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Application of entropy weighted multivariate loss function for control of process parameters during drilling hybrid composites

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Abstract. Composites are now being used to replace traditional metallic structures in a variety of industries that including aerospace, aircraft, and military, that demand structural materials of high stiffness-to-weight and strength-to-weight ratios. This work is aimed at investigation on drilling process parameters of a hybrid composite. A hybrid composite is prepared with Epoxy as matrix with Jute and Glass fibre reinforced material. It is attempted to investigate the delamination tendency of hybrid composite along with optimization of drilling parameters. The two parameters considered are speed and feed rate. Each of this is considered at 3 levels. Response characteristics are thrust force, torque, delamination factor. L9 orthogonal array will be considered for experimentation. Standard Analysis is performed to discriminate significant and insignificant factors. Optimized process parameters are obtained for each of response characteristics. The objective is to optimize drilling process parameters of a hybrid compositeTaguchi's L9 3-level orthogonal array was employed in this work. Entropy weighted multivariate loss function optimizes the multi-responses with a single desired response for drilled hybrid composites at the common factor level. Spindle speed and feed rate operate as control elements, the responses are dependent on torque, thrust force, and delamination. Medium spindle speeds with smaller feed rates enhance drilling success, according to the findings. The results also showed that spindle speed has a higher influence on the quality of holes drilled.

1 Introduction

Composite materials are commonly used by designers in automotive, aerospace, defence industries because of the properties like lightweight, high stiffness, and strength [1]. These materials' inherent qualities, including restricted heat conductivity, high heterogeneity, abrasive structure, and heat sensitivity, make them challenging to treat. These materials

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exhibit various flaws during machining such as deboning, matrix cracking, and delamination [2]. Researchers studying GFRP composite drilling have focused on the impact of thrust force on machining flaws, particularly delamination. Khashaba et al. [3] studied how machining conditions affect delamination and thrust force in GFRP composite laminates, utilising both empirical and analytical methods. Kumar et al. [4] reduce the need of fabricating glass strands with fusing typical jute filaments at the point where the resultant distinctive composite exhibits increased quality when compared to carbon or glass strand fortifications. Velu and collegues [5] investigated whether the composite made by jute-glass-epoxy improves significantly in tensile, bending, and impact strength when the jute concentration weight fraction increased. Bisaria and collegues [6] reported that the flexural, and ductile properties were significant for the jute fiber strengthening. Sridharan et al. [7] found that while drilling with jute-fiber (untreated) strengthened having epoxy matrix composites. They found the suitable feed rates, cutting velocity for both leave and passage regions are 0.03 mm/rev, and 9.42 m/min. GRA was used to identify the best cutting settings in terms of feed and speed, as well as statistical analysis for identification of most compelling influence on fiber pullout.

Sathyanarayana et al. [8] done experiments on hybrid composite materials and assessed delamination under various operating circumstances. 20 mm/min feed and 795 rpm speed yielded the lower delamination results. The factorial design, ANOVA were utilized for optimisation of the drilling settings. Their ANOVA findings showed that speed was the significant effect on delamination. Recent research explored the machining characteristics of composites that reinforced using jute and glass fibers. Machinability of cotton fiber and jute fiber reinforced composites of varying proportions [9].

Researchers have been simultaneously optimising the processing parameters for multi responses such as delamination, thrust force, dimensional errors, and surface finish while drilling GFRP and hybrid composite laminates by using various multi response optimisation techniques [10-13]. Shanmugam et al [14] done a recent investigation on drilling a hybrid composite made using redmud to be filler, sisal fiber as a reinforcement and discovered that at the drilling cycle starting, its cutting edges were actively removing material, so the thrust force suddenly reached its maximum. The resultant thrust increased proportionally to the spindle speed and feed rate.

Grey Relational Analysis reduces ambiguity in processes of decision-making by quantifying the link between several aspects. GRA is very beneficial for dealing when limited sample numbers. It is useful in instances when there is insufficient knowledge on the variables being studied. The TOPSIS is one of the MCDM technique that ranks alternatives according to their proximity to the ideal answer. It entails measuring the distances among every alternative, either the solution of positive-ideal or negative-ideal. The alternative featuring the closest distance from the PIS with the greatest distance towards the NIS is deemed the best. The TOPSIS technique has various advantages, including simplicity, quick implementation, and the capacity to handle both qualitative and quantitative requirements. It also gives a clear rating of alternatives according to their proximity near the best solution. On the other hand, a multivariate loss function measures error or loss across several criteria at the same time, treating the decision issue as a combined optimization rather than a collection of distinct single-criterion problems. This produces richer and more reliable decision support in MCDM scenarios.

The full consistency technique (FUCOM) is one of the MCDM technique that uses the comparison (pairwise) and variation from the maximum consistency ideas. The FUCOM weighting technique produces more reliable findings than other methodologies since it employs the fewest possible comparisons according to its theory. The most fundamental drawback of FUCOM is being identified as its subjectivity. Another subjective weighing method known as Level-based weight-assessment was proposed as one of the ways out for comparison (pairwise) issues. Unlike the subjective approaches described above, objective methods are free of any starting information or judgment provided by decision-makers instead, they simply examine the data accessible for establishing the weightages. The above-mentioned strategies are familiar for reducing any potential bias related to subjective evaluation, therefore boosting objectivity. The Entropy Weight approach (EWM) is an extremely effective approach for analyzing weights. It has been demonstrated to be adequate in identifying both the combined contrasting intensity, deviation of responses, opposed to incorrectly allocating weightages.

According to the literature there has been a limited amount of study on the optimisation of control factors with machining characteristics such as torque, thrust force, and delamination factor while drilling of hybrid composites utilising multi variate loss function. As a result, the current study focusses on the drilling of holes, with feed and speed as process parameters. This study took into account performance factors like torque, thrust force, and delamination. The Taguchi technique, which is cost-effective, is used to optimise individual attributes, however it was shown to be ineffective when many responses with inconsistent goals were evaluated. In this work, a multi-variate loss function is utilised to obtain a single response from various performance characteristics then optimise the process parameters while drilling hybrid composite laminates.

2 Experimentation

In this work, hybrid composite (60% Matrix + 30% Jute + 10% Glass Fibre laminates arranged symmetrically in the [0, 90] form was used. E-Glass fibres and Jute fibres were employed, and the resin applied was grade L-12 using K-6 hardener. The thickness measured is 6 mm. This hybrid composite laminate was then cut in to the size (250 x 40 x 4 mm^3). Drilling studies on hybrid laminates were done using a diamond-coated 10 mm twist drill, as described by Taguchi's 9 orthogonal array. For general use drills, a minimum speed of is suggested for drilling hybrid composites. This study optimises spindle speeds between 500-2000 rpm for the specified material. Feed rates are determined accordingly as given in Table 1. All experiments were done on a radial drilling machine. To limit experimental error, each experiment was repeated twice.

Table 1. Drilling parameters with the levels.

Levels	**Feed [mm/rev]**	**Speed [rpm]**
1	0.032	560
2	0.05	1120
3	0.08	1800

This investigation used digital image processing techniques to identify exit delamination. The amount of delamination was assessed by scanning these drilled holes with a scanner with a resolution of 1200dpi. The scanned photos were loaded into the image editing software Image J. An image of acceptable quality necessitates careful selection of numerous parameters, which are discussed in greater depth in [15]. The key parameters are brightness intensity, image improvement, noise reduction, and edge detection. The processed image is then transformed to a binary image, with delaminated areas represented by white pixels and non-delaminated areas by black pixels. The number of white pixels is counted to determine the delamination area using Image J analysis software. The current study uses Babu et al.'s [15] effective equivalent delamination factor approach to determine the delamination damage severity at the hole's exit and detailed equations used in assessing delamination could be found in [15].

3 Methodology

3.1 Muti-variate loss function

Quality functions are essential for assurance of quality and should effectively measure product quality. Artiles-Leon, Ma, and Zhao suggested a multivariate loss function, which was later enhanced in two ways to make it more acceptable for real-world applications. The majority of performance features will be of the "nominal best" (N-type), which means that each feature may have optimal value according to the customer's perspective. The loss generally related to square of deviated value from the goal value for quality. Taguchi devised a quadratic loss for estimating quality.

$$\boldsymbol{Loss\ (y) = k(y-t)^2} \tag{1}$$

y = product's quality feature, t = goal value of x which is the quality feature, and quality loss coefficient is k. k value must be calculated in such a way that the formula aforementioned can accurately represent the real economic loss in the interested region. To ensure the loss may not be unaffected by the unit technique utilised for determining the performance features, Artiles-Leon applied a symmetric loss function where the targeted value is at central location of these requirements and then loss function equals unity whenever possible. So, the k value turns into:

$$\boldsymbol{k = \left(\frac{2}{USL-LSL}\right)^2} \tag{2}$$

On substitution in the Eq. (1), then loss functional value may be:

$$\boldsymbol{L(y) = 4\ \left(\frac{y(x)-t}{USL-LSL}\right)^2} \tag{3}$$

here USL= upper specified limit, and LSL= lower specified limit. Artiles-Leon determined the maximum standard loss function as TS Loss, which corresponds to quality features Y_1, Y_2, Y_n. This function is dimensionless and can be applied to multiple quality characteristics if their values are uncorrelated.

$$\boldsymbol{TS\ Loss(Y_1, Y_2, Y_3, \ldots\ldots, Y_n, X, T\ ) = 4\ \sum_{i=1}^{n}\left(\frac{y_i(X)-t_i}{USL_i-LSL_i}\right)^2} \tag{4}$$

In this equation, ti, USLi, and LSLi represent the targeted value, upper specified limit, lower specified limits of the i^{th} quality feature Yi, that is determined by designed variables of X. The loss value in the Eq. (3) offers a feasible solution for multi-criteria issues. Some of its shortcomings must be addressed. On one side, the characteristic features of "smaller the better" and "larger the better" are unacceptable. However, the association between replies is not examined. Modifications are necessary to address real-world concerns.

3.2 Enhancement of loss function of artiles-leon for all the quality characteristics

Zhao and Ma [14] devised an enhancement multi-variate loss function strategy for grading quality features as "larger the better", type-L, "smaller the better", type-S, or "nominal the best", type-N. Determine the least acceptable quantity for a type-L feature Yi, then greater value above that no further improvement is possible in the product efficiency. Then loss functional value for the L-type feature may be stated as below:

$$L(Y_i(X), X, Y_{Ui}) = \left[\frac{Y_i(X) - Y_{Ui}}{Y_{Ui} - Y_{Li}}\right]^2 \tag{5}$$

Similarly, for *S*-type feature, the loss functional value may be shown as follows:

$$L(Y_i(X), X, Y_{Li}) = \left[\frac{Y_i(X) - Y_{Li}}{Y_{Ui} - Y_{Li}}\right]^2 \tag{6}$$

Thus, the Artiles-Leon's loss function (extended version) is given as,

$$L(Y_i(X), X,) = \sum_{i\varepsilon N} 4 \left[\frac{Y_i(X) - t_i}{USL_i - LSL_i}\right]^2 + \sum_{j\varepsilon L} \left[\frac{Y_j(X) - Y_{Uj}}{Y_{Uj} - Y_{Lj}}\right]^2 + \sum_{l\varepsilon S} \left[\frac{Y_l(X) - Y_{Ul}}{Y_{Ul} - Y_{L;}}\right]^2 \tag{7}$$

where S, *N*, and *L are* the values of *S*-type, *N*-type and *L*-type characteristics of the quality.

3.3 Artiles-leon's loss function (improved) of entropy weighted

When for multi-responses, not all responses have equal impact on product performance and quality. Higher weights will be assigned to more desirable response. Using the criteria weightages, the loss function may be changed as,

$$\textit{Total Loss}\ (, Y_i(X_2), Y_i(X_3), \ldots., Y_i(X_n)) = \sum_{i\varepsilon N} w_i\, Y_i(X_1) \tag{8}$$

where *wj* is the weight of *j*th response. The summation of all *wj*s = 1. For a better performance, the total loss value must be the lowest.

3.4 Entropy method

Shanon and Weaver developed this method in 1947, Zeleney modified the same in 1982 for computing objective weightages for every response. Entropy measures the degree of uncertainty in data. The entropy values for each response are then calculated (9).

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} P_{ij}\ lm\ P_{ij} \tag{9}$$

$$P_{ij} = \frac{y_{ij}}{\sum_{i=1}^{m} y_{ij}} \tag{10}$$

Here, and m is the total no. of tests conducted. In this study, m = 9. The performance response increases or decreases with the entropy (e_j). The individual weights can be calculated with Equation (11).

$$w_j = \frac{(1 - e_j)}{\sum_{i=1}^{m} (1 - e_j)} \tag{11}$$

The calculated normalized, P_{ij}, and P_{ij} ln P_{ij} values for all responses are given in the Table.2 Utilising these numbers, the entropy, weightages are determined for all responses utilising Eq. (10) and (11), respectively. These values are given in the Table 3. The complete methodology utilised in this work is given in Figure 1.

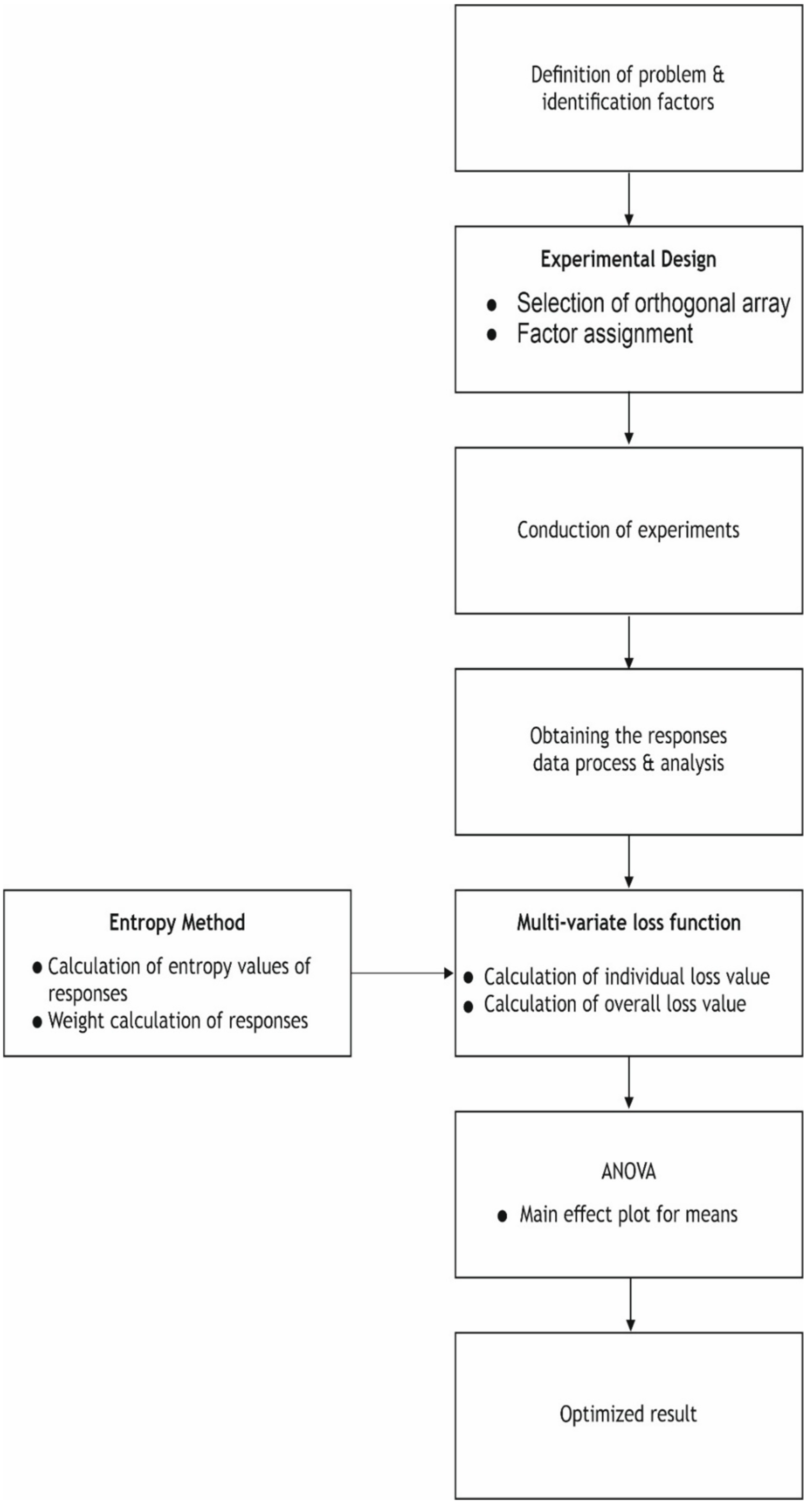

Fig. 1. Methodology utilised in the present work.

4 Results and discussions

The experimental results of delamination factor, torque, and thrust were noted for the experiment conditions as shown the Table 1 are shown in Table.2.

Table 2. Experimental values of the responses.

Exp. No	Speed, rpm	Feed, mm/min	Experimental results of		
			Torque (A)	Thrust force (B)	Delamination Factor (C)
1	560	0.032	0.04	0.4	1.36
2	560	0.05	0.029	0.12	1.45
3	560	0.08	0.025	0.13	1.5
4	1120	0.032	0.028	0.14	1.28
5	1120	0.05	0.038	0.11	1.38
6	1120	0.08	0.031	0.08	1.45
7	1800	0.032	0.034	0.06	1.22
8	1800	0.05	0.1	0.1	1.31
9	1800	0.08	0.02	0.77	1.16

The calculated normalized, Pij, and Pij ln Pij values for all responses as given in the Table.2 is represented in the Table.3. Utilising these numbers, the entropy and weightages are determined for all responses utilising Eq. (10) and Eq. (11). These values acquired are shown in the Table 4. It can be noted that with small feed, the drill bit's resistance to the hybrid composite materials in the direction of feed is relatively low, resulting in less friction and a reduction in torque and thrust. However, as the feed rate rises, the area of the shear plane widens, producing thrust and torque. This will result in significant damage around the hole within the hybrid composite. The results show that the delamination factor was low at 1120 rpm, but there is a rapid increase in delamination about 1800 rpm compared to the expected lesser value. This could be owing to the fact when speed rises at low feed rates, the heat generated and accumulated at the drilling zone causes severe softening in the matrix & fiber. As a result, fiber machining becomes harsher on the machining edges, increasing delamination damage.

Table 3. Normalized, $\boldsymbol{P_{ij}},\ \boldsymbol{and\ P_{ij}\ \ln P_{ij}}$ values for responses.

Ex. No.	Normalized			P_{ij}			$P_{ij}\ln P_{ij}$		
	A	B	C	A	B	C	A	B	C
1	0.250	0.479	0.690	0.121	0.248	0.120	-0.256	-0.346	-0.254
2	0.113	0.085	1.000	0.055	0.044	0.174	-0.159	-0.137	-0.304
3	0.063	0.099	1.172	0.030	0.051	0.204	-0.106	-0.152	-0.324
4	0.100	0.113	0.414	0.048	0.058	0.072	-0.147	-0.166	-0.189
5	0.225	0.070	0.759	0.109	0.036	0.132	-0.242	-0.121	-0.267
6	0.138	0.028	1.000	0.067	0.015	0.174	-0.181	-0.062	-0.304
7	0.175	0.000	0.207	0.085	0.000	0.036	-0.209	0.000	-0.119
8	1.000	0.056	0.517	0.485	0.029	0.090	-0.351	-0.103	-0.216
9	0.000	1.000	0.000	0.000	0.518	0.000	0.000	-0.341	0.000
Sum of $\sum_{i=1}^{m} P_{ij}\ln P_{ij}$							-1.650	-1.427	

Response A entropy value is,

$$e_j = -\frac{1}{lnm}\sum_{i=1}^{m} P_{ij}\ln P_{ij} = -\frac{1}{ln9}(-1.650) = 0.751$$

Table 4. Weights of all three responses utilising entropy method.

Response	e_j	$(1 - e_j)$	w_j
A	0.751	0.249	0.36
B	0.649	0.351	0.50
C	0.899	0.101	0.14
Sum		0.701	1

In this study all the responses, thrust force, torque and delamination should be lower for better drilling performance hence Eq. (6) was used. Individual loss values and total loss considering the entropy weights and ranking is shown in Table.5

Table 5. Individual loss, total loss and ranking of the experiments.

Exp. No	Speed, rpm	Feed, mm/min	Individual loss value			Total loss Value	Rank
			Torque (A)	Thrust force (B)	Delamination Factor (C)		
1	560	0.032	0.023	0.109	0.038	0.169	5.5
2	560	0.05	0.081	0.004	0.069	0.154	4
3	560	0.08	0.051	0.006	0.090	0.146	3
4	1120	0.032	0.073	0.007	0.018	0.098	1
5	1120	0.05	0.176	0.003	0.044	0.224	8
6	1120	0.08	0.099	0.001	0.069	0.169	5.5
7	1800	0.032	0.130	0.000	0.008	0.138	2
8	1800	0.05	0.176	0.002	0.025	0.203	7
9	1800	0.08	0.203	0.461	0.002	0.665	9

Figure 2 shows the main effect plots for the means, as all the responses small the better characteristics. Figure 1 shows that speed of 1120 rpm, feed of 0.032 mm/min are the optimum condition for the multi-performance optimisation of drilling parameters. Table.6 shows ANOVA for multi-variate loss which shows spindle speed has more influence than feed rate.

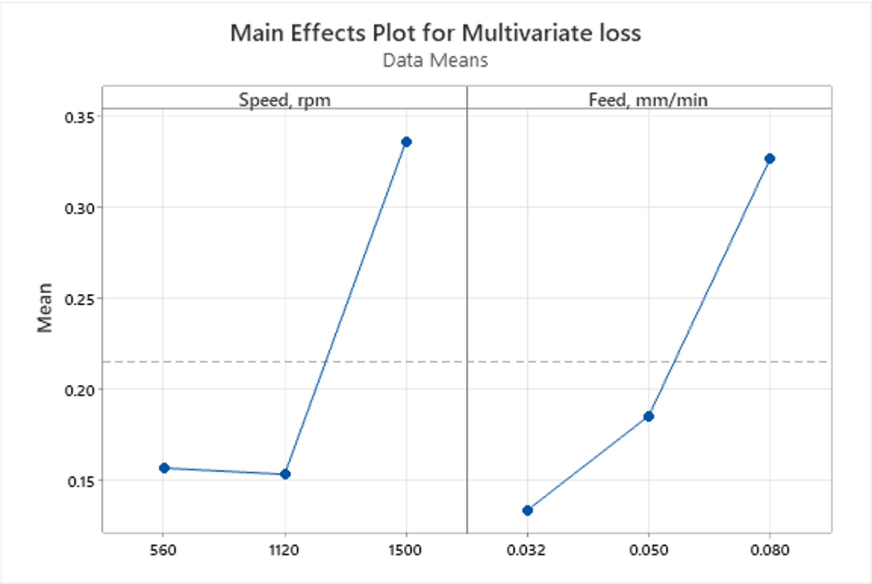

Fig. 2. Main effects graph for multi-variate loss.

Table 6. Analysis of variance of multi-variate loss.

Source	DF	SS	MS	F	% of C
S	2	0.9881	0.4040	1.42	39.86
F	2	0.7310	0.2655	0.93	29.49
Error	4	0.7595	0.2849		30.65
Total	8	2.4786			100

From the Table 6, it can be noticed that the parentage of contribution of spindle speed on drilling performance is about 40, whereas the same for feed and error are about 30. This shows spindle speed is the most influencing factor for drilling performance for minimising the responses like torque, thrust force and delamination simultaneously. Limited number of factors with only three levels may be reason for higher percentage of error's contribution. Future study can be focused on including the greater number of factors such as drill diameter, geometry and even materials and with a greater number of levels for minimising the error contribution and increasing the accuracy of the results.

In this investigation, the thrust force has obtained greatest weight (0.5). As a result, it has the potential to influence other responses. According to the research, tiny changes in the proportion of weight result in significant changes on the final ranking. The sensitivity analysis may thus provide additional insight into the causes for changes in the ranks and effective application of weightages. To demonstrate the sensitivity analysis, the influence of a small increase in value from 0.1 to 0.9 on thrust force was evaluated, as shown in Table 7. The ranking of the experimental trials with varying weightage of thrust force from 0.1 to 0.9 and corresponding changed weightages of torque and delamination factor are calculated and shown in the Table 8. However, the weightages 0.8 and 0.9 are given to the thrust force and the corresponding weightages for delamination factor are negative and hence not considered for ranking analysis.

Table 7. Responses with changing of weights.

Response	Weightages values								
Torque	0.36	0.56	0.51	0.46	0.41	0.31	0.26	0.25	0,2
Thrust force*	**0.5 (normal)**	**0.1**	**0.2**	**0.3**	**0.4**	**0.6**	**0.7**	**0.8**	**0.9**
Delamination	0.14	0.34	0.29	0.24	0.19	0.09	0.04	**-0.05**	**-0.1**
Total	1	1	1	1	1	1	1	1	1

Table 8. Ranking for the experiments by sensitivity analysis when weightage of thrust force varies from 0.1 to 0.7.

Ex. No	**Weightage values of responses for sensitivity analysis with ranks of experiments**						
	0.1	**0.2**	**0.3**	**0.4**	**0.5 (normal)**	**0.6**	**0.7**
1	2	2	2	3	5.5	8	8
2	3	4	5	5	4	4	3
3	5	5	4	4	3	2	2
4	1	1	1	1	1	1	1
5	6	7	7	7	8	6	6
6	7	6	6	6	5.5	5	4
7	4	3	3	2	2	3	5
8	8	8	8	8	7	7	7
9	9	9	9	9	9	9	9

*For 0.8 and 0.9, the weightage of delamination will be negative and hence not considered

5 Conclusions

This work presents the optimization of control parameters during drilling Hybrid (jute and GFRP) composite using entropy-based multi-variate loss function approach. Feeds and speeds are two of the process variables that were tested in this experiment and the performance attributes or responses like torque, thrust force, and delamination were considered. All of the drilled hybrid composites' responses were transformed to single total multi-variate loss, which then optimized with the common input factor levels. The speed at 1120 rpm with 0.032 mm/min feed were found to be the ideal combination of control factor for drilling for least torque, thrust force, and delamination. Spindle speed was found to have a considerable effect on the drilling performance compared to the feed rate. Contribution of error can be minimized by considering a greater number of levels of input factors can be studied in the future. Sensitivity analysis concluded that changes in weightages of the responses changed the ranking of most of the experimental trials, however the first and last ranked trials remained same in the present investigation.

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