science, engineering and health studies

Research Article

Science, Engineering and Health Studies
https://li01.tci-thaijo.org/index.php/sehs
ISSN (Online): 2630-0087

Optimization and parametric economic analysis for carbon fiber reinforced plastic composites with Taguchi-present worth method

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Received: *21 September 2023*
Revised: *21 June 2024*
Accepted: *18 July 2024*
Published: *2 October 2025*

Citation:
Oluwo, A., Ogunmola, B. Y., Oke, S. A., Rajan, J., Jose, S., Lathashankar, B., Aderibigbe, S. B., & Odudare, S. O. (2025). Optimization and parametric economic analysis for carbon fiber reinforced plastic composites with Taguchi-present worth method. Science, Engineering and Health Studies, 19, 25040002.

ABSTRACT

Within the drilling community, an integrated method of the technical and economic parameters is needed to improve profit margins and for sustainable operations. In this article, a novel framework that establishes the economic dimension of the drilling operation for the carbon fiber-reinforced plastic (CFRP) composites is presented by fusing the Taguchi method with the present worth method. The present worth, level, interest rate and the value of the optimal parametric setting at the various levels are integrated. Then the optimal points for variables are identified based on derivatives with response tables developed from the orthogonal array and signal-to-noise ratios with parametric ranking. The optimal parametric setting obtained using the Taguchi method was $SP_3PA_1FR_3TF_1/TF_3$, matched against the optimal result of $PW(i)_{SP3}PW(i)_{PA3}PW(i)_{FR3}PW(i)_{TF2}$ for the present worth derivative with respect to *n*. The Taguchi method yielded 3000 rpm (speed), 100° (point angle), 500 mm/min (feed rate) and 84.23 N (thrust force). However, the optimal results for the present worth derivative with respect to *i* were interpreted as 3000 rpm (speed), 135° (point angle), 500 mm/min (feed rate) and 197.35 N (thrust force). Moreover, the optimal results regarding the derivative of present worth with respect to *n* are 1000 rpm (speed), 135° (point angle), 100 mm/min (feed rate) and 197.35 N (thrust force). In addition, when Oke and Fagbolagun's model was deployed, the positions of the parameters/response with respect to the *T-PW* method's evaluation were the thrust force (1st, -40.0460), spindle speed (2nd, -51.0999), point angle (3rd, -50.1034) and feed rate (4th, -50.2274). Thus, the work provides help to process engineers to control their operators and for budget planning purposes.

Keywords: optimization; optimal; drilling; operations; polynomial; exponential

1. INTRODUCTION

At present, the drilling industry is losing substantial profits that may be gained through operational savings by the workers (Bosco et al., 2015; Anand et al., 2018; Jadoun et al., 2006; Jayaprakash et al., 2020). If the technical operational standards are tied to some economic standards, the operational drilling activities will be driven by both technical (including optimization) and economic measures (Kaviarasan et al., 2019; Manickam & Parthipan, 2020; Neseli, 2014). The prevailing practice in the optimization of process parameters during the drilling operations involves the Taguchi method of experimentation: the signal-to-noise ratios are summarized into a response table which defines the optimal parametric setting for the composite being drilled (Juliyana & Prakash, 2022; Akdulum & Kayir, 2023; Rai et al., 2023; Senthil Kumar et al., 2023). However, attempts to use this model to control the technical operations have failed; time value is not accounted for in the model and operators may perform to the expected threshold only at will (Akdulum & Kayir, 2023, Rai et al., 2023). More disturbing is the fact that the performance of the operator changes from time to time during the drilling operation and the static model of present worth may fail if applied to this situation (Padhee et al., 2012; Rajmohan et al., 2012; Park, 2013). In this regard, the derivatives of the present worth factor may be the most adequate models for the implementation of the performance behavior of the operator at the machine shop. However, such derivatives may yield different results under different functions of polynomial and exponential forms.

Regarding the literature review on the optimization of drilling parameters of composites in general and the carbon fiber-reinforced plastic (CFRP) composites in particular, it was found that the available optimization models cannot be effectively used to quantify the economic aspects of the drilling process since it needs the incorporation of an economic parameter, which till now is not in existence in the literature (Singh et al., 2013; Srinivasan et al., 2017; Vinayagamoorthy, 2017). However, composites should be produced economically for lower production costs, improved safety regulatory compliance, higher performance, and lower weight of the composites. Since the drilling operations regarding CFRP composites may not only be viewed in the static form, the dynamic aspect is important as the completion of the drilling work spans over a specified time (Shunmugesh & Pratheesh, 2020; Odusoro & Oke, 2021a, 2021b, 2021c; Adedeji et al., 2023). However, there are no models to account for this dynamic behavior of optimization parameters of drilling while drilling CFRP composites (Srinivasan et al., 2017).

The efficient and sustainable operations of the machine shops require a complementary aspect of economics to the technical drilling parameters, which is absent in the literature (Mercy et al., 2022). It has further been observed that substantial laxity in the control of operators on the machine floor exists without tying their performance to economic issues that will reveal whether their contributions are sustaining the machining shop or causing its instability or decline in performance. This is closely tied to investment and daily operation cost issues. It was observed that a possible solution to the problem is to introduce the present worth factor into the Taguchi optimization framework as a control strategy since it has a component of the interest rate (Okponyia & Oke, 2020). Furthermore, the inflationary factor may be introduced to augment the interest rate to have a complete overview of the economic outlook of the machine shop at any instant in time (Park, 2013). The interest rate is introduced at the signal-to-noise computation of the parameter/response table of the Taguchi method (Okponyia & Oke, 2020).

Consequently, the principal motivation of this article is that the present worth factor is generally an effective tool to analyze the time value of money for the drilling operations in a machining shop where the technical crew are biased only towards the mechanical aspects of the operations with little or no emphasis on the economic aspect. However, the general manager of the machine shop reports on both the technical and financial aspects to the board of directors. The present worth method can prove particularly useful for the machining of CFRP composites since it is a hard material and requires substantial energy resources for drilling (Park, 2013). Skills are also required for efficiency in drilling for this material. Energy conservation may also be encouraged by the introduction of the present worth method in the machine shop.

Machining processes are one of the largest technical operational activities among manufacturing processes. These processes have a huge potential as an economic base that surpasses several other processes in the manufacturing domain. However, the drilling industry occupies an important location with this machining industry when viewed from volumetric counts of activities in comparison with grinding and broaching tasks. The CFRP composite industry, being one of the largest, competes with the glass fiber-reinforced composite industry and the agro-based composite industry, catering for the needs of diverse areas such as aerospace and automobile among others.

Moreover, the drilling operations of the CFRP composites have long experienced a high level of economic instability prompting researchers and practitioners to raise questions on the effectiveness of existing operational measures and deficiencies in economic knowledge that could drive sustainability and enhanced employee commitment. Thus, to sustain the drilling operations of CFRP composites, it is essential to optimize the drilling process parameters, which can be quantified by using the Taguchi method as an indicator. For example, Shi et al. (2023) evaluated the bond strength of carbon fiber-reinforced polymer combined with steel. It was reported that an improved arithmetic optimization algorithm coupled with a hybridized random forest had superior performance over other categories tested in the work. The impact of the study on the engineering community is that more evenly distributed stress will be achieved in the bond joints. Vibrations may be absorbed easily with less damage to the material. Nonetheless, the economics of the optimization, which has been left unexplored shows promise for improvement and a greater impact.

Zhang et al. (2023) on their part contributed an upcycling approach to the mitigation of the environmental effects of CFRP. The study found that the proposed upcycling approach exhibited superior properties when compared with the commercial T700 short-cut carbon fiber. Interestingly, the study highlighted a reduced necessity for new production; it eliminated pollution to air, water and greenhouse gas emissions. However, incorporating optimization and economics were unfortunately omitted. This deficiency has the potential to impact society.

Furthermore, Deng et al. (2023) proposed an efficient recycling process for carbon fiber-reinforced composites using a solvothermal decomposition procedure to decompose a carbon fiber-reinforced boron phenolic resin composite. The study reported that recycled carbon fibers fortified with boron phenolic resin composite exhibited better punch category of shear strength because of the enhanced wettability and interfaces. The study significantly impacts society in that decomposition is controlled and may be quickly achieved, thereby saving the environment from pollution-related issues including prolonged water and air pollution. Nonetheless, the optimization aspect and the economics being considered concurrently had been ignored. This aspect has the potential for highly beneficial research outcomes.

In two separate studies, Ateeq et al. (2023) and Ateeq (2023) presented comprehensive surveys, which strengthened the need for the present study on a combined Taguchi optimization present worth method (i.e., optimization-economic study). In Ateeq (2023) the remanufacturing and recycling of carbon fiber polymer composite were considered. With over 80 articles reviewed, research gaps were established which included optimization of recycling procedures for CFRP. The second review article by Ateeq et al. (2023) focused on the 3D printing of CFRP composites that were recycled. The study showed that an additive manufacturing–oriented method to recycle CFRP composite waste was cost-effective and environmentally attractive. However, the economic aspect was missing in their contribution.

From the foregoing, it was established that an economic approach is also required in evaluating and formulating techno-economic policies at the machine shop for all employees to contribute to the sustainable practice through an appreciation of the time value of money concept among others (Park, 2013). By integrating the two concepts of optimization and economics enhancement, the performance of the team is guaranteed. This section aims to analyze the literature on the drilling of CFRP composites.

The following relevant papers to this research have previously demonstrated successful hybridization of the Taguchi method with other methods in solving diverse engineering problems. Shunmugesh and Pratheesh (2020) analyzed the micro-drilling parameters from the perspective of integrating the Taguchi method and grey relational analysis by varying the drill bits and focusing on CFRP. Out of the three input factors, namely drill diameter, spindle speed and feed rate, two are the same as those examined in the present work—spindle speed and feed rate. Krishnamoorthy (2011) utilized point angle instead of drill diameter as it was less studied at the time of investigation, and infusing new information into the knowledge base of the CFRP composites brings significant enhancements to practice. Another interesting variation of the study conducted by Shunmugesh and Pratheesh (2020) is the linkage of optimization mechanisms with the lowered wear rate and material removal rate. These are excluded as responses in the present work for investigation on less studied combined forms of eccentricity, torque and thrust force besides the delamination factor (entry and exit) that were studied in the two reports.

2. MATERIALS AND METHODS

In drilling operations, the thrust force, torque, delamination, eccentricity and surface roughness are the most widely used responses for fiber-reinforced composites. Their significance varies from one drilling operation to another. Thus, this section justifies each of the responses used in this work.

2.1 The key responses in the drilling of CFRP composites

2.1.1 Delamination

In the development of a selection strategy for the drilling operation of CFRP composites, delamination is an important task. This occurs when composites fracture into layers due to high interlaminar stresses combined with inherently low through-thickness strength. It compromises the structural integrity of the material, reduces assembly tolerances, and is typically initiated by matrix, bending, or shear cracks. Delamination has also been associated with reduced compressive strength in composite materials. Consequently, while choosing drilling operations responses for the CFRP composites, it is extremely important to consider delamination both at the entry and exit positions in drilling.

2.1.2 Eccentricity

Drilling produces circular holes and the concepts of concentric circles and eccentric circles. These are well documented in engineering drawing textbooks, and explain the ideas of eccentricity or concentricity during the drilling of CFRP composites. A workpiece is said to be concentrically drilled if the holes of the different drill bit sizes are drilled perfectly with the center of the smaller hole aligning with that of the bigger one perfectly. This is not a defect as it may be desired to have concentric holes according to the design of the component being drilled. However, the drilling output becomes a defect if any of the holes shift at the center from the marked points. In this case, an eccentric hole is produced. Thus, eccentricity is the property of the drilled hole(s) that shows how much the drill bit differs from drilling a circular hole in the workpiece. In the drilling of CFRP composites, eccentricity is often formed as a factor that contributes to component damage, because the material is hard and difficult to machine. However, eccentricity may be predicted to enable the researcher to find the value of drilling eccentricity at diverse depths for holes at inclination angles. The effects of eccentricity include faster wear and tear of the material.

Consider a bolt and nut used to fasten two plates with one of the plates attached to a moving object or part of another machine, as the machine works, it generates forces that produce stress transferred to the joint where the bolt and nut hold the plates together. For bolts fixed perfectly to holes of the size of the bolts, there is no movement of the bolt and nuts and the stress is evenly concentrated at the joining point. However, for CFRP composites whose holes are eccentrically drilled, as the force is sent to the plates, the stress generated is distributed according to the movement of the interfacing plate. This it is usually uneven as the plates wear faster at the point of joining.

2.1.3 Surface roughness

The machining literature defines surface roughness as the shorter frequency of real surfaces weighed against troughs. The idea is that machined parts contain a complicated shape made of a set of peaks and troughs exhibiting different heights and spacing. Therefore, the idea of surface roughness is to establish different measurement grades for distances between one peak and another, or between a combination of peaks and troughs. While surface roughness is attached to the roughness average, which is a term used to assess a particular measurement, the term surface finish may also replace surface roughness to describe the quality of finishing of the workpiece during the drilling activity.

2.1.4 Thrust force

This refers to a type of force that ensures the correct pushing of the drill bit axially into the workpiece. The thrust force acts among the spindle axis.

2.1.5 Torque

This is the force that causes the drill bit to rotate. It influences the effectiveness and control of the drill bit's rotational force. It is known that the higher the torque, the higher the twisting force and vice-versa.

2.1.6 Feed rate

This refers to the velocity at which the drill bit is fed against the composite workpiece.

2.1.7 Drilling point angle

The point angle is located on the head of the twist drill. Point angle ensures that a good center point is maintained during the composite drilling exercise. The smaller the point angle, the easier it is for the centering of the workpiece and vice-versa. In the context of spindle speed, cutting speed refers to the surface speed at the outer diameter of the drill. It represents the relative speed between the cutting edge of the drill and the surface of the plastic composite.

2.2 The signal-to-noise criteria

Equation 1 shows the larger the better signal-to-noise criterion for the spindle speed, as suggested by Oji and Oke (2021).

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{1}$$

where y_i is the performance attributed containing the i^{th} observed value, and n is the trial experimental number.

Furthermore, Krishnamoorthy (2011) argued that the smaller-the-better signal-to-noise criterion is the appropriate choice for the point angle as a parameter of the drilling process. The argument was built on the fact that as torque reduces with a growth in point angle, likewise a growth in the thrust force triggers an increase in the point angle. Consequently, since the reverse is desired, the suggestion of a lower point angle as the ideal selection for drilling is an accepted idea. This suggests Equation 2 is appropriate for choice in the present article (Oji & Oke, 2021).

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}y_i^2\right) \tag{2}$$

where y_i is the performance attributed containing the i^{th} observed value, and n is the trial experimental number.

Thus, Equation 2 is the smaller-the-better criterion of the signal-to-noise ratio. Furthermore, Krishnamoorthy (2011) asserted that the higher feed rates yield extended thrust force coupled with a rough surface finish. Conversely, minimum feed rates yield heightened heat generation in the work material coupled with a reduced material removal rate. As Krishnamoorthy (2011) added, an appropriate feed rate is desired. Thus, the normal-the-best criterion of the signal-to-noise ratio is desired for the feed rate for drilling the CFRP composites considered in this article. The formula is given in Oji and Oke (2021) and Equation 3.

$$S/N = -10\log_{10} y_i^2/s^2 \tag{3}$$

where y_i is the performance attributed containing the i^{th} observed value, n is the trial experimental number, and s^2 is the variance of observations, given as Equation 4:

$$s^2 = \frac{\sum_{i=1}^{n}(y_i-\overline{y})^2}{n-1} \tag{4}$$

Furthermore, in arguing for the choice of the signal-to-noise criterion for the point angle, the smaller-the-better S/N criterion was chosen. This is based on the premise that a lower thrust force is desired. Thus, the response, thrust force, indicated in the results and discussion section will be treated with the smaller-the-better S/N criterion, Equation 2.

From the foregoing, it can be deduced that three different criteria are required to analyze the three parameters of the CFRP composite proposed by Krishnamoorthy (2011). Yet there is a need to calculate the overall signal-to-noise ratio for each experimented trial. To overcome this constraint, two methods are proposed. The first method entrails considering each criterion of the signal-to-noise ratio based on the type of parameter concerned and sum up the signal-to-noise ratio to represent the overall for each experimental trial. This method may be called the sum-each-criterion (SEC). The second method entails the introduction of the weights obtained from the AHP as a factor to multiply the SEC method.

2.3 The SEC method of signal-to-noise (S/N) ratio computation

Oke and Fagbolagun (2021) suggested a method to fuse the Taguchi method and present worth method for the economic prosperity of the organization. Given the potential of the method in a drilling process context, the method is suggested to improve the parameters in drilling the CFRP composite. The procedure for the adoption of the method is stated as follows (Oke & Fagbolagun, 2020).

Step 1: Observe the process and bring out its key factors;
Step 2: Determine the associated orthogonal array of the optimization-economic problem;
Step 3: Develop the factor table to reflect the orthogonal matrix being mapped to each factor. Notice that this has to be linked to the computation of the signal-to-noise ratios;
Step 4: Link the signal-to-noise ratios to the three criteria essential for evaluation: nominal the best, lower the better and higher the better;
Step 5: Develop the response table from the signal-to-noise ratios. The researcher characterizes the pattern to find the averages of the signal-to-noise ratios;
Step 6: Parameter values at optimal thresholds are determined. Here, choices of maximum values of the average signal-to-noise ratios are picked;
Step 7: Consider the level and i (interest rate) and evaluate the present worth of each parameter. Consider also beneficial and non-beneficial sides of the flow diagram;

Step 8: Establish each parameter's present worth; and
Step 9: Ranking each parameter is done by considering the highest value first and subsequent ranks follow.

To analyze using the present worth method, Equation 5 (Oke & Fagbolagun, 2020) was used.

$$PW_{S/PA/FR/TF} = L\,(1 + i)^{-n} \quad (5)$$

where $PW_{S/PA/FR/TF}$ is the present worth and L represents the value of the parameter at particular levels.

3. RESULTS AND DISCUSSION

3.1 Taguchi method

While the analytic hierarchy process method selects the best responses or parameters, the Taguchi method finds its purpose in optimizing the process parameters or responses through the organized stages of factor/ response-level specification, the introduction of an orthogonal array, signal-to-noise computation and the initiation of the optimal parametric setting where the delta values are specified. Furthermore, the analytic hierarchy process method also selects the order of strength of parameters/responses defined and the combination of parameters from the different levels to yield optimal results. While drilling the CFRP composite, the deployment of the AHP method reveals that the thrust force is the most desired response among others, including the entry delamination, exit delamination, eccentricity, torque, and surface roughness. None of the responses were optimized, and the Taguchi methods have the potential of optimizing them. Consequently, the Taguchi method was introduced to optimize the drilling responses and to concurrently select and optimize the response. The starting point was the experimental results of Krishnamoorthy (2011) where the drilling situations with the response achieved for the HSS drill were specified. There are 27 experiments and the aim was to establish levels for the parameters (speed, point angle, and feed rate) and the thrust force as the most preferred response from the AHP method of analysis. From Krishnamoorthy (2011), speed has the following levels: 1000, 2000, and 3000. Point angle has the following levels: 100, 118, and 135. While feed rate has the following levels: 100, 300, and 500.

Furthermore, it was observed that the thrust force, measured across 27 experimental trials, produced 27 distinct values. Treating each value as a separate level would be impractical and overly complex to manage. Thus, to resolve this issue, a convenient scale of levels was determined for the thrust force. Guided by the fact that each of the three parameters—speed, feed rate, and point angle— was set at three levels, it was decided to also define three levels for the thrust force. To achieve this, the range of values of the experimental trials covering the 27 data points of thrust force was established and then segregated into three equal parts or data points. The range of values of the thrust force were 84.23–310.47 at data points 19 and 6 for the lowest and highest values in the range, respectively. The data was scaled into three distinct levels: 84.23 (Level 1), 197.35 (Level 2), and 310.47 (Level 3). These levels were determined by calculating the midpoint between the minimum value (84.23) and the maximum of the range. The difference, 226.24 (i.e., 310.47–84.23), was divided by 2 to obtain 113.12. Adding this midpoint value to the minimum (84.23 + 113.12) resulted in Level 2, 197.35. Level 3 corresponds to the upper end of the range (310.47). These scaled values were used to analyze the thrust response. Consequently, Table 1 was developed as the factors response-level assignment for the drilling operation.

An orthogonal array was employed involving three factors and three levels. The corresponding change in the thrust force was noted as 746.048 while the average change was 74.6048%. In addition, the changes in the feed rate from 0 to 100% were noted to produce a 307.014% change in the thrust force, with an average of 30.7014%. By comparing the changes in each of the parameters that were affected, the one representing the point angle produced the highest value and therefore was the most sensitive among the three parameters tested.

Table 1. Factors/response-level assignment for the carbon fiber reinforced plastic composite drilling operation

	Description		
	Level 1	**Level 2**	**Level 3**
Parameter			
Speed (rpm)	1000	2000	3000
Point angle (θ)	100	118	135
Feed rate (mm/min)	100	300	500
Response			
Thrust force (N)	84.23	197.35	310.47

Source: (Krishnamoorthy, 2011)

Table 2 contains the orthogonal arrays and factors for the drilling problem. However, the components of the table require the computation of the signal-to-noise ratio for each of the nine experimental trials. Consequently, Krishnamoorthy (2011) was studied to understand the signal-to-noise criteria essential for each of the spindle speeds, point angle and feed rates. Krishnamoorthy (2011) argued that the higher cutting speed triggers low thrust force and superior surface finish. Since these responses are desired in the present article, the authors concur with the proposal of a higher cutting speed by Krishnamoorthy (2011) and then subscribe to the signal-to-noise criterion of larger-the-better for the spindle speed, as suggested in Oji and Oke (2021), expressed in Equation 1.

To illustrate the working of the Taguchi method, the first experimental trial was analyzed. Here, for the spindle speed parameter, the larger-than-better S/N ratio criterion (Equation 1) was desired. Take note at this point, that only an entry, 1000, is involved. The obtained value after deploying Equation 1 on the value of 1000 yields 60 for experimental trial 1. The same value was repeated for experimental trials 2 and 3 while the values for experimental trials 4, 5, 6, 7, 8, and 9 yielded 66.02, 66.02, 66.02, 69.54, 69.54, and 69.54, respectively. For the point angle, Equation 3 was deployed and values ranging from -42.61 to -40 were obtained from the range of experimental trials 1 to 9. For the feed rate, Equation 4 was deployed. However, since a single item was considered, there is no variance value and the component of the S/N ratio for the feed rate becomes zero for the entire nine experimental trials. While treating the thrust force (response), Equation 3, which is the smaller-the-better criterion of the S/N ratio, was used. In this case, the range of values obtained is from -45.90 to -38.51. With the entire computations of the S/N ratios for the S, PA, FR and TF, the sum was obtained and values ranging from -32.45 to -11.58 were obtained. The next step was to obtain the response table (Table 3) that summarizes the optimal parametric settings for the speed, feed rate and point angle parameters, and the optimal response setting for the thrust force. The decision on the optimal settings was reached as the highest values of the levels under each factor were recognized as the best outcome. Consequently, for the speed parameter, a value of -16.56 was chosen, indicated with an asterisk. By using the same idea, for the point angle, -20.43 was obtained as the desired value, and for the feed rate, -20.43 was achieved as the desired value while a tie of -14.19 was obtained for the thrust force as the desired level. To interpret the result, consider the parameter, speed, with a value of -16.56 at level 3. This is read from Table 1 under level 3 but along the row of the speed parameter as 3000 rpm. For the point angle, level 1 was chosen, by reading the value given under level 1 and along with the point angle parameter in Table 1, a value of 100° is chosen. Similarly, for the feed rate under level 3, along the row for the feed rate in Table 1, a value of 500 mm/min is obtained.

Table 2. Taguchi's orthogonal arrays, factors and signal-to-noise ratios for the drilling problem

Experiment No.	Orthogonal array				Factors				Signal-to-noise ratio type				Signal-to-noise ratios
									LTB	STB	NB	STB	
	S	PA	FR	TF	S	PA	FR	TF	S	PA	FR	TF	
1	1	1	1	1	1000	100	100	84.23	60.00	-40.00	0	-38.51	-18.51
2	1	2	2	2	1000	118	300	197.35	60.00	-41.44	0	-45.90	-27.34
3	1	3	3	3	1000	135	500	310.47	60.00	-42.61	0	-49.84	-32.45
4	2	1	2	3	2000	135	300	310.47	66.02	-42.61	0	-49.84	-26.43
5	2	2	3	1	2000	100	500	84.23	66.02	-40.00	0	-38.51	-12.49
6	2	3	1	2	2000	118	100	197.35	66.02	-41.44	0	-45.90	-21.32
7	3	1	3	2	3000	100	500	197.35	69.54	-40.00	0	-45.90	-16.36
8	3	2	1	3	3000	118	100	310.47	69.54	-41.44	0	-49.84	-21.74
9	3	3	2	1	3000	135	300	84.23	69.54	-42.61	0	-38.51	-11.58

Note: Speed–S; point angle–PA; feed rate–FR; thrust force–TF; Smaller-the-better–STB; Larger-the-better–LTB; Nominal-the-best–NB. (Krishnamoorthy, 2011)

For the thrust force, two options are given. One is at level 1 and the other is at level 3 of the thrust force row in Table 1. Here the thrust force was obtained as 84.23 N at level 1 and 310.47 N at level 3. However, since the lower thrust force is desired to achieve the goal of the drilling economy, 84.23 N is accepted as the value to use in implementation. Furthermore, Table 3 provides the delta values used to rank the parameters and response. It was observed that the delta values ranged from 1.35 to 9.54 and the corresponding ranks to S, PA, FR, and TF are 1st for the spindle speed (S), 2nd for the thrust force (TF), and third for the point angle (PA) and feed rate (FR), respectively.

Table 3. Taguchi signal-to-noise ratio response table

Level	SP	PA	FR	TF
1	-26.10	-20.43*	-20.52	-14.19*
2	-20.08	-20.52	-21.78	-21.67
3	-16.56*	-21.78	-20.43*	-14.19*
Delta	9.54	1.35	1.35	7.48
Rank	1	3	3	2

3.2 Present worth analysis

Concerning the data, Equation 5 was translated as below:

$Ps = -26.10\ (1 + i)^{-n} - 20.08\ (1 + i)^{-n} - 16.56\ (1+i)^{-n}$

The value of i in the three terms is 12%, while n for the first, second and third terms are 1, 2, and 3 respectively. This translates the expression to $Ps = -26.10\ (1+0.12)^{-1} - 20.08\ (1+0.12)^{-2} - 16.56\ (1+0.12)^{-3}$ to yield $Ps = -26.10\ (0.8929) - 20.08\ (0.7972)\ - 16.56(0.7118) = -23.3047 - 16.0078 - 11.7874 = -51.0999$.

For the computation of PW_{PA}, the following expression was obtained:

$PW_{PA} = -20.43\ (1+0.12)^{-1} - 20.52\ (1+0.12)^{-2} - 20.52(0.7972) - 21.78\ (0.7118) = -50.1034$

Then, the PW_{FR} was computed as below:

$PW_{FR} = -20.52\ (1+0.12)^{-1} - 21.78\ (1+0.12)^{-2} - 20.43\ (1+0.12)^{-3} = -50.2274$

Furthermore, PW_{TF} was calculated as follows: $PW_{TF} = -14.19\ (1+0.12)^{-1} - 21.67\ (1+0.12)^{-2} - 14.19\ (1+0.12)^{-3} = -40.0460$. Consequently, the performance flow diagrams to obtain P_{WS}, PW_{PA}, PW_{FR}, and PW_{TF} are in Figures 1a, 1b, 1c, and 1d, respectively.

Using the logic applied to assess PW_S, the values of PW_{PA}, PW_{FR}, and PW_{TF} were calculated as 51.0999, -50.1034, -50.2274, and -40.0460, respectively. Table 4 shows the summary of results for the economic analysis using the present worth method. Since the ranking of the parameters is based on individual values, the first, second, third and fourth ranks are PW_{TF}, PW_S, PW_{PA}, and PW_{FR}, respectively.

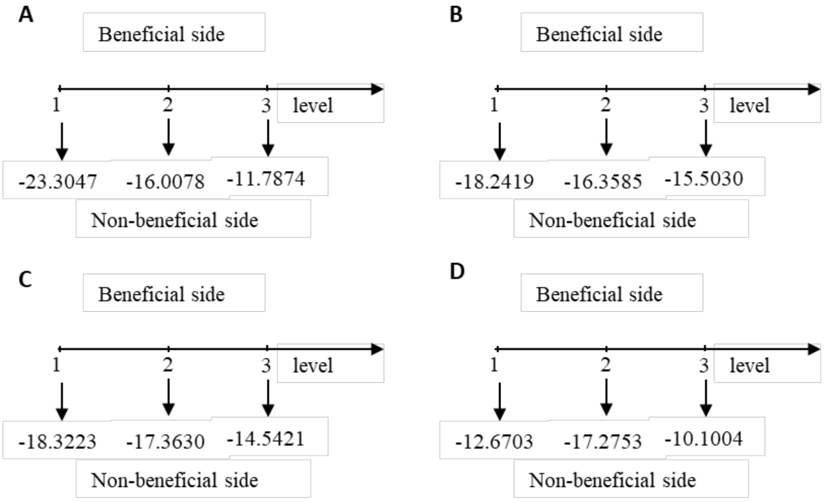

Figure 1. (A) T-PW method's performance flow for parameter S (spindle speed), (B) T-PW method's performance for parameter PA (point angle), (C) T-PW method's performance flow for parameter FR (feed rate), and (D) T-PW method's performance for parameter TF (thrust force)

Table 4. Present worth at optimal values of Taguchi method for a static situation

Description	PW_S	PW_{PA}	PW_{FR}	PW_{TF}
Value	-51.0999	-50.1034	-50.2274	-40.0460
Rank	2nd	3rd	4th	1st

This implies that thrust force is the most economically significant response parameter, whereas feed rate has the least economic impact.

3.3 Optimal combined Taguchi-present worth (*T-PW*) method

In a previous article, Oke and Fagbolagun (2020) defined the present worth method in terms of *L*, *i*, and *n*, which are the value of the parameter at a particular level, the interest rate and the level term, respectively. However, this formula does not give the optimal results. To overcome this shortcoming, the derivatives of the original equation proposed by Oke and Fagbolagun (2020), which is Equation 6 in this paper, was pursued. From calculus knowledge, it is known that derivatives give values at turning points which may be more than a turning point in this dulling situation. The derivatives yield the optimal values of L^*, i^*, and n^*, which should produce better overall PW^* results when the procedure for the computation of the PW^* in terms of optimal results is followed. From the knowledge of differential calculus, optimal results may be desired from the drilling data by using different mathematical functions, including the polynomial function, which may be in the power of 2 and higher orders. Furthermore, concerning the present worth derivatives, there are several parameters involved, including L, n, and I, which are the values at levels, number of levels and interest rates, respectively. Before applying the derivative formula, these parameters remained in their normal forms. However, as they are differentiated, optimal values of these parameters exist since they could be obtained at the turning points of the graph as L^*, n^*, and i^*, for optimal values at levels, number of levels and interest rates, respectively.

3.3.1 Optimal combined *T-PW* method using the polynomial form

The drilling parametric optimization cum economic issue assessment was accomplished by formulating the problem in a polynomial form. It was understood that by obtaining the derivatives of *PW*, the optimal values of all the parameters of the model would be obtained. This is done when the *PW* is differentiated with respect to *i* and also with respect to *n*, which are the interest rate and the level factor, respectively. The differentiation was done with respect to *i* and it is believed that there ought to be a minimum value of interest rate, i^*, that is most desirous by the machine shop administration. Also, differentiating with respect to n shows us the best level and optimal level. To analyze the present worth, a method using the dynamic combined *T-PW* method, Equation 6 is differentiated with respect to *i*:

$$\frac{dPW}{di} = nL(1+i)^{-(n+1)} \tag{6}$$

The formula was then applied to the CFRP composite drilling data obtainable from the single-to-noise ratio response table. As an example in the calculation, consider the spindle speed parametric value at level 1, which is -26.10. This means L = -26.10, n = 1, I = 12% = 0.12, and the application of Equation 6 yields 20.81. This value is the $PW(i)_{SP\text{-}1}$, which is the derivative of *PW* with respect to *i* for the parameter spindle speed and the first level. But the computation on the aspect of $PW(i)_{SP}$ should also include the performance flow diagram (Figure 2a, see also Figure 2b for $PW(i)_{PA}$). So, the values of $PW(i)_{SP}$ for levels 2 and 3 were determined as 28.59 and 31.57, respectively. The two aims of this section were to (i) obtain the $PW(i)$ values for all the parameters and responses, weigh them against one another and determine their positions from the first to the last, and (ii) decide if the optimization was effective by comparing the values obtained using Equation 5 and 6. For the computation of $PW(i)$, the following is used:

$PW(i)_{SP}$ = 20.81 (1 + 0.12)$^{-1}$ + 28.59 (1 + 0.12)$^{-2}$ + 31.57 (1 + 0.12)$^{-3}$ = 63.84.

Similar computations could be made for the point angle, feed rate and thrust force as follows:

$PW(i)_{PA}$ = 16.29 (1+0.12)$^{-1}$ + 29.21 (1 + 0.12)$^{-2}$ + 41.52 (1 + 0.12)$^{-3}$ = 67.38

$PW(i)_{FR}$ = 16.36 (1 + 0.12)$^{-1}$ + 31.01 (1+0.12)$^{-2}$ + 38.95 (1+0.12)$^{-3}$ = 67.05

$PW(i)_{TF}$ = 11.31 (1+0.12)$^{-1}$ + 30.85 (1 +0.12)$^{-2}$ + 27.05 (1 + 0.12)$^{-3}$ = 53.95

The performance flow diagram for the feed rate is shown in Figure 2c and the performance flow diagram for the thrust force response is shown in Figure 2d.

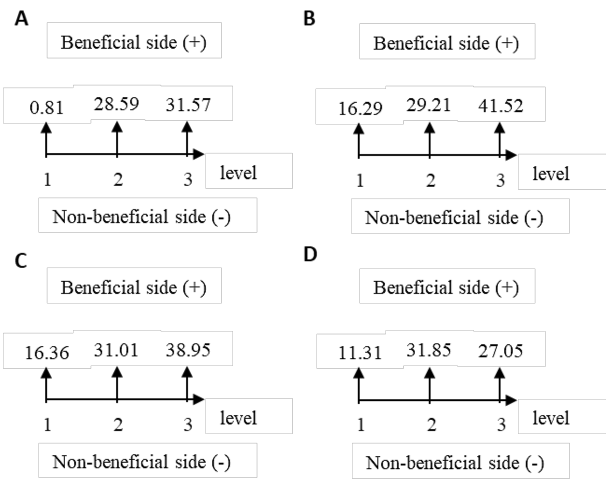

Figure 2. (A) T-PW method for SP using polynomial form, (B) T-PW method for PA using the polynomial form, (C) T-PW method for FR using the polynomial form, and (D) T-PW method for TF using the polynomial form

For the spindle speed, the $PW(i)$ obtained was 63.84. However, by extending the logic applied to assess the PW(i) for spindle speed to the point angle, feed rate and thrust force, the respective values obtained were 67.38, 67.05, and 53.95. Table 5 shows the summary of the results for all the parameters and responses at the optimal levels.

Since the ranking of the parameters and responses are based on individual values, the first second, third and fourth ranks are point angle, feed rate, spindle speed and thrust force, respectively. Surprisingly, there was a divergence of opinion on this result from the earlier one, which placed the thrust force as the most important response. Here, the choice is the point angle.

The implication of this is that the most economically strong parameter/response is the point angle while the thrust force is the least economically strong. Surprisingly, there is a contradiction in the results of the application of Oke and Fagbolagun's (2020) model and the optimized values where the derivative of PW with respect to was used to obtain optimal results. The question is how reliable is the optimal method shown in Equation 7. Hence, it is assumed that if Equation 7 is effective, it should increase the PW of each parameter/response when compared with Equation 6. In Oke and Fagbolagun (2020), the $PW(i)_{SP}$ gives a negative value, -51.0999 against 63.84 given by the optimized value at $PW(i)$ for the spindle speed. The difference is substantial, of at least 100 units. For the point angle parameter, feed rate and thrust force, gains of more than 100, 100 and 80 were revealed by the optimal results. So, in all cases, the optimal method showed better results and could be regarded as effective and recommended for use by process engineers in drilling machine shops. Furthermore, Equation 6 is differentiated with respect to n to obtain Equation 7.

$$\frac{dPW}{dn} = -(n(1+i)L(1+i)^{-n} \tag{7}$$

To give an example of its application to the CFRP composite drilling problem, consider the spindle speed at level 1, where i = 0.12, L = -26.10, then Equation 8 yields 2.64. By a similar approach, other values are obtained from levels 2 to 3 for spindle speed and levels 1, 2, and 3 for other parameters and the response, the thrust force. The results are displayed in Table 6.

Table 5. $PW(i)$ (optimal values) of the *T-PW* method for the polynomial form

Description	$PW(i)_{SP}$	$PW(i)_{PA}$	$PW(i)_{FR}$	$PW(i)_{TF}$
Value	63.84	67.38	67.05	53.95
Rank	3rd	1st	2nd	4th

Table 6. Dynamic combined Taguchi method-present worth method performance evaluation under polynomial functions

Level	Spindle speed			Point angle			Feed rate			Thrust force		
	SP	*PW(i)*	*PW(n)*	*PA*	*PW(i)*	*PW(n)*	*FR*	*PW(i)*	*PW(n)*	*TF*	*PW(i)*	*PW(n)*
1	-26.10	20.81	2.64**	-20.43	16.29	2.07**	-20.52	16.36	2.08**	-14.19	11.31	1.44
2	-20.08	28.59	1.81	-20.52	29.21	1.85	-21.78	31.01	1.97	-21.67	30.85*	1.96**
3	-16.56	31.57*	1.34	-21.78	41.52*	1.76	-20.43	38.95*	1.65	-14.19	27.05	1.14

Note: *Optimal setting (polynomial) for differential of PW with respect to i: $PW(i)_{SP3}PW(i)_{PA3}PW(i)_{FR3}PW(i)_{TF}$;
**Optimal setting (polynomial) for differential of PW with respect to n: $PW(n)_{SP1}$ $PW(n)_{PA1}PW(n)_{FR1}PW(n)_{TF2}$

3.3.2 Optimal combined Taguchi method-present worth method: Exponential form

To analyze the present worth method using the dynamic combined *T-PW* method of the exponential form, Equation 6 is differentiated but in exponential form as Equation 8:

$$\frac{dPW}{di} = \frac{d(e^{L(1+i)^{-n}}}{di} = \ln{(1+i)}^{-(n+1)e^{(1+i)^{n}}} \qquad (8)$$

As an example in the calculation, consider also the spindle speed, L = -26.10, n=1, i=12% = 0.12, PW = 1.718 x 10^{-11} and the value is recorded in Table 7. In a similar manner, the computed values of spindle speed for Levels 2 and 3, as well as those of point angle, feed rate, and thrust force across all three levels, are presented in Table 7. The findings of Okponyia and Oke (2020) who deployed the present worth performance flow diagram conclude that it is feasible to deploy the approach for quantitative tasks even though the application was on the electrical discharge machining. However, the application is different from drilling, which is the focus of the present work. The material used in the previous work was AA6061/10%Al_2O_3 AMMCs, but this is different from the CFRP which is tested in this work that has never been analyzed using the present worth method. Besides, Okponyia and Oke (2020) did not optimize the parameters treated in the work. The Taguchi method was deployed to analyze the problem in the current paper, which gives an opportunity to concurrently optimize the drilling parameters and develop economic parameters to quantify the performance of the system.

Table 7. *Dynamic* combined Taguchi method-present worth method performance evaluation under exponential functions

Level	Spindle speed			Point angle			Feed rate			Thrust force		
	SP	*PW(i)*	*PW(n)*	*PA*	*PW(i)*	*PW(n)*	*FR*	*PW(i)*	*PW(n)*	*TF*	*PW(i)*	*PW(n)*
1	-26.10	1.71695E-11	2.00055E-10	-20.43	2.71252E-09	2.47396E-08	-20.52	2.50308E-09	2.293E-08	-14.19	7.12876E-07	4.51594E-06
2	-20.08	3.79687E-08	2.02597E-07	-20.52	2.67356E-08*	1.45784E-07**	-21.78	9.79167E-09	5.66706E-08	-21.67	1.06891E-08	6.1552E-05
3	-16.56	3.44616E-06*	1.0155E-05**	-21.78	8.38914E-08	3.25133E-07	-20.43	2.19297E-07*	7.97236E-07**	-14.19	1.8619E-05*	4.70136E-05**

Note: *Optimal setting (exponential) for differential of *PW* with respect to *i*: $PW(i)_{SP3}PW(i)_{PA2}PW(i)_{FR3}PW(i)_{TF3}$;
**Optimal setting (exponential) for differential of *PW* with respect to *n*: $PW(n)_{SP3}PW(n)_{PR2}PW(n)_{FR3}PW(n)_{TF3}$

3.4 Validation of the results with literature data

In the present study, the authors deployed a new approach to concurrent optimization and economic consideration, referred to as the Taguchi method-present worth method. Here, the current authors first compared the results in terms of the grading of the present worth values of PW_S, PW_{PA}, PW_{FR} and PW_{TF}, representing the Taguchi method-present worth method outcomes for the spindle speed, point angle, feed rate and thrust force parameters/ response, respectively. Shunmugesh and Pratheesh (2020) were subjected to further optimization by using a new method that concurrently optimizes and prioritizes parameters, named the Taguchi–Pareto method. So, data from Shunmugesh and Pratheesh (2020) was used as the basis. The working principle of the Taguchi-Pareto method entails subjecting roughly 80% of the contribution to analysis such that the optimal parametric setting is determined only for parameters that come under 80% contribution. However, looking at Shunmugesh and Pratheesh (2020), only the speed parameter qualifies for analysis with a 79% contribution. Since analysis may not be conducted for the speed parameter alone, it is concluded that the *T-PW* method confirms that the spindle speed is the most important parameter in the drilling process of the CFRP composites. To assess the relative importance of the parameters, the present authors rigorously applied the proposed method to the dataset of Shunmugesh and Pratheesh (2020), aiming to verify whether spindle speed remains the most influential parameter. To achieve this goal, Equation 1 was applied and the relevant values were substituted into it:

$P_A = 8.578\ (1+i)^{-n} - 3.044\ (1+i)^{-n} - 3.047\ (1+i)^{-n}$

The first, second and third terms, n =1, 2, and 3, respectively, imply the levels of parameter A (spindle speed). This translates to $P_A = -8.578\ (1+i)^{-1} - 3.044\ (1+i)^{-2} - 3.047\ (1+i)^{-3}$ where i = 0.12, and P_A is given as -12.549. By following the procedure followed for P_A, the values of P_B could be obtained as -12.6356. Besides, P_C gives -12.7054. Consequently, the performance flow diagram to obtain PW_A, PW_B and PW_C are in Figures 3a, 3b, and 3c, respectively.

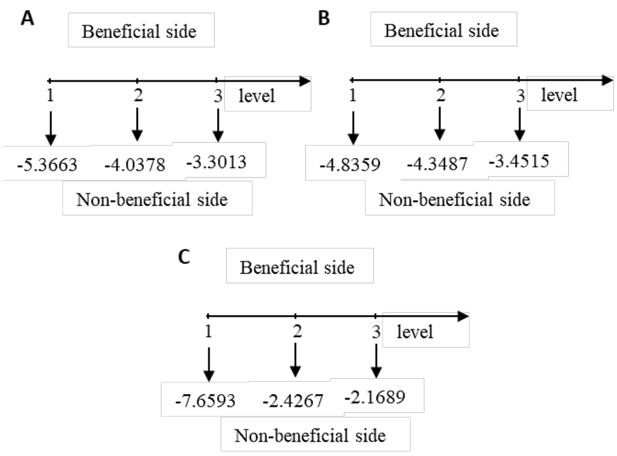

Figure 3. (A) T-PW method's performance flow for parameter A (Spindle Speed), (B) T-PW method's performance for parameter B (feed rate), (C) T-PW method's performance for parameter C (Drill Parameter)

Using the logic applied to evaluate the PW_A, PW_B, and PW_C, the calculated values deployed are -12.2549, -12.6356, and -12.7054, respectively. Table 8 shows the summary of results for the optimization cum economic analysis using the *T-PW* method. Since the ranking of the parameters is based on individual values, the first, second, and third ranks are PW_A, PW_B, and PW_C respectively. The implication of this is that the most economically strong parameter is the spindle speed.

Table 8. Present worth at optimal values of Taguchi method (validation)

Description	PW_A	PW_B	PW_C
Value	-12.2549	-12.6356	-12.7054
Rank	1st	2nd	3rd

3.5 Comparison of the present article with the literature

In comparison with Shunmugesh and Pratheesh (2020), some issues are interesting. While the present study focused on the combined *T-PW* method to optimize parameters/response Shunmugesh and Pratheesh (2020) examined the Taguchi grey relational analysis to optimize the CFRP composites, which is the material being drilled in the two cases. For the two cases, the first point of comparison is the results obtained using the Taguchi grey relational analysis in Shunmugesh and Pratheesh (2020) and compared with the Taguchi method in the present article. First, the present article chose the parameters of the drilling process as the spindle speed, feed rate and point angle while Shunmugesh and Pratheesh (2020) chose the spindle speed, feed rate and drill diameters as the drilling parameters so the spindle speed and feed rate are common to both and their results may be compared. The optimal parametric setting of $A_2B_3C_3$ indicates 4000 rpm of spindle speed, 30 mm/min of feed rate and 0.9 mm of drill diameter as the optimum. Whereas in the present study, the optimum parametric setting is $S_3PA_1FR_3$ indicating 300 rpm for the spindle speed, 100° for the point angle and 500 mm/min for the feed rate. Given that the spindle speed and the feed rate are common in both articles, the optimal spindle speed in the present study is lower by 1000 rpm compared to Shunmugesh and Pratheesh (2020). However, the feed rate in the present study is higher than that of Shunmugesh and Pratheesh (2020) by 470 mm/min. Since a lower speed is desired, the results obtained in the present study are preferred. For the feed rate, the nominal best criterion was pursued, which suggests that not too high or low a feed rate is desired. In that respect, Shunmugesh and Pratheesh (2020) yielded a better result. The differences in the results may be accounted for by considering the following issues. In the present article, a novel method that accounts for multiple criteria of the signal; to noise ratio is presented, which might have enhanced the results of the spindle speed. However, since the grey relational analysis was combined with the Taguchi method as Taguchi grey relational analysis in Shunmugesh and Pratheesh (2020), this might have enhanced the results obtained on the feed ratio.

Furthermore, in the present study, the spindle speed is considered as the first position with a delta value of 9.54 while the feed rate occupied the third position with a delta value of 1.35. Interestingly, Shunmugesh and Pratheesh (2020) concurred with these results as the authors also rated the spindle speed first with an extremely high delta value of 5.527 when compared with the third position of the feed rate with a low delta value of 0.606. Thus, the results imply that it is safe to rate the spindle speed as the just parameter in drilling operations decision. However, this suggestion is only limited to the report given by Shunmugesh and Pratheesh (2020) and the results obtained in the present study. Another aspect of comparison between the two studies is the outcome of the rating of the responses. In the present work, only delamination was considered from the list of responses reported by Shunmugesh and Pratheesh (2020), which included delamination, material removal rate, and tool wear rate. However, delamination was not given the first position in the AHP method's ranking.

Another interesting article to compare the current study with is Mercy et al. (2022), where the author considered the optimization features of machine parameters that impact the thrust force while drilling pineapple composites. In Mercy et al. (2022), the genetic algorithm was used for optimization. However, this was compared with the Taguchi method in this work. In Mercy et al. (2022), two of the parameters, namely spindle speed and feed rate are the same as those investigated in the present study while the third parameter in each case differs. According to Mercy et al. (2022), the drill diameter is important while the point angle is important to the current work. The spindle speed was chosen at three levels 1000, 2000, and 3000, which are the same in both studies. Though the feed rate was common to both studies, the levels of 100, 300, and 500 mm/min chosen for the present work (as given by Krishnamoorthy, 2011) is exclusively for the hard material, the CFRP composite. The three levels chosen in Mercy et al. (2022), 15, 20, and 25 mm/min are particularly for pineapple fiber composites, which are organic-based and not hard.

As expected, for organic material reinforced composites, the thrust force associated with the drilling of pineapple ranged between 16.12 and 17.7 N, as given by the highest and lowest genetic algorithm results. This could be compared with the value of 84.23 N that the present study yielded based on the Taguchi results. Understandably, the value for the thrust force using Taguchi exceeds that of Mercy et al. (2022) by roughly 66.53 N because the hard material. Furthermore, in the present study, the Taguchi method yielded the optimal parametric setting of 3000 rpm for the spindle speed, 100° for the point angle and 500 mm/min for the feed rate. Out of these three parameters, the spindle speed and the feed rate can be compared with the values generated by the genetic algorithm of Mercy et al. (2022). For Mercy et al. (2022), the lowest and highest spindle speeds were 2993 and 2830 rpm against the current paper's declared value of 3000 rpm. These values are comparatively close. For the feed rate, Mercy et al. (2022) declared 15 mm/min as against the present paper's Taguchi output of 500 mm/min for the hard CFRP composite.

3.6 Implications, limitations and future studies

This study's outcomes offer several important implications for managers of drilling organizations. First, this study shows that inflation and interest rates affect the present worth of the organization. As such managers are expected to change the present orientation of workers from technical issues alone to incorporating economic issues into technical issues to have a global perspective in the management of drilling operations. Consequently, managers need to be aware of the dynamics of inflation and interest rates, and diffuse information to the operations flow so that operators can take advantage of it. Moreover, if the two factors reduce to the benefit of the company, the workers may still be encouraged to maintain that level of performance for productivity gains and incentive recognition by the management. Meanwhile, the process engineer, in a quest to improve the drilling process, can practically apply this research by first conducting a company-wide campaign on the need to improve operational performance, expanding the scope of measurement conducted in the plant. Then, the operators could be given two-week on-the-job training on the fundamentals of the Taguchi method and economic parameters, which should be limited to inflation and interest rates. After this, measures of parameters could be displayed on a board on the factory floor. The optimized values of parameters should be presented together with the economic parameters. These would be displayed on the board weekly and the performance of the crew measured. The compilation of this performance of the workers would show the production capacity of the workers, which can be aggregated for budgetary planning.

Furthermore, despite extending the frontier of knowledge on drilling, this study has many important limitations that offer scope for future investigations. This study's findings are based on the present worth alone. However, present worth, future worth and annual worth are interchangeable in engineering economics study. To be able to plan effectively for drilling operations in annual plans organized by companies once or twice a year, analysis from the annual worth perspective may be worthwhile. Also, for future investments or expansion activities in drilling, the future work perspective may be suitable. Moreover, since the study relies on only two economic indicators vis-à-vis interest and inflation rates, additional indicators such as cost indicators involving the number of rejects over periods and claims on drilled product rejects may be fused to the two indicators used in this study. Our study examines parameters limited to spindle speed, point angle and feed rate while the response is the thrust force. However, other studies in the literature have suggested additional parameters of the drilling process. These include the depth of the hole, diameter of the core bit, coolant properties, vibration and tolerance of holes. Responses could extend to vibration, and wear. By treating these parameters and responses in the context of optimization, economic indicators and cost indicators, a wide variety of new knowledge will be added to the literature. Next, extensive testing may be done under different optimization techniques apart from the Taguchi method. Thus, the wide variety of non-conventional optimization methods such as particle swarm optimization, genetic algorithm and ant colony optimization might provide a good platform for testing the ideas presented in this study.

4. CONCLUSION

Analysis was conducted on experimental data from the literature (Krishnamoorthy, 2011) to study the feasibility of using a newly proposed optimal combined Taguchi method-present worth method on the CFRP composite while undergoing drilling operation. The drilling parameters used were the spindle speed (rpm), point angle (in degrees), and feed rate (mm/min) while the thrust force (N) was the response from the drilling process. Following the analysis using the data from Krishnamoorthy (2011), the findings and conclusions observed are stated herein:

1) The optimal combined *T-PW* method improved the present worth value (polynomial form) of both the parameters (speed, point angle, and feed rate) and response (thrust force) in drilling CFRP composites, yielding optimal $PW(i)_{SP}$, $PW(i)_{PA}$, $PW(i)_{FR}$, and $PW(i)_{TF}$ as well as optimal $PW(n)_{SP}$, $PW(n)_{PA}$, $PW(n)_{FR}$, and $PW(n)_{TF}$.
2) Among the four parameters/responses, the $PW(i)_{PA}$ produced the best performance compared with all other parameters/responses of the drilling operation.
3) The optimal results using the derivatives were compared with those of experimental results and the one achieved by the Taguchi method. The optimal parametric setting by the Taguchi method is $SP_3PA_1FR_3TF_1/TF_3$ matched against the optional result of $PW(i)_{SP3}PW(i)_{PA3}PW(i)_{FR3}PW(i)_{TF2}$ for the present worth derivative with respect to *i*.
4) The optimal results of $PW(n)_{SP1}PW(n)_{PA3}PW(n)_{FR1}$ $PW(n)_{TF2}$, which is the present worth derivative with respect to *n* were obtained.
5) The interpretation from the experimental results provided by Krishnamoorthy (2011), the Taguchi method yielded 3000 rpm (speed), 1000° (point angle), 500 mm/min (feed rate) and 84.23 N (thrust force). However, the optimal results for the present worth derivative with respect to *i* are interpreted as 3000 rpm (speed), 1350° (point angle), 500 mm/min (feed rate) and 197.35 N (thrust force). Furthermore, when Oke and Fagbolagun's (2020) model was deployed, the positions of the parameters/response with respect to the *T-PW* method's evaluation is the thrust force (1st, -40.0460), spindle speed (2nd, -51.0999), point angle (3rd, -50.1034) and feed rate (4th, -50.2274). However, when the *T-PW* model was optimized with the polynomial function, the results changed to point angle (1st, 67.38), feed rate (2nd, 67.050, spindle speed (3rd, 63.84) and thrust force (4th, 53.95).

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