and painting	Visual inspection	Water jetting work
	Light scraping of surface	Sandblasting work
	Hard scrapping of surface	Grit-blasting work
	Dry film thickness measurement	Paint preparation and application works
General service	Crane facility planning	Dock and Jetty crane operation work
	Forklift facility planning	Forklift operation work
	Heavy load Transport Facility Planning	Heavy load Transport Operation work

Source: Authors.

Table 1 provides a comprehensive breakdown of different repair and maintenance activities for docking ships, based on the author's practical experience. While some ships may require emergency repairs, the table mainly focuses on common maintenance tasks performed at regular intervals. These tasks include sandblasting, painting, inspections of the rudder and propulsion system, sea chest and grating maintenance, anchor and anchor chain load tests, zinc slab renewal, valve maintenance, and more. Additionally, during the docking period, occasional repair and maintenance work may be carried out, such as main engine and gearbox overhauling, boiler and turbine maintenance, and updates to navigational equipment like sonar systems and eco-sounders. It's important to note that only some of the repair works listed in Table 1 are applicable to every type of ship. The repairs are categorized based on ship types and the specific requirements of ship owners.

Both routine and occasional repair maintenance tasks heavily rely on man-hours and machine-hours in the ship repair industry, constituting a significant portion of the work. Approximately 60-70% (Abdullah, et al., 2022). of the costs are typically allocated to hiring manpower at various skill levels.

Consequently, optimizing revenue and maximizing profits in this industry hinge on effectively managing raw material costs, consumable item costs, and man-hour expenses. Implementing a proper work plan is essential to minimize these cost factors. There are several strategies to reduce man-hours. Firstly, conducting a thorough assessment, estimation, and distribution of man-hours is crucial. Secondly, assigning tasks based on the skill levels of workers, whether high-skilled, medium-skilled, or low-skilled, helps optimize labor hours. Lastly, experienced managers with a deep understanding of the factors influencing man-hours are indispensable. Monitoring the progress of the work with fixed targets is also essential for efficient management.

Sufficient literature exists regarding operating, repairing, and related expenditures in the shipping industry. However, there is a notable gap when it comes to research on ship repairing man-hours. This lack of available financial data and information can be attributed to the fact that Chittagong dry dock is the only internationally standardized repairing dry-dock in Bangladesh. In light of this research gap, the author, who possesses extensive direct experience in ship repair and maintenance, undertook the challenge of developing a mathematical model to estimate ship repairing man-hours.

In this research, ship repairing man-hours refer to the total amount of time spent by individual workers on repairing a docked ship. The counting of man-hours begins when the ship enters the dry dock and concludes upon its departure, specifically at the undocking time. The authors have solely focused on man-hours associated with routine repair and maintenance tasks, excluding emergency or occasional repairs. The main objectives of this article are twofold: 1) to develop a mathematical model for preliminary estimation of ship repair man-hours, and 2) to understand the interrelationships among independent variables, thereby identifying influential parameters that significantly impact ship repair man-hours.

2. Literature Review.

Numerous studies have been conducted on the financial implications of expenditures related to new building and repair projects. One notable study among them is "Modelling and Analysis of Labor Cost Estimation for Shipbuilding: The Case of China Shipbuilding Corporation" by Chou, C.C. and Chang, P.L. (2001). This research theory proves particularly valuable during the initial stages of a project. The primary objective of this paper was to explore the key factors influencing labor costs and to construct models for estimating the man-hours required for building new ships. While this research presents ten independent variables and showcases a few developed models, it only includes part of the model or the one incorporating the maximum considered variables.

Another noteworthy paper focusing on the estimation of man-hours for new shipbuilding subassembly is titled "The Man-hour Estimation Models & Its Comparison of Interim Products Assembly for Shipbuilding" by Bin Liu and Zu-Hua Jiang (2005). This article establishes a connection between estimated man-hours and several influential variables that help regulate the man-hour count.

A comprehensive examination of Dry-docking costs for tankers was conducted in a paper authored by Apostolidis, A., Kokarakis, J., and Merikas, A. (2012). This study stands out as the first of its kind to analyze the relationship between Dry-docking costs and various independent variables. The authors manually collected data from shipyards and proceeded to develop a mathematical model for estimating Dry-docking costs. The paper identified size, age, and the number of stay days as the primary determining factors influencing operational costs. Additionally, factors such as repair work, organizational overhead costs, dock rent, and logistic support rent were deemed crucial for enhancing the R^2 value.

In another paper titled "Decision Support System for Production Planning in the Ship Repair Industry," a system of decision support for short-term planning is expounded upon. The primary objective of this research article was to maximize system input while minimizing production-related costs. The implementation of this system during the project duration effectively addresses issues such as unnecessary internal costing, project delivery delays, and resource overloading or wastage.

Another notable study (Kr Dev, A. and Saha, M., 2015) highlighted on the Dry-Docking duration for crude oil tankers. The authors aimed to establish a relationship between dependent and independent variables through multiple linear regression analyses. The repairing time for the ship was considered as the output data, while various scopes of repairing works and two additional variables were treated as independent variables. Among these independent variables, the authors specifically focused on hull coating. It is important to note that prior to hull coating, proper steps such as hull cleaning (including water jetting, light scraping, and hard scrapping) and surface preparation (sandblasting) need to be undertaken. The paper by Kr Dev, A. and Saha, M. (2015) solely considers the hull coating area as an independent variable. However, the authors discuss all three variables separately in their analysis.

In a separate research article (KR DEV, A. and SAHA, M., 2015), the focus was on the labor cost associated with ship repairs, which directly corresponds to the labor (measured in person-days) allocated to the repair tasks. The authors of this article made an effort to identify the various factors that influence the number of person-days required for ship repair works (the dependent variable) and how these factors are interconnected. Additionally, they introduced a mathematical model aimed at estimating the labor cost involved in ship repairs.

Very recently, the author has undertaken the task of developing a comprehensive approach for constructing mathematical models applicable to various types of vessels (Abdullah, et al., 2022). These models are designed to accurately estimate the man-hours required for repair works. Furthermore, a separate study by Awal, Z. I. and Abdullah, A. (2021) focuses specifically on estimating repair time for cargo vessels. In this particular article, the authors have taken into account different dependent variables compared to the previous study. They have also considered a larger number of variables, resulting in improved outcomes compared to the study conducted by KR DEV, A. and SAHA, M. (2015). Additionally, another study authored by Abdullah, A. (2021) provides an in-depth examination of ship repair procedures and also includes discussions on repair time estimation.

3. Theoretical Framework.

In the previous works, the authors had developed a mathematical model to estimate the ship repair time (the dependent variable) considering other independent variables. In this present work the same methodology (multiple regression analysis) is used as before to develop the model for estimating the total man hour required for ship repairing. Multiple regression analysis is an effective tool to find the effect of two or more independent variables on a single dependent variable. The complex relationship among a dependent variable and multiple independent variables can closely estimate using this method. Least square technique has been used here to develop the multiple regression analysis.

In this article, vessel repair manhour (Y_{LH}) has been taken as dependent variable and ship displacement (SFD), plate works (PW), piping works (P), general service (GS), hull cleaning and painting works (HCP), underwater fittings (UWF) and draft (D) have been taken as dependent variable. The theoretical details on regression model is discussed in subsequent steps.

3.1. Regression Equation.

Considering y as dependent variable (ship repair man hour) and x as independent one (ship displacement, age, plate works, etc.), the function for regression model can be considered as:

$$y = f(x_1,\ x_2,\ x_3\ , \ldots ., x_k) \tag{1}$$

Taking n numbers of measured data for the dependent variable (y) and k numbers of independent variable (x) the regression equation for the model (1) can be written as follows:

$$y_n = b_0 + b_1 x_{1i} + b_2 x_{2i} + \cdots + b_k x_{ki} \quad (2)$$

Here,

i = 1, 2, 3…... n

b_i = slope constant/ regression coefficient for each independent variable.

b_0 = y- intercept in portion.

Adding the model's error term/ residual term e_i in the equation (2) the model equation becomes:

$$y_n = b_0 + b_1 x_{1i} + b_2 x_{2i} + \cdots + b_k x_{ki} + e_i \quad (3)$$

To find the best fitted line using least square techniques the error needs to be low as possible. The error term/ residuals can be defined as follows:

$$\text{SSE} = \int_{i=1}^{n} e_i^2 = \int_{i=1}^{n} (y_i - b_0 - b_1 x_{1i} - b_2 x_{2i} \ldots . - b_k x_{ki})^2 \quad (4)$$

In multivariable calculus to minimize error of the model the equation (4) needs to be partially differentiated with respect to each regression co-efficient (b_1, b_2, b_3…. b_i) and set the derived equations to zero.

$$\frac{\partial (SSE)}{\partial b_i} = 0 \quad (5)$$

This will provide k+1 numbers of equations with different parameters. Solving those equations using any approved method will provide the values of the coefficients.

3.1.1. Coefficient of determination, R^2.

Coefficient of determination is a complex idea to express the variability of one variable (dependent) in relation to another variable(independent). It is also termed as 'goodness of fit' that represents how perfectly a model fits to a given data set. SSR is equal to the sum of the squared differences between the predicted value of y and, the mean value of y. On the other hand, SSE is equal to the sum of the squared differences between the observed value of y and the predicted value of y (Levine et al., 2019). Although R2 is a good indicator of fitness of a model, it solely cannot be used to predict the correctness of model. It does not take into account whether a variable is significant to the model or not. In multiple linear regression analysis, it is important to determine which independent has significant contribution to the model. According to Levine et al. coefficient of determination can be written as:

$$R^2 = \frac{SSR}{SST}$$

Here,

SSR = Sum of Squares due to Regression.

SST = Total Sum of Squares.

3.1.2. Adjusted Coefficient of determination, R^2adj.

The adjusted R^2 becomes handy in this scenario to include more appropriate variables to the data set. The adjusted R^2 increases only if the new term improves the model more than would be expected by chance. It decreases when a predictor improves the model by less than expected by chance (Levine et al., 1997 and Mendenhall et al., 2013). adjusted R^2 can be written as follows:

$$R^2\,(adj.) = 1 - \left[\left(-R^2\right) \frac{n-1}{n-k-1}\right]$$

Here,

R^2 = coefficient of determination.

k = number of variables.

n = number of samples.

3.1.3. Mean square error (MSE).

Mean square error (MSE) refers to the mean of the square of the difference between actual and estimated values. The smaller the values of MSE the closer will be the regression line to the best fitted one. It is calculated by subtracting estimated y value from observed y value and adding the errors. The error can be both positive and negative. Hence, errors are squared and added together. Finally, the summation is averaged and square rooted.

3.1.4. Mallows's C_p Statistic.

C_P is a statistical parameter which is generally used to identify the best subset model where a number of independent variables or predictors are available for forecasting some output. Small C_P is effective for identifying the best subset among the so many combinations of independent variables. A large value of C_p not near p+1, suggests that some important predictors / independent variables have missed from the analysis. In this case, it is suggested to use the smallest value of C_p near p+1. C_p statistics can be written as:

$$C_P = \left[\frac{SS(RES)_P}{MSE_{all}} + 2\,(p+1) - n\right]$$

Here,

p = number of independent variables.

$SS(Res)_p$ = residual sum of square from p number of variable subsets.

MSE_{all} = mean square error including all independent variable.

n = number of samples.

3.1.5. Standard error.

The standard error (SE) measures the approximate standard deviation of a given data set. It uses standard deviation to determine the accuracy of the distribution of the given data set with respect to observed values. Standard errors can be written as follows:

$$s = \sqrt{\frac{SSE}{n-k-1}}$$

3.1.6. F-Statistics.

F-statistics is used to find out whether the estimated results have significant meaning or not. In F-test there two parts one is F critical value ($f_{critical}$) or F statistic and another one is F value which is calculated one. If F value (f) is larger than the F critical value, the null hypothesis can be rejected. That means the results do not have any significance in reality.

$$f = \frac{\frac{SSR}{k}}{\frac{SSE}{n-k-1}} = \frac{\frac{SSR}{k}}{s^2}.$$

3.1.7. Variance Inflation Factor, VIF.

Multicollinearity is a significant problem in selecting the best-suited mathematical model by using the multiple linear regression method. The multiple linear regression method depicts that there is no presence of multicollinearity among the independent variables. When independent variables are correlated with each other than the value of standard error increases and the variance of the predictor's coefficients is inflated. To identify the correlated variables, a tool is used which name is variance inflation factor (VIF). Daoud, J. I. (2017, December).

$$\text{VIF} = \frac{1}{1 - R^2}$$

4. Data Collection and Model Development.

4.1. Data Collection.

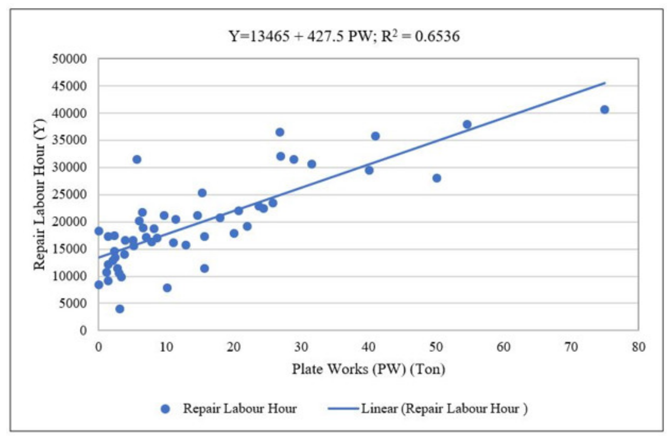
This study collected data on ship repair from the esteemed Chittagong Dry Dock Limited (CDDL) in Bangladesh, which is recognized as one of the leading dry docks in the country. Strategically located near Chittagong Port, the dock provides direct access to the Indian Ocean through the Bay of Bengal. For this study, a comprehensive database was compiled, encompassing ship repair data spanning 36 years from 1980 to 2016. The database comprises a wide range of ship repair information, such as displacement, repair man-hour, principal particulars, and other relevant details. The primary dry-dock database encompasses a wealth of ship-related parameters. However, for the purpose of this study, nine specific parameters were selected and given priority such as length (L) of ship(m), breadth (B) of ship (m), draught (D) of ship(m), full load displacement (Ton), general service works (Days), plate works (Ton), hull cleaning and painting (Sqm), piping works (m) and underwater fittings (Nos).

4.2. Dependency Check.

Figure 2 to figure 7 illustrates a scatter plot depicting the relationship between repair man hours and various independent variables. In the subsequent visualization, it becomes evident that plate work and general services exhibit a notable and positive correlation with labor hours, with R-squared values of 0.653 and 0.652, respectively. Similarly, hull cleaning and painting operations also display a good linear relationship with repair man hours, as most data points cluster closely around the trend line, highlighting a positive trend. Conversely, when it comes to pipe works, underwater fittings, and two ship-specific parameters (draft and full load displacement), their association with repair man hours demonstrates a modest degree of linearity, with relatively lower R-squared values compared to the aforementioned variables.

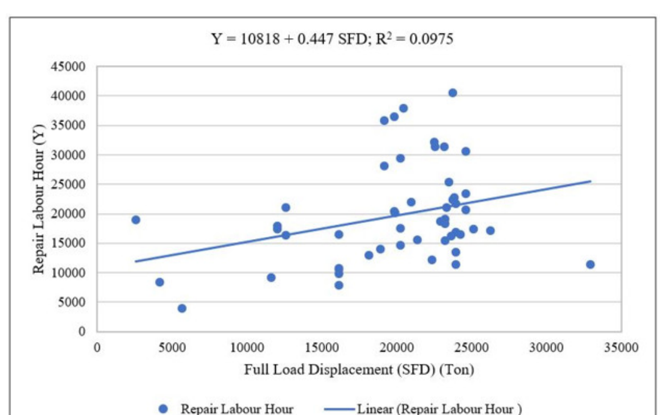
Nevertheless, it is important to note that all variables still maintain positive R-squared values, indicating a positive correlation between the dependent and independent variables discussed in this article.

Figure 1: Plot between manhour vs plate work.



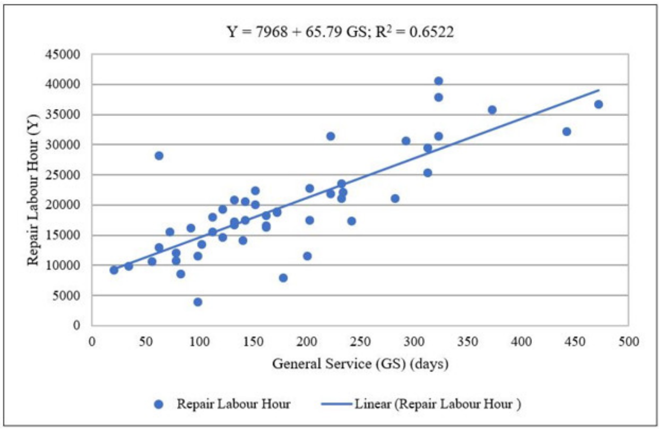
Source: Authors.

Figure 2: Plot between manhour vs displacement.



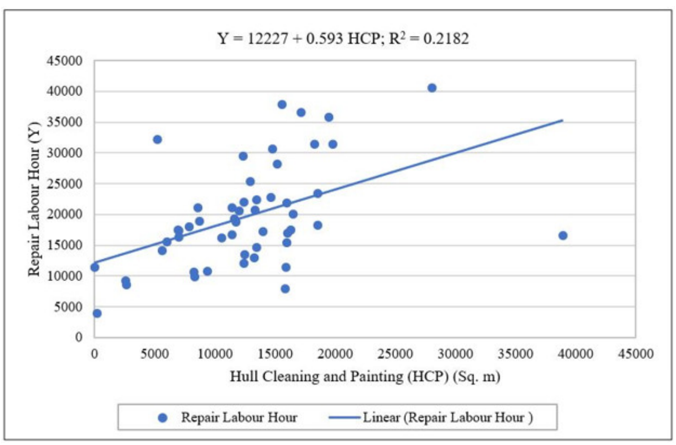
Source: Authors.

Figure 3: Plot between manhour vs General Service.



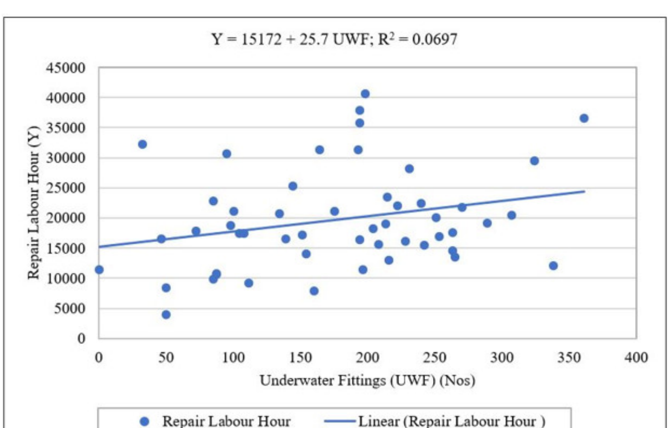
Source: Authors.

Figure 4: Plot between manhour vs Cleaning and Painting.



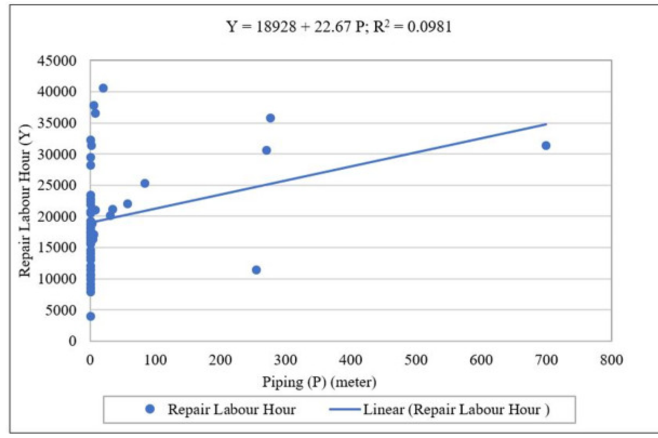
Source: Authors.

Figure 5: Plot between manhour vs hull underwater fittings.



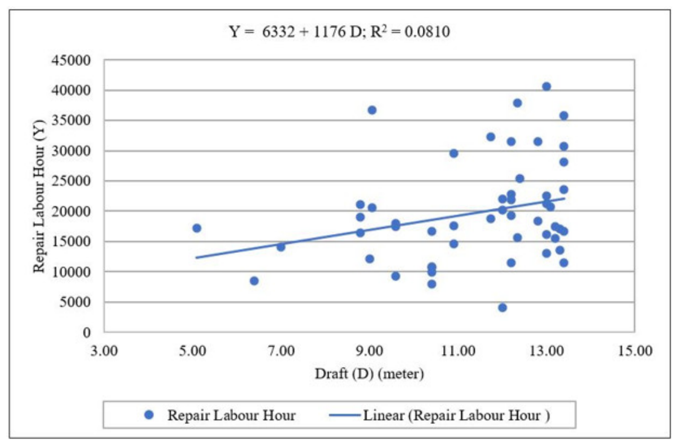
Source: Authors.

Figure 6: Scatter plot between manhour vs pipe work.



Source: Authors.

Figure 7: Scatter plot between manhour vs draft.

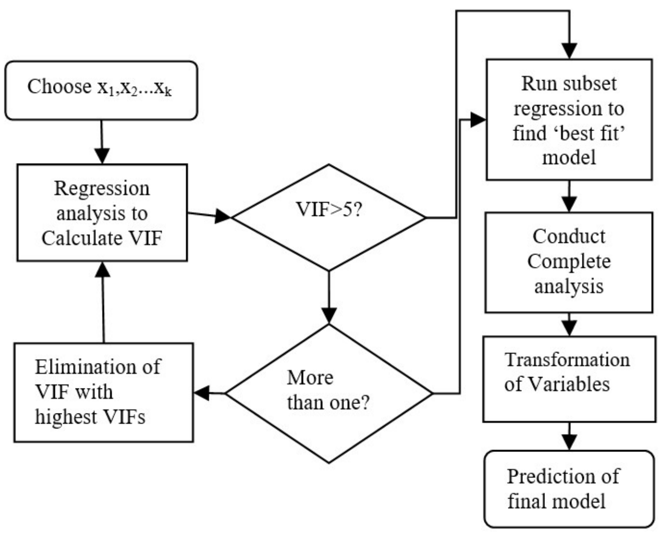


Source: Authors.

4.3. Steps in model development along with Validation.

In order to develop a mathematical model using multi-variable regression analysis, a series of sequential steps known as the model-building flowchart are followed. These steps provide guidance for constructing an effective model. Firstly, the process begins with the selection of independent variables. Next, the data is checked for multicollinearity using the Variance Inflation Factor (VIF). The linearity of the data is then verified through scattered graphs. Stepwise regression is employed to identify the best subset of independent variables. Once the subset is determined, the model is finalized to ensure it meets all requirements. Subsequently, a final analysis is conducted, including a thorough examination of residuals. If necessary, variable transformations are applied to address violations such as non-linearity and other assumptions. Finally, the model is optimized and prepared for accurate prediction. By meticulously following these steps, researchers can develop a robust mathematical model using multi-variable regression analysis. During the model development process, Table 2 presents the collinearity statistics, specifically the Variation Inflation Factor (VIF), for the independent variables. In the realm of multi-variable linear regression analysis, minimizing significant multicollinearity among independent variables holds substantial importance. The VIF values provided in Table 2 offer valuable insights into the observed level of correlation, with certain variables exhibiting higher values, such as 35.21. Therefore, addressing variables with elevated VIF values becomes imperative to ensure the model's reliability.

Figure 8: Model development flowchart.



Source: Authors.

It is important to mention that a VIF greater than 5 indicates a high level of correlation among variables (Daoud, J. I. 2017, December), which can impact the reliability of the model. Therefore, it is recommended to remove variables with high VIF values from the analysis. Table 2 provides a comprehensive overview of the VIF values for all the independent variables considered in this study.

Table 2: Representations of VIF values with all independent variables.

Variables (independent)	Collinearity Statistics	Collinearity Statistics	Collinearity Statistics
	VIF (Including all variables)	VIF (L removed)	VIF (L & B removed)
L	7.01	-	-
B	4.39	2.00	-
D	2.17	1.91	1.64
SFD	2.32	1.80	1.70
GS	1.76	1.74	1.72
PW	1.66	1.66	1.60
HCP	1.61	1.60	1.53
P	1.26	1.26	1.26
UWF	1.33	1.27	1.17

Source: Authors.

4.4. Ship Repair Manhour Model.

In this section, the ship repair man-hour model is discussed, with a focus on presenting the statistical relationship between dependent and independent variables. The following equation expresses the repair man-hour as a function of certain variables (repair works).

$$Y_{LH} = f(R_D, R_{SFD}, R_{GS}, R_{PW}, R_{HCP}, R_P, R_{UWF} \quad (6)$$

In this context, Y_{LH} represents the desired output, which relies on several independent variables to define the ship's repair man-hour. R_D corresponds to the draft's measurement in meters (m), while R_{SFD} quantifies the full load displacement in terms of weight (tons). R_{GS} signifies the duration of general service works, R_{PW} measures structural steel repair works in weight (tons), R_{HCP} evaluates hull cleaning and painting works in square meters, R_P quantifies piping repair works in length (meters), and finally, R_{UWF} represents the quantity of underwater fitting works based on the number of fittings required for the repair process.

The following expression of the linear equation is constructed where the independent variables are linearly associated with the dependent variable based on the function as mentioned earlier:

$$Y_{LH} = b_0 + b_1 R_D + b_2 R_{SFD} + b_3 R_{GS} + \\ b_4 R_{PW} + b_5 R_{HCP} + b_6 R_P + b_7 R_{UWF} \quad (7)$$

Where, b_0, b_1, ..., b_6, and b_7 are regression coefficients and others with their usual meaning. With the collected data for input variables Y_{LH}, R_D, R_{SFD}, R_{GS}, R_{PW}, R_{HCP}, R_P, and R_{UWF}, simultaneous equations can be generated using the least square method (Walpole, et. al., 2012). Following this, statistical testing is carried out to confirm the accuracy of the model.

4.5. Best Fit Model.

The assessment of linearity serves as the initial step before venturing into the intricate world of stepwise regression. Stepwise regression is a laborious and demanding process primarily because it involves the derivation of numerous potential regression models from various combinations of candidate predictors. The ultimate goal is to identify the most suitable subset of regression models. In this particular study, we examine seven independent variables, opening the door to a multitude of possible combinations among them. Among these possibilities, a total of 2^7 combinations involving one, two, three variables, and so forth, are thoughtfully evaluated in accordance with the criteria and flowchart previously outlined. Remarkably, within each of these models, the F-statistics consistently fall below the critical F-value, as detailed in Table 3.

To conclude this analytical journey, it is imperative to validate residual plots and finalize the selection criteria for the mathematical model, as outlined in reference (Levine et al., 2019). The residual analysis entails generating individual plots for each independent variable, which illustrate the relationship between predicted values and their corresponding residuals (the observed value minus the predicted value). Notably, all these graphs exhibit distinctive and irregular shapes, signifying the model's readiness for predicting or estimating repair man hours.

Table 3: Navigation and maritime traffic management regime in Spanish waters.

Y_{LH} = f (R_{pw}, R_{GS}, R_{HCP}, R_{UWF}, R_p, R_D, R_{SFD})	Y_{LH} = f (R_{pw}, R_{GS}, R_{HCP}, R_{UWF}, R_p, R_D)	Y_{LH} = f (R_{pw}, R_{GS}, R_{HCP}, R_{UWF}, R_p)	Y_{LH} = f (R_{pw}, R_{GS}, R_{HCP}, R_{UWF})	Y_{LH} = f (R_{pw}, R_{GS}, R_{HCP})	Y_{LH} = f (R_{pw}, R_{GS})	Y_{LH} = f (R_{pw})	Mathematical Models
5664.31	5666.16	4723.7	4551.28	6009.71	8000	13465.47	**b_0**
268.78	267.13	264.15	255.09	257.97	278.76	427.47	**PW**
36.53	36.82	37.09	40.81	40.58	42.78	NA	**GS**
0.157	0.166	0.155	0.168	0.212	NA	NA	**HCP**
12.48	12.85	12.9	11.45	NA	NA	NA	**UWF**
7.9	7.89	7.56	NA	NA	NA	NA	**P**
-140.39	-93.83	NA	NA	NA	NA	NA	**D**
0.0367	NA	NA	NA	NA	NA	NA	**SFD**
2861.45	2834.09	2807.78	2896.43	3020.83	3271.91	4928.35	**SE**
0.8975	0.8971	0.8967	0.88	0.87	0.85	0.6536	**R^2**
0.8808	0.88	0.88	0.87	0.86	0.84	0.6465	**R^2_{adj}**
8187899.5	8032068.4	7883658.8	8389346.6	9125421.5	10705450.3	24288641.5	**$MSE_{(residual)}$**
8	6.2	4.3	6.1	9.4	17.8	98.4	**Cp**
53.81	63.97	78.17	90.9	109.85	136.49	92.48	**f**
2.23	2.31	2.42	2.57	2.8	3.19	4.04	**f (critical 0.05)**

Source: Authors.

4.6. Model Validation.

A case study has been conducted to assess the proposed model's accuracy in estimating ship repair man-hours compared to the actual man-hours required. The term "actual ship repair man-hour" pertains to the total hours needed to complete all repairs listed as defects. For validation purposes, five ships have been selected at random from the cargo vessel database to serve as the subjects of this case study, ensuring a fair evaluation of the mathematical model (equation 8). To calculate the deviated value, repair work data are gathered from the work completion certificates, encompassing various repair operations such as general maintenance, plate work, hull cleaning and painting, underwater fittings, piping, etc.

The calculated repair man-hours (model values) have been determined for each vessel and the summary of both the actual and model values is presented in Table 4. From the findings in Table 4, it is evident that the model value exceeds the actual value for BANGLAR KAKOLIA, whereas, for the other four cases, the model value is lower than the actual value. The deviation values fall within a range of 16%, which is relatively close to the estimated model error of 10.25%. The model's accuracy value, often referred to as the R-square value in Table 4, stands at 0.8975. This figure holds significance in justifying the model's effectiveness, indicating that 89.75% of the variation in the dependent variable can be attributed to changes in the independent variables. The remaining 10.25% is considered the error of estimation, which exceeds the deviation values presented in Table 4. The analysis of case studies conducted on a specific set of five vessels has yielded positive results for the formulated model.

Table 4: Model deviation.

Ship name	Manhour (Actual)	Manhour (Model)	Deviation (%)
MV Banglar Gourav	15836	14328.6	9.51
MV Banglar Kollol	30568	28294.2	7.43
MV Banglar Urmi	24342	22830.7	6.20
M.V Ksl Lake Hill	18230	15343.9	15.83
M.V. Banglar Kakoli	24879	28594.7	-14.93

Source: Authors.

5. Discussion.

In adhering to the VIF criteria and aiming to maintain low VIF values as outlined in Table 1, the length and breadth dimensions were omitted from this study. To formulate an innovative mathematical model, we have taken into consideration five repair operations and two principal parameters as our independent variables. The resulting regression model, which includes coefficients and essential statistical parameters for all seven independent variables, is comprehensively presented in Table 2. It is imperative for this statistical parameter to meet the model's validation criteria. It is noteworthy to mention that among the 2^7 possible combinations, the table represents the subsets that yield the best results.

Table 2 clearly illustrates the progressive inclusion of independent variables and the concurrent rise in R^2 (multiple determination), which serves as the primary criterion for selecting the most suitable model subset. This progression not only substantiates the model's adequacy but also provides valuable insights. Through a meticulous evaluation, we have identified the optimal subset model as Y_{LH} = f (R_{PW}, R_{GS}, R_{HCP}, R_{UWF}, R_P), chosen based on the highest adjusted R^2, lowest mean square error (MSE), and lowest C_P values. However, when considering the maximum R^2 value for all repair work, we have selected the final model as Y_{LH} = f (R_D, R_{SFD}, R_{GS}, R_{PW}, R_{HCP}, R_P, R_{UWF}). This model stands as the ultimate choice for calculating repair labor man-hours, and its regression equation is as follows:

$$Y_{LH} = 5664 + 268.8R_{PW} + 36.53R_{GS} + 0.1574R_{HCP} + 12.48R_{UWF} + 7.91R_P - 140R_D + 0.0368R_{SFD} \quad (8)$$

Considering the two models presented, Y_{LH} = f (R_D, R_{SFD}, R_{GS}, R_{PW}, R_{HCP}, R_P, R_{UWF}) and YLH = f (R_{PW}, R_{GS}, R_{HCP}, R_{UWF}, R_P), it can be readily observed that the adjusted R^2 values are nearly identical, and the mean square error (MSE) is very close. It's worth noting that in the six-variable model YLM = f (R_D, R_{GS}, R_{PW}, R_{HCP}, R_P, R_{UWF}) and the seven-variable counterpart Y_{LM} = f (R_{PW}, R_{GS}, R_{HCP}, R_{UWF}, R_P, R_D, R_{SFD}), the R^2 value does not show significant improvement upon the inclusion of the variable R_{SFD}. Furthermore, the coefficient value for R_{SFD} is notably small (0.0367). Consequently, it is evident that R_{SFD} has a minimal impact on repair labor man-hours.

In addition to the aforementioned theoretical explanation, it is essential to discuss certain practical findings derived from the selected model. Firstly, plate work emerges as a pivotal factor influencing labor man-hours, as indicated by the model's coefficient for this variable, which stands at a significantly higher value of 268.8 compared to other variables. Notably, the process of plate cutting for hot work necessitates the collection of a gas-free certificate and entails the cleaning of tanks and compartments, both of which incur additional man-hours. It is well-established that plate repair work demands three times the labor hours compared to new construction due to its intricate work sequence. This sequence involves the initial step of cutting old plates along with internal frames, then the preparation of new plates using templates and fitting the new structure, including frames. Lastly, the welding process is carried out, and if any welding points fail (Dhar, et al. 2023) during Non-destructive testing, additional labor hours are required for redoing the welding. Therefore, it becomes clear that the theoretical influence of the independent variable-plate work, closely resembles the actual industry practices, emphasizing its significant influence on labor man-hours.

Secondly, the category of general service work emerges as the second most significant factor impacting labor hours. Within the developed model, this variable carries a coefficient of 36.53. General service work encompasses various supporting tasks that relate to all the other repair processes listed. This general service category encompasses activities such as crane operations, forklift assistance, machining, and docking and undocking procedures, among others. Each of these repair processes heavily relies on the availability of general service work. For instance, the proper execution of plate work is contingent upon the operational status of the crane; its malfunction can lead to extended labor hours. Similarly, the absence of forklift support can hinder the completion of certain facility tasks, resulting in additional labor hours being expended. Therefore, the model's prediction of the coefficient for general service work closely aligns with practical observations.

Underwater fitting is the third most influential factor affecting labor hours. In this model, the coefficient for this variable is 12.48, representing a moderate impact. Underwater fitting encompasses tasks like zinc anode fitting, propeller and rudder maintenance, shaft work, and underwater valve servicing, all of which involve manual labor and interdependencies. For instance, when shaft work is necessary, the removal of the propeller and rudder becomes a prerequisite, leading to additional labor hours. Moreover, the installation of new bushings or bearings along with the shaft is a time-consuming process that demands high technical expertise. Any disparity between the required technical skill and the time allocated can disrupt the progress of other tasks.

Fourthly, pipe work contributes a coefficient to the model that falls between both high and low. This is due to the individualistic nature of pipe work, which is relatively independent of other repair processes, primarily owing to the pipe spool system and flange connections. While the significance of pipe work in terms of ship repair man-hours is undeniable, it remains relatively minor compared to the ship's hull, accounting for a maximum of 5% in commercial vessels. Consequently, the time needed to complete pipeline repairs and associated tasks is relatively shorter, resulting in lower labor man-hours.

Fifthly, hull cleaning and fitting (HCF) as well as full load displacement (SFD) have a minimal impact on the calculation of ship repair man-hours. Hull cleaning and fitting represent independent tasks that do not significantly relate to other repair activities. When all the necessary materials are readily available, the yard can carry out fitting and apply paint after hull cleaning without requiring extensive man-hours. Similarly, full load displacement plays a limited role in labor man-hour calculations as it is not directly connected to repair processes. While an increase in displacement can lead to a higher volume of repair work, it remains a relatively less influential factor. Therefore, a coefficient of 0.0368 is reasonably suitable for the selected model from this perspective.

The last remaining variable is ship draft. In the above regression equation, all variables have positive signs but ship depth (D) has a negative coefficient. This negative value indicates the bigger the vessel (i.e., high depth) the lesser the repair manhour. Reason behind this negative value is self-explanatory itself. A larger depth vessel has more space to do the repair work, and multiple repair work can be done simultaneously. Hence, when D increases then repair labour manhour decreases practically.

Conclusions.

This article introduces an approach for devising a mathematical model tailored to estimate labor hours in ship repairing across diverse ship types. Illustrated in Figure-1, this method empowers shipyards and dockyard authorities to craft bespoke mathematical models utilizing their specific data. These constructed models serve as valuable tools for the comparative analysis and precise estimation of labor hours in ongoing and future projects.

This study meticulously outlines the detailed calculations involved in creating a mathematical model for estimating man-hours. It further validates the model using distinct datasets, demonstrating satisfactory results. Additionally, the article identifies key parameters that significantly contribute to the augmentation of manhours in ship projects or repairs.

The presented mathematical tools prove to be effective for both shipyards and drydock authorities, facilitating the computation of preliminary estimates. Upon completion of the entire project, these entities can compare the results and gauge the variance from the initial estimation. In essence, this tool serves as a vital resource for management in navigating a competitive market by providing foresight into labor hours prior to the docking of a ship.

In summary, the utilization of this tool not only aids in survival but thrives in a competitive market by enabling accurate forecasting of labor hours. Future research avenues may explore the development of methodologies for estimating manhours in new shipbuilding projects, considering various parameters, thereby offering additional benefits to shipyard authorities.

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References.

Abdullah, A. (2021). Development of a mathematical model for ship repair time estimation [Master's Thesis, Bangladesh University of Engineering and Technology (BUET)]. BUET Central Library. http://lib.buet.ac.bd:8080/xmlui/handle/123456789-/5943.

Abdullah, A., Moinuddin, A., Khan, R., Islam, A. (2020). Advancement of Ship Recycling Industry of Bangladesh in Comparison to Rest of the World with Obstacles, Root Causes, and Propositions. 12th International Conference on Marine Technology (MARTEC 2020), Ambon, Indonesia. [Online] Available: https://www.researchgate.net/publication/351281142.

Abdullah, A., Rahman, H., Uddin, M. I., & Mia, M. J. (2022) A General Method to Develop Mathematical Model for Estimating Ship Repairing Man-Hour. 1st International Conference on Mechanical, Manufacturing and Process Engineering (ICMMPE2022), DUET.[Online] Available: https://scholar.google.com/citations?view_op=view_citation&hl=en&user=X9rlUxMAAAAJ&citation_for_view=X9rlUxMAAAAJ:iH-uZ7U-co4C.

Awal, Z. I., & Abdullah, A. (2021). Multiple linear regression model for ship repair time estimation. 12th International Conference on Marine Technology (MARTEC 2020), Ambon, Indonesia. [Online] Available: https://scholar.google.com/citations?view_op=view_citation&hl=en&user=X9rlUxMAAAAJ-&citation_for_view=X9rlUxMAAAAJ:j3f4tGmQtD8C.

Chou, C. C., & Chang, P. L. (2001). Modeling and analysis of labor cost estimation for shipbuilding: The case of China Shipbuilding Corporation. Journal of ship production, 17(02), 92-96.

Liu, B., & Jiang, Z. H. (2005). The man-hour estimation models & its comparison of interim products assembly for shipbuilding. International Journal of Operations Research, 2(1), 19-14.

Ahluwalia, R., & Pinha, D. (2014). Decision support system for production planning in the ship repair industry. Industrial and Systems Engineering Review, 2(1), 52-61.

Apostolidis, A., Kokarakis, J., & Merikas, A. (2012). Modeling the Dry-Docking Cost-The Case of Tankers. Journal of Ship Production & Design, 28(3).

Daoud, J. I. (2017, December). Multicollinearity and regression analysis. In Journal of Physics: Conference Series (Vol. 949, No. 1, p. 012009). IOP Publishing.

Berenson, M. L., Levine, D. M., Szabat, K. A., & Stephan, D. (2019). Statistics for Managers Using Microsoft Excel. Pearson.

Walpole, R.E., Myers, R.H., Myers, S. and Ye, K. (2012) Probability & Statisticsfor Engineers & Scientists. Prentice Hall. ISBN 10: 0-321-62911-6 .

Draper, N.R. and Smith, H. (1998) Applied Regression Analysis (Vol. 326). John Wiley & Sons. ISBN 0-471-170482-8.

Kr Dev, A., & Saha, M. (2016). Modeling and analysis of ship repairing labor. Journal of Ship Production and Design, 32(04), 258-271.

Dhar, U. K., Rahman, M. F., Ayanoglu, M. O., & Abdullah, A. (2023). Welding on C67 steel grade sheet: Influence of the parameters and post welding heat treatment. AIMS Materials Science, 10(3), 453-464.