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Enhancing Material Efficiency in Ship Production: A Taguchi Method Approach to Optimal Plate Nesting

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***Abstract*— This study seeks to enhance material use efficiency in plate nesting procedures for tugboat production through the application of the Taguchi method. Three critical criteria were assessed: plate profile dimensions, cutting margin, and number of parts, aimed at reducing material waste in steel plate cutting processes. Numerical simulations were performed with ProNest software, and the nesting output data were examined using Minitab to ascertain the ideal design via the Smaller-the-Better methodology. Experimental findings indicate that the ideal parameter configuration was attained with a plate profile dimension of 508 mm, a cutting margin of 10 mm, and a production quantity of 95 units. This setup resulted in little material waste, demonstrated by a maximum Signal-to-Noise Ratio (SNR) value of -49.17 dB, which is nearly zero. These findings indicate that this parameter combination can serve as a benchmark in production processes to improve material efficiency and minimize waste in tugboat fabrication.**

Keywords— Ship Production, Material Efficiency, Plate Nesting, SNR

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I. Introduction

The shipping industry plays a strategic role in supporting the maritime transportation sector, both for logistics, industrial purposes, and natural resource exploration [1]. With the increasing need for more efficient, reliable, and sustainable maritime transportation, this industry is required to continuously innovate in various aspects of its production [2]. One key aspect of this industry is shipping fabrication, a complex process encompassing various stages, from design and material selection to manufacturing and assembly [3]. At each stage, production efficiency is a key factor that not only affects operational costs but also contributes to the shipping industry's global competitiveness [4]. Therefore, optimization in ship fabrication is essential to increase productivity, reduce material waste, and ensure the final quality of ships meets international standards [5].

In the fabrication process, material efficiency is a key factor influencing production costs, industrial sustainability, and environmental impact [6]. The materials used in shipbuilding, particularly steel plate, are relatively expensive, necessitating optimization strategies for their use [7]. Inefficient material use can lead to wasted resources, increased operational costs, and reduced the competitiveness of the shipping industry in the global market [8]. Furthermore, excessive material waste increases the burden of waste management, negatively impacting the environment and increasing company operational costs [9]. Therefore, innovative approaches to optimizing material utilization are becoming increasingly crucial.

One crucial aspect of ship fabrication is the cutting of steel plate; the primary material used in ship construction [10]. This steel plate must be cut in an optimal pattern to minimize material waste and increase production efficiency. Suboptimal plate cutting will result in large amounts of material waste, which can ultimately increase production costs and reduce manufacturing efficiency [11].

Notwithstanding advancements in computer-aided production, a consensus on the optimal selection and regulation of critical factors, including profile plate layout, cutting margins, and order part quantities, remains elusive [12]. The interaction of these parameters profiles among themselves shapes the output of material, production time duration, and profit at the end of the manufacturing processes nesting [13]. Individual past researchers have studied optimization of process parameters, but the applicability and practical implementation of their outcomes across various manufacturing environments have remained limited [14].

In response to these challenges, this study is structured around three primary objectives. First, to systematically study the effects of cutting margins and parts quantities on material usage, with special focus on profile plate nesting. Second, develop and validate an optimization framework based on statistical design of trials for parameter selection. Three, enrich the simulation-driven data with industry-standard equipment for a complete predictive analytic framework plus an operational hands-on approach [14]. The Taguchi method has become a prevalent experimental design and

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optimization technique in manufacturing research, due to its effective management of multivariate parameter spaces and capacity to determine optimal settings with minimal experimentation [15]. Its applications encompass a wide array of industrial operations, including metal cutting, additive manufacturing, and welding, effectively boosting surface polish, minimizing tool wear, and augmenting production efficiency [16].

The approach utilizes orthogonal arrays for experimental design and employs analysis of variance (ANOVA) to assess the relevance of each parameter concerning process outcomes [17]. This study employs ProNest software, the premier industrial software for profile plate nesting and cutting optimization, to provide a comprehensive set of capabilities for virtual process planning, material waste estimation, and analysis of machine utilization. The nested data are then analysed with Minitab software, allowing a wide range of statistical analysis and visualization of the multivariate process behaviour. Thus, this computational-statistical pipeline supports informed decision-making and ensures the validity and industrial applicability of the findings [18]. This work focuses on improving the current profile plate manufacturing process by providing a simulation based statistically validated framework for optimizing key process parameters [19]. Using this method, manufacturers are able to achieve substantial material savings, as well as a high degree of process reliability and overall cost efficiency in the production.

II. METHOD

Cutting parameter optimization in the nesting process is performed through the integration of AutoCAD and ProNest software. Parameter configuration includes plate profile dimensions, cutting margins, and part quantities. Plate profiles determine the geometric variations of the processed material [20], while cutting margins are set to control tolerances between cuts, thereby minimizing material scrap [21]. Furthermore, part quantities, which represent the number of components produced from a single sheet of plate, are a critical indicator of material utilization efficiency during the nesting process [22]. The synergy of these three parameters enables a comprehensive analysis of the cutting process's effectiveness and its impact on production optimization. In its implementation, AutoCAD plays a role in designing and visualizing the profile geometry. At the same time, ProNest is used to optimize the nesting layout to achieve minimal material waste and maximum material efficiency. Table 1 is the basic data used in this study.

A. Experimental Design

This study used the Taguchi method to design an experiment aimed at evaluating the influence of three key parameters in the nesting process on material utilization efficiency, specifically in the context of profile plate cutting in the manufacture of tugboat hulls. This method was chosen because of its ability to reduce the number of experiments required without sacrificing the quality of the analysis. This method thus ensures greater efficiency of time and resources in the experimental process.

The three independent variables used in this study are:

1) Plate Profile (mm); Level.1: 500, Level.2: 506, Level.3: 508
2) Cutting Margin (mm); Level.1: 10, Level.2: 20, Level.3: 30
3) Quantity Part (mm); Level.1: 92, Level.2: 93, Level.3: 95

The three parameters were combined by using an orthogonal array. Orthogonal arrays are used for the purpose of designing experiments to examine the effect of multiple independent variables while keeping the number of trials low. This array helps in identifying the most effective combination of independent variables with fewer experiments compared to a full factorial design [23]. For the current study, the L9 orthogonal array was applied. The choice of the L9 orthogonal array was based on the constitution of the input variables, which consists of three independent variables with three levels each; hence, the L9 array allows for the study of three factors at three levels using only nine trials [24]. Accordingly, the three parameters were combined using the Taguchi orthogonal array (3^3), resulting in nine different experimental configurations. This combination allows for determining the effect of each variable on the output in terms of the amount of waste material produced after the nesting operation. Then, in the analysis that was performed using the Taguchi method, ANOVA was utilized to identify the independent variables that had a significant effect on the observed response.

The variance analysis (ANOVA) is used to identify the factors and interactions that have a notable effect on the response variable [25]. For an experimental design that includes factors X and Y, as well as the interaction X.Y, the total sum of squares can be calculated using the following formula Ordinary Least Squares;

$$SS_T = \left[\sum_{j=1}^{N} y_j^2\right] - \frac{T^2}{N} \quad (1)$$

Where SS_T is sum of squares; yj is observation response to *j*; T is overall response to the observation; N is number of observations.

Then, the main objective of this research is to minimize material waste, using the Smaller-the-Better method in Taguchi analysis. The Signal-to-Noise Ratio (S/N) value for each experimental result is calculated using the following formula;

$$\frac{S}{N} ratio(\eta) = -10 log_{10} \frac{1}{n} \sum_{i=1}^{n} y_i^2 \quad (2)$$

Where y_i are response value (waste material) and n are number of experimental replicates. Each combination in Table 2 will be used as input in a nesting simulation using ProNest software. The output, in the form of material waste from each scenario, will be used to calculate the S/N ratio as the basis for analysis and drawing conclusions regarding optimal parameters.

TABLE 1.
DATA MODEL

Type of Ship	Tugboat		
Material	MS 8 mm		
Plate Dimension	9144 x 2450 mm		
	Part Separation (mm)	*Plate Edge Separation (mm)*	*Pierce Separation (mm)*
ProNest Parameter	10	10	10
	20	20	20
	30	30	30
Cutting	*Plasma Cutting*		

TABLE 2.
EXPERIMENTAL DESIGN

No.	*Plate Profile (mm)*	*Cutting Margin (mm)*	*Quantity Part (mm)*
1.	500	10	92
2.	500	20	93
3.	500	30	95
4.	506	10	93
5.	506	20	95
6.	506	30	92
7.	508	10	95
8.	508	20	92
9.	508	30	93

B. Measurement of the Weight of Waste Material Generated from Nesting

The amount of waste material produced by nesting can be calculated mathematically using the given variables; the calculation of the material waste is based on crop utilization data obtained from nesting simulations performed using ProNest software. Crop utilization is defined as the ratio of the total area of the plate actually utilized to cut the profile according to the design requirement. A high value of crop utilization indicates improved efficiency of material usage, and a low value indicates an increase in material waste.

To calculate how much of the material is unused, first, calculate the total area of the steel plate used, which is 9144 x 2450 mm, or about 22.39 m2. The crop utilization figure is then deducted from 100% to arrive at the percentage waste material. This is then multiplied by the overall plate area to calculate the area of unused material. Then, to get the weight of the waste material, the area is converted to weight using the formula mass = volume x density. The fact that the steel plate has a certain thickness means that the remaining volume can be calculated by multiplying the area by the thickness. This volume is multiplied by the density of steel, 7.85 tons/m3, to arrive at the weight of the material discarded.

C. Data Processing and Nesting Simulation

Nesting pertains to the strategic placement of component shapes on a steel plate before cutting, with the aim of reducing raw material consumption and, in turn, waste [26]. The starting point of nesting simulation is creating a component design with AutoCAD.

In this stage, a technical drawing of each plate to be cut is created in a two-dimensional (2D) form. The completed design is then saved in the .DXF (Drawing Exchange Format) file format, given that this is a universally accepted file format by most cutting programming software, including ProNest. During this process, it is important to ensure dimensions, line types, as well as layers, are properly set to avoid any discrepancies during the importation process.

The component design created in AutoCAD is imported to ProNest software for simulating the nesting. ProNest reads the contours of the .DXF file automatically and shows the component shape in the work area. Users can define here the steel plate size, plate margins, number of plates to cut, and other process parameters. Process Parameters, Part List, Plate List, Simulation, and Report Optimization are the five steps involved in nesting using ProNest software.

III. RESULTS AND DISCUSSION

The model simulation is set to generate data representing the mass (kg) of waste material against each simulated variable. The data generated will enable analysis of values of waste material for every variable that is put to test. Then, the results obtained from the variables that have been tested are compared to determine which among them have a great impact in minimizing material waste. Table 3 is the experimental design of the Taguchi method with an orthogonal array. Table 3 delineates the influence of the independent variables on the steel plate nesting process, thereby establishing the foundational data for the subsequent Taguchi analysis to determine the optimal parameter combination. The Taguchi Means Analysis uses these predicted values to understand and improve the performance of a process or system [27]. As can be seen from Table 3, the lowest mean value for waste material is at 255.27 kg, corresponding to a 508 mm plate profile, a cutting margin of 10 mm, and a part quantity of 95 pieces. On the contrary, the highest output was at 1705.02 kg, corresponding to a 506 mm plate profile, a cutting margin of 30 mm, and a part quantity of 92 mm.

The Taguchi Means Analysis utilizes the predicted values to understand and improve the performance of systems or processes [27]. In Table 3, the highest mean value of 1705.08 kg corresponds to the combination of the 506 mm plate profile, 30 mm cutting margin, and part quantity of 92 pieces. In addition, the Taguchi prediction table computes an average residual value, representing the difference between actual and predicted values, of 312.654, which indicates that the overall mean value adequately addresses the response variability of the experimental data. The mean error is determined as 0.0086%. The relatively low average error indicates that the mean value has a high degree of accuracy in predicting system response values.

Taguchi SN-Ratio analysis is a method under the overall Taguchi methodology that measures the performance of products or systems. From the outcome of the SNR (Signal-to-Noise-Ratio) table calculation, it can be determined that the combination of process parameters for the most optimum performance is plate profile variation 508, cutting margin 10 mm, and part quantity 95, with an SNR value of -48.13 dB. In the Taguchi approach, for the "Smaller is Better" characteristic, the SNR value is employed to analyze the stability and quality of the results of a process. The larger the SNR (or the nearer to zero on the negative scale), the lower the variation from the minimum target value, which, in this situation, corresponds to the weight of scrap material or unused material consumption in the nesting process.

Technically, the larger the value of SNR, the more capable the system is of minimizing the impact of interference or noise during the process. Thus, this set of variables can be deemed the best setting, or the setting that yields the optimal system performance in controlling scrap material utilized during the nesting process.

Then the identification of independent variables in product or process performance in ANNOVA produces experimental results on steel nesting plates in tugboat fabrication in table 4. In the table 4 indicates that the equation including the three independent variables has a highly significant impact on the response. When distinguishing between the impact of each of the independent variables, cutting margin has a strong and highly significant impact on the response, with an F-value of 15.01 and a P-value of 0.012. This signifies that changes in cutting margin have a significant influence on material waste. However, the plate profile and part quantity variables don't significantly affect material waste. The plate profile variable has an F-value of merely 0.01 and a P-value of 0.924, while the part quantity variable has an F-value of 0.01 and a P-value of 0.924. Both P-values are less than the general cutoff of 0.05, which means that these two variables don't have a significant impact compared to the cutting margin variable, which has a P-value near 0.

Regression models of equations are employed to predict output in a process or a system and to express the relation between independent and dependent variables. The equation coefficients can tell us the degree of influence of every independent variable on the resulting response. The model of the equation is achieved through the Ordinary Least Squares method. Regression equation models are used for the purpose of predicting results in a given process or system, thus describing the interaction between independent and dependent variables. The coefficients obtained from the equation provide information on the level of effect of each independent variable on the resulting response. The equation model is developed based on the Ordinary Least Squares method. Table 5 is a significant basis for realizing the impact of different independent variables on waste material output and effectively enhancing system performance. The analysis results also show that all independent variables have a P-Value lower than the common significance, indicating that these variables significantly affect the scrap material. In addition, there is no indication of multicollinearity problems, as noted by the VIF values close to 1 for all independent variables. Thus, this equation model provides a useful understanding of the independent variables that affect scrap material in the steel plate nesting process during tugboat fabrication, which can be used for better decision making in the process setting.

The results of the analysis of variance (ANOVA) for the mean values of the three independent variables considered—Plate Profile, Cutting Margin, and Quantity Part—are presented in Table 6. From Table 6, all the variables presented a p-value of 0.000, which is lower than $\alpha = 0.05$. This shows that the model is capable of explaining data variation effectively and can significantly affect the response [27]. Among the variables studied, cutting margin had the greatest effect on the data, as evident from its p-value, which was lower than 0.05 [28] at 0.012. A high F-value also suggests strong influence. Cutting Margin showed the largest F-value, at (29042904.42), which was far larger than the F-values of Plate Profile (14710.29) and Quantity Part (14716.00). This explains that cutting margin is the most influential factor in determining material efficiency in the nesting process among the other two factors, plate profile, and part quantity. In addition, the Adjusted Mean Square value of the cutting margin was 1980082, whereas PP and QP were only 1003, which further confirms the dominant impact of the cutting margin variable on the research output.

The degrees of freedom (DF) of each factor were 2, as there were three levels of each variable being tested. The residual error, on the other hand, was zero, showing that there was no variation in the data that could not be accounted for by the model. The overall Sequential Sum of Square of 3964176 was also allocated nearly completely to the three main variables, demonstrating that the accuracy of the model in predicting the data was extremely high. In all, this ANOVA analysis demonstrates that the model employed is very valid, and all the variables have a significant contribution to the efficiency of steel plate nesting in the fabrication process of tugboats. ANOVA of SNR is important in experimental design and process optimization as it enables the comprehension and enhancement of product or process quality through the determination of the most statistically dominant independent variables. The Analysis of Variance (ANOVA) reveals that cutting margin is the sole independent variable with a statistically significant influence on the Signal-to-Noise Ratio (SNR). The decisive evidence for this is an F-value of 13295.69 coupled with a P-value of 0.000, indicating that variation in the cutting margin is a primary factor affecting signal quality. Although both plate profile and part quantity also had significant effects, their effects on SNR were not as high as the effect of the cutting margin. Therefore, improving signal quality should mainly focus on adjustments to the cutting margin.

TABLE 3.
DESIGN OF EXPERIMENT METODE TAGUCHI, MEAN VALUE, AND SIGNAL NOISE RATIO (SNR)

No	*Plate Profile* (X_1)	*Cutting Margin* (X_2)	*Quantity Part* (X_3)	Result	*Means*	Residual	*Error*	SNR
1	500	10	92	325.556	325.665	234.696	0.72%	-50,25
2	500	20	93	313.738	313.8	468.762	1.49%	-49,93
3	500	30	95	1697.14	1696.97	234.97	0.14%	-64,59
4	506	10	93	286.022	285.85	233.437	0.82%	-49,12
5	506	20	95	261.964	262.073	470.289	1.79%	-48,36
6	506	30	92	1705.02	1705.08	233.236	0.14%	-64,63
7	508	10	95	255.210	255.273	235.338	0.92%	-48,13
8	508	20	92	291.508	291.337	467.892	1.61%	-49,29
9	508	30	93	1686.31	1686.41	235.265	0.14%	-64,53
		Average		758.051	785.051	312.654	0.0086%	

TABLE 4.
ANOVA TAGUCHI

Source	DF	Adj SS	Adj MS	*F-Value*	*P-Value*
Regression	3	2974425	991475	5,01	0,057
Plate Profile	1	1999	1999	0,01	0,924
Cutting Margin	1	2970420	2970420	15,01	0,012
Quantity Part	1	2007	2007	0,01	0,924
Error	5	989751	197950		
Total	8	3964176			

TABLE 5.
REGRESSION MODEL COEFFICIENTS

Term	*Coeff*	*SE Coeff*	*T-Value*	*P-Value*	VIF
Constant	2681	24659	0,11	0,918	
Plate Profile	-4,4	43,6	-0,10	0,924	1,00
Cutting Margin	70,4	18,2	3,87	0,012	1,00
Quantity Part	-12	119	-0,10	0,924	1,00

TABLE 6.
ANOVA MEANS

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Plate Profile	2	1,660	1,660	0,830	46,50	0,021
Cutting Margin	2	474,604	474,606	237,302	13295,69	0,000
Quantity Part	2	1,789	1,789	0,894	50,11	0,020
Residual Error	2	0,036	0,036	0,018		
Total	8	478,089				

Table 7 presents the response table for Signal-to-Noise Ratios (SNR) of the "Smaller is Better" characteristic, which is employed to evaluate the process stability in reducing material waste. Here, the largest SNR value (the smallest negative value, as smaller is better) provides the best conditions, since the smaller the negative value, the smaller the variation or deviation from the minimum target. The table lists average values of SNR for each level of the three primary variables: profile plate, cutting margin, and quantity part, along with delta and rank values to identify the impact of each variable on the response.

TABLE 7.
SNR RESPONSE

Level	*Plate Profile*	*Cutting Margin*	*Quantity Part*
1	-54,93	-49,17	-54,73
2	-54,04	-49,20	-54,53
3	-53,99	-64,59	-53,70
Delta	0,94	15,42	1,03
Rank	3	1	2

TABLE 8.
MEANS RESPONSE

Level	*Plate Profile*	*Cutting Margin*	*Quantity Part*
1	778,8	288,9	744,0
2	751,0	289,1	762,0
3	744,3	1696,2	738,1
Delta	34,5	1407,2	35,9
Rank	3	1	2

Based on the data in the table, the profile plate has the largest signal-to-noise ratio (SNR) value at Level 3 (508 mm), which is -53.99, indicating its optimality over the other levels. As for cutting margin, the maximum SNR value is found at Level 1 (10 mm) with a value of -49.17, thereby making it the best configuration in minimizing material waste. However, for quantity part, its best level is marked by Level 3 (95 parts) with an SNR value of -53.70, which is the closest to zero compared to the other levels. Based on this largest SNR value, the best configuration determined in this study consists of plate profile at Level 3, cutting margin at Level 1, and quantity part at Level 2.

In addition, the delta value (the difference between each variable's highest and lowest SNR values) shows that cutting margin impacts yield variation most, at 15.42, and therefore ranks first. part quantity is second with a delta of 1.03, followed by profile plate, which is third with a delta of 0.94. This implies that while all the variables affect material cutting efficiency, changes to the cutting margin parameter will have the most pronounced effect in minimizing material wastage and enhancing overall nesting efficiency.

Based on the results shown in table 8, which is used to establish the optimal level of each factor, it can be seen that all of the variables under investigation—profile plate, cutting margin, and part quantity—have a different level of effect on the output response of the nesting process in terms of waste material. The most among these is the cutting margin variable with a Delta value of 1407.2, which is the difference between the minimum and maximum value for each of the variables. This means that variations in the levels of the cutting margin cause the most significant changes in outcomes, thus making the cutting margin variable the most dominant factor.

In the meantime, the part quantity variable is the second with a Delta value of 35.9. Even though its effect is not as high as cutting margin, this variable also contributes significantly to the output, which means the choice of part quantity variations, i.e., the number of parts, also affects the efficiency of arrangement and cutting in the nesting process. In the meantime, the profile plate variable has the smallest Delta value of 34.5, showing that the variation of the processed profile plate size has the least effect in comparison to the other two variables. Through the average value at each level, the optimal level for every variable is the profile plate at level 1 (value 778.8) cutting margin at level 3 (value 1696.2) and the quantity part value at level 2 (value 762.0).

From the above analysis, the best condition was found to have a plate profile of 508 mm, a cutting margin of 10 mm, and a quantity of 92 parts. The measurement results gave an SNR value of -48.13 with a mean of 255.27. A larger SNR value confirms that the signal quality is better compared to the existing noise level. In addition, a stable mean measurement near this best condition implies that the results are most likely to be stable and optimum under these conditions. Therefore, the best condition defines a set of variables that yield high signal quality along with stable measurement results.

IV. CONCLUSION

Based on the analysis and data processing conducted in the research on optimizing the efficiency of material use in plate nesting patterns in ship fabrication, several findings were obtained as follows: Based on the results of the study indicate that variations in the dimensions of the profile plate do not have a significant effect on material efficiency in the nesting process. However, the profile plate with a size of 508 mm produces the lowest material waste and the highest Signal-to-Noise Ratio (SNR) value (-49.17 dB) when combined with other supporting factors, namely a cutting margin of 10 mm and a quantity of 95 parts. Thus, the 508 mm plate can be considered the most optimal configuration to minimize material waste in cutting tugboat plates. then for the Effect of Cutting Margin, the cutting margin variable is proven to have a significant effect on plate cutting efficiency. A cutting margin of 10 mm produces the lowest material waste compared to other levels. A smaller cutting margin allows for the placement of more parts in one plate without sacrificing cutting accuracy. The highest SNR value (-49.17 dB) was also obtained in this configuration, so that a cutting margin of 10 mm can be recommended as the optimal parameter to maximize material efficiency. Meanwhile, for Quantity Part, the number of components (quantity part) cut from one plate also affects nesting efficiency. The configuration with 95 parts showed the most optimal results in this study. Excessive increase in the number of parts does not always increase efficiency because it can complicate the layout process (nesting). However, the quantity part of 95 parts has been proven to be able to balance between arrangement density and ease of cutting, while producing minimal material waste. Thus, the combination of parameters in the form of a 508 mm profile plate, a 10 mm cutting margin, and a quantity part of 95 parts is the best configuration to achieve material efficiency in the nesting process in tugboat fabrication.

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