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Fundamental Study on Influence of Independent Factors on Response Variable Using Response Surface Methodology and Taguchi Method †

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Abstract: Optimization approaches provide a strong foundation for analyzing and forecasting actions within a selected domain. This approach may be used to assess the extent of the effect of input variables on responses. There are several optimization tools and methodologies available, but each has its numerical approach and degree of accuracy with experimental data. As a result, several optimization methods are constantly evolving, and many new studies have focused on them. This study analyzes new optimization approaches employed to handle the issue of the location and size of distributed generating units for diverse applications, particularly focusing on tribological aspects. In addition, this work examines the modern technological, technical, economic, and regulatory factors that have created interest in distributed generation integration, as well as an overview of the challenges that must be overcome. Finally, it evaluates all relevant strategies for integrating dispersed generation from renewable energy sources using optimization techniques. The main methods of Response Surface Methodology (RSM) and the Taguchi optimization technique were chosen because they have been used in many technical investigations and provide more significant predictions.

Keywords: optimization; RSM; Taguchi; regression equation; ANOVA; variables

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1. Introduction

Many studies have many numbers of variables; arranging all of the variables in a logical order is difficult, costly, and requires more experiments. All of these issues can be solved using optimization approaches. The majority of optimization algorithms take side constraints into account independently from equality and inequality constraints. Direct implementation of the algorithm can efficiently handle side restrictions. None of the side constraints will ever be violated by a good algorithm. There are no equality or inequality constraints in an unconstrained optimization problem, but there may be side constraints. The optimization problems are with or without side constraints. However, in the constrained optimization problem, it has one or more equality and/or inequality constraints. The Taguchi L9 orthogonal array was used by Jenish et al. [1] to forecast the optimal parameters and influence level on the dry sand three-body abrasive wear behavior of CQSF/epoxy with and without red mud and CSA particulate-filled composites. Four input parameters were employed in this investigation at three levels. The main input parameters were velocities, abrading distance, load against wear, and filler content. As a reaction, a certain wear rate was employed (output parameter). The coded factors were +1, 0, and +1, and the Minitab software 19.2.0 output an L9 (43) design table with 9 runs. CCD-RSM was used to investigate the two-body sliding wear behavior of CQSF/epoxy with and without red mud and CSA particulate-filled composites in this work [2]. The abrasive wear behavior of CQSF/epoxy with and without red mud and CSA particulate-filled composites was studied using the Taguchi optimization technique. Although fiber hybridization is the most effective strategy for improving performance, behavioral studies are difficult to analyze due to the large number of factors [3–5]. The characteristic study of polymeric materials has improved significantly recently due to the requirements of such materials, but analytical investigations of the parameters are still common due to a lack of understanding of the optimization technique; if it is understood, the number of experiments can be reduced and proper interpretation of results can be achieved for all the input variables [6]. In polymer composites, every individual input parameter has an impact on the output response, and additionally, the mechanical behavior comprises many input variables, such as filler percentage, fiber percentage, fiber length, and the type of polymer [7,8]. Polymer composites have abundant variables which affect the results [9–13]. These variables are difficult to investigate using conventional methods [14–17]. In order to overcome this issue, polymer composites' characterizations can potentially be evaluated with many techniques to identify the behavior of the composites [18,19].

Using a recent highly referenced work for this research, a solid understanding of the optimization technique and methods of analysis contained in the optimization process is achieved. This paper provides an overview of the background and relevance of response surface methodology (RSM) and the Taguchi method in the context of investigating the influence of independent factors on a response variable. While these methodologies have been extensively utilized in various fields, there remains a need for a comprehensive study that systematically compares and evaluates their effectiveness in real-world applications. Additionally, this study aims to address the knowledge gap by highlighting the advantages and limitations of both RSM and the Taguchi method, offering insights into when and how these techniques can be optimally employed.

2. Techniques for Optimization

To analyze the input and output parameters of experimental results, optimization techniques are widely used. Within the boundary conditions, the input parameter must be chosen. The independent or input parameter is a parameter that can be changed within the domain. The response or output parameter refers to the experiment's result. Different optimization strategies may be used to optimize for lowest or maximum responsiveness. For the experimental design table, an ANOVA table is usually prepared. The accuracy of the model is investigated using regression mean square and modified regression mean square. If the p-value is less than 0.05, the model is significant.

2.1. Response Surface Methodology (RSM)

The influence level of different input variables on output responses can be investigated using RSM. The invention of this statistical method took place in 1951 by George E. P. Box and K. B. Wilson. The optimum level of all the responses can be identified using the principle of this unique method. The most preferable equation to execute this technique was recommended by Box and Wilson to be second-order polynomial expression. Regarding the execution of prediction only for the data, which must be within the boundary levels and criteria, if the data go beyond the limit, the prediction would have considerable residual values. Statistical tools, as opposed to conventional methodologies, can analyze the connection between process variables.

In a tribological investigation, there are uncontrolled factors; namely, sliding velocity, load, sliding distance, and filler are considered input parameters, which have been labeled A, B, C, and D for both responses [6]. Equations (1) and (2) [6] show how RSM framed the second-order polynomial equation to mention the response surface 'Y' for the selected input parameters.

$$Y = b_0 + \Sigma b_i x_i + \Sigma b_{ii} x_i^2 + \Sigma b_{ij} x_i x_j + e_r \quad (1)$$

$$\text{SWR or CoF} = b_0 + b_1(A) + b_2(B) + b_3(C) + b_4(D) + b_{11}(A^2) + b_{22}(B^2) + b_{33}(C^2) + b_{44}(D^2) + b_{12}(AB) + b_{13}(AC) + b_{14}(AD) + b_{23}(BC) + b_{24}(BD) + b_{34}(CD) \quad (2)$$

where b_0 is the average value of the responses; b_1, b_2, b_3, and b_4 are the coefficients of the linear effects of the individual parameters; b_{11},b_{22},b_{33}, and b_{44} are the coefficients of interaction effects of the same parameter; and b_{12}, b_{13},b_{14},b_{23},b_{24}, and b_{34} are the coefficients of the interaction effects of the parameters.

2.2. Taguchi Method

The Taguchi orthogonal array was invented by Dr. Taguchi of Japan as an optimization method for a minimum variable. This method is accurate and well balanced. The Taguchi method's effectiveness is boosted by the Design of Experiments' collaboration with it. Furthermore, the investigation of the impact of input factors and their interactions on the output parameter yields more similar results. The best input parameters are found by using criteria like "smaller–the–better", "bigger–the–better", and "normal–the–better" for the signal-to-noise ratio (S/N) table condition.

Jenish et al. [20] used the RSM regression model to determine the optimal parameters of sliding wear behavior of CQSF/epoxy with and without red mud, as well as CSA particulate-filled composites. The CCD technique was utilized to create a design table in the "Design of Expert" program in this empirical statistical RSM. Loads (10, 20, and 30 N), sliding lengths (500, 1000, and 1500 m), sliding velocities (2, 3, and 4 m/s), and fillers (0, 5, and 10 wt. percent) were utilized as input parameters with three different levels. The coefficient of friction (CoF) and wear rate were calculated based on the results of 30 runs. +1, 0 and −1 were the coded factors.

To perform the analysis using traditional complete factorial approaches, 64 (43) experiments were required. To predict the optimum parameters among three categories of quality characteristics, the "lower-the-better" condition was chosen [21].

$$\frac{S}{N} = -10 \times \log \frac{1}{n} \sum (SWR)^2 \quad (3)$$

where *SWR* represents the specific wear rate of the sample, and *n* represents the total number of experiments. The influence level of each parameter is identified from Equations (4)–(7).

Step: 1 Calculation of S/N ratio.

Step: 2 Computation of overall mean of the S/N ratio. The overall mean can be calculated from this step.

$$\frac{\overline{S}}{N} = \frac{1}{9} \sum_{i=1}^{9} \left(\frac{S}{N} \right)_i \quad (4)$$

Step: 3 Computation of the sum of squares. The sum of squares represents the square of the difference in the mean average of S/N, and the S/N ratio can be calculated from this step.

$$\varphi = \sum_{i=9}^{9} \left(\left(\frac{S}{N} \right)_i - \frac{\overline{S}}{N} \right)^2 \quad (5)$$

Step: 4 Computation of the *i*th process parameter. The sum of squares of the *i*th parameter due to variation about the mean can be calculated from this step.

$$\varphi_i = \sum_{j=1}^{4} \left(\left(\frac{S}{N} \right)_{ij} - \frac{\overline{S}}{N} \right)^2 \quad (6)$$

Step: 5 Computation of the *i*th parameter's "percentage of contribution". In the final step, the percentage of contribution of each process parameter can be calculated.

$$\text{Percentage of contribution, } P_i = \frac{\varphi_i}{\varphi} \times 100 \tag{7}$$

The optimum response for "lower-the-better" with all the process parameters is given in Equation (8). The average S/N ratio for the recommended condition is computed using this equation. Then, the SWR is calculated by substituting the S/N ratio in the "lower-the-better" condition.

$$S = H + \left(A_p - H\right) + \left(B_q - H\right) + \left(C_r - H\right) + \left(D_s - H\right) \tag{8}$$

where S is the predicted average S/N ratio for SWR, H is the overall experimental mean of the S/N ratio, and Ap, Bq, Cr, and Ds are the S/N ratio values for the recommended level of the process parameters. Selecting variables and orthogonal arrays are important processes in the Taguchi technique. Once all the processes are over, the software provides the necessary solution for the model. The result could be a regression equation, contour plot, or the influence of the input parameter.

3. Studies on Response Surface Methodology

The behavior of iron mud filler particulate filled with glass fiber/epoxy composite was analyzed using response surface methodology. For response surface analysis, the sliding distance, sliding velocity, and iron mud filler content were considered independent variables. An ANOVA was used for all the optimization techniques in order to obtain the numerical significance and percentage contribution. The response surface approach was used to find the best settings for the lowest SWR. The best values were 20 percent iron mud content, a 35 N weight, a 50 m sliding distance, and a 100 cm/s sliding velocity under experimental conditions. With a desirability value of 1, the SWR for this optimum condition was 0.0056591 mm^3/N-m. The observed error percentage ranged from 0 to 10%, as determined by a comparison table of the observed and predicted responses.

Using the RSM prediction tool, Parikh and Gohil [22] investigated the sliding wear of cotton fiber-reinforced polymer composites with SiC filler. The percentage of response contribution was calculated. When comparing 3 wt. percent SiC filler composites to 5 wt. percent SiC filler composites, the researchers discovered that 5 wt. percent SiC filler increased wear resistance. Under high load conditions, the 3 wt. percent SiC filler composite had a lower wear rate. The tribological behavior of natural and synthetic fiber-reinforced polymer with and without filler composite has been studied extensively. Many papers have concluded from the study's findings that speed and load distance are the major controlling parameters for wear, and that adding filler reduces wear.

Babu et al. [23] used RSM to forecast the surface roughness of turned nano-Khorasan-based pineapple leaf fiber-reinforced polyester composites. The F-value from the ANOVA table in this study is 21.37. This indicates that the analytical model performs well. The presence of p-values less than 0.05 for the specified parameters indicates that they are highly significant.

Rajmohan and Palanikumar [24] used RSM under CCD to perform parametric research. CCD is better for creating mathematical models that anticipate output reactions like thrust force, surface roughness, and burr height. The impact of the input parameters and their interactions were addressed, and the RSM model was used to identify the expected control variables. If the p-value was less than 0.05 in the ANOVA table, the parameter was considered insignificant. All unimportant parameters were removed from the ANOVA table and predicted equation in order to obtain a better result. Because the experimental and predicted values were so similar, the model was more useful for analysis.

Sharma et al. [25] experimented with the sliding wear characteristics of Al6082 alloy composites filled with graphite. The experiment was performed using a pin-on-disc wear tester, and the parametric analysis of wear was analyzed via RSM. The design table for statistical analysis was prepared using the CCD approach. Percentage reinforcement, load, sliding speed value, and sliding distance were the input parameters for the analysis. The R2 and adjusted R2 rates were both above 95%. Because the input and output parameters were clearly important, the regression model was more trustworthy for parameter analysis. The *p*-value in the ANOVA table was less than 0.05, indicating that the model was 95 percent confident.

3.1. Regression Line from RSM

The regression equation summarizes the linear correlation between the obtained and analytical data, and the significance of each datapoint is also determined. The accuracy level of the responses, such as particular wear rate and CoF, are discussed based on the regression line, which was obtained using a normal plot of residuals from the design expert-13 software [2]. Residuals emphasize the discrepancy between the observed and expected values. It is revealed that the residuals decrease close to the accuracy line. All the typically framed values are nullified through this process.

3.2. Description of Surface Plot from RSM

Figure 1 depicts the 3D surface plot of the specific wear rate (SWR) for various input parameters and variations in filler content, indicating the optimal condition for SWR with regard to filler content. For all studies, the SWR ranges from 0.000114 to 0.000931 mm^3/Nm.

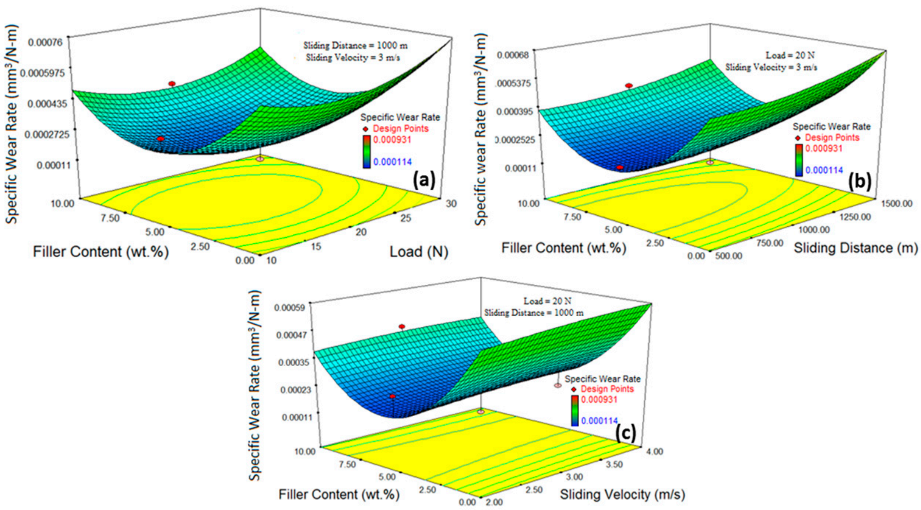

Figure 1. Contour plots of (**a**) Filler—load influence on SWR, (**b**) Filler—sliding distance influence on SWR, and (**c**) Filler—sliding velocity influence on SWR [2].

Figure 1a depicts the differences in SWR with regard to filler content and their corresponding load when the sliding velocity is 3 m/s and the sliding distance variable is 1000 m. The value of the filler content exhibits a negative link with SWR up to 5 wt. percent filler addition, and thereafter, the wear rate increases with filler content due to filler particle debonding. Similarly, the variation in SWR with regard to load is minimal throughout the testing. The filler material percentages are 4% to 6% by weight, and the wear rate is at its lowest.

Figure 1b denotes the SWR variation with regard to the corresponding filler substances and concerns sliding distance when the particular sliding velocity and corresponding load on the pin are 3 m/s and 20 N, respectively. The SWR drops with increasing wt. percent of filler addition up to 5 wt. percent, and then, reverses its behavior with an increase in SWR. The variation in wear rate with regard to sliding distance proves minimal up to 1000 m, and it exhibits a linear trend beyond that. It should be noted that the SWR variation with regard to filler content is minimal in the range of 4 wt. percent to 6 wt. percent for sliding distances ranging from 500 m to 1000 m.

Figure 1c illustrates the SWR values with regard to certain filler substances and concerns sliding velocity, while the applied load on the disc and the sliding distance is 20 N and 1000 m, respectively. The wear rate variation exhibits an initial negative slope with regard to filler content up to 5 wt. percent, and then, the slope reverses due to increased wear losses. The effect of sliding velocity on SWR is nearly consistent throughout the test, with the velocity ranging from 2 m/s to 4 m/s. The optimization plot confirms that the best red mud filler content to lower the SWR was between 4% and 6% by weight.

4. Studies on the Taguchi Method

Using an ASTM standard G99 [2] pin-on-disc machine, Prabhu et al. [26] examined the wear characteristics of glass fiber/epoxy filled with CSP composites. In a signal-to-noise ratio analysis, the amount of time saved from the investigation was admirable. The signal-to-noise ratio can forecast the outcomes inside the domain and suggest the best parameter. The inclusion of coconut shell powder in epoxy resin augmented the wear resistance of the composite materials, according to the findings. The mechanical characteristics were also enhanced by the presence of CSP.

The abrasive wear of fiber/epoxy composites was analyzed and the surface behavior was improved by Swain and Biswas [27]. The trials were carried out using the ASTM-G65 three-body rubber wheel abrasive wear test. In the Minitab software, Taguchi's orthogonal array was used for this study. The important input parameters used for the investigation were a distance of 70 m, fiber content of 30 wt.%, a load of 10 N, and an abrasive size of 200 mm. These parameters were analyzed from the S/N ratio table under the "lower-the-best" condition and offered a superior SWR.

Taguchi Interpretation

The S/N ratio under lower-the-better conditions was selected and the optimum input parameters were evaluated by Jenish et al. [1]. All the input parameters (velocity, load, filler, and distance) were used for the experiment. The method employed for these experiments was three-body abrasive wear test. The plot showed the optimum parameters at all the upper peaks. The interaction between each parameter for this study was also determined, as shown in Figure 2. The interaction effect of SWR was assessed by looking the peak of the line and the movement of the line. All the mean values were used to complete this interaction plot. For the most significant level in the finite element analysis, even these techniques provide a better solution [28]. Polymer composites represent a widely growing sector, which means the use of this optimization is highly recommended for all sectors. Mechanical characterization is common for polymer composites [29,30]. However, driving experiments with minimum data may not give a clear and complete picture of the performance of the materials. So, optimization is highly recommended to analyze more data and to obtain significant reports.

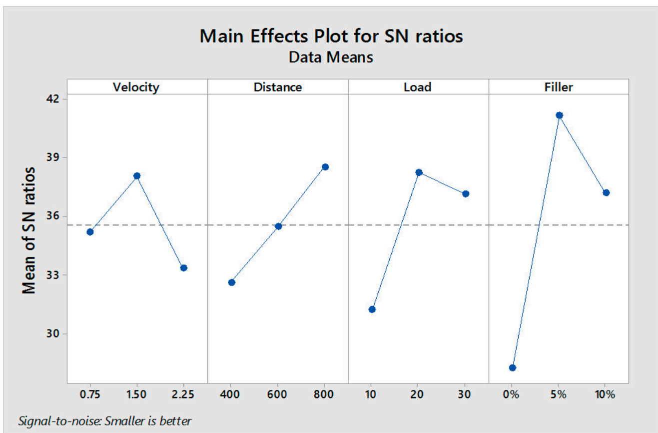

Figure 2. Signal-to-noise ratio [1].

5. Conclusions

By choosing acceptable input components, the response surface approach and Taguchi orthogonal array are more suited for predicting the experiment's output response. This article illustrates why optimization approaches are needed for efficient parameter integration, particularly for input and output variables. It describes the worldwide setting that aided the development of regression analysis, as well as the decentralization of generating units through methodologies. The exponential growth in research publications utilizing optimization strategies to handle variable placement and size problems demonstrates the high interest in this area among all traditional methods. This article provides an overview of current research on the use of various optimization approaches to determine the optimum position and magnitude of variables in analyses for this issue. It outlines and analyzes the many traditional and optimization strategies used to solve this issue, taking into account their key benefits and drawbacks.

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