THIS FILE IS UNDER FORMATTIUNG AS THE PDF IS READY FILE WILL BE REPLACED

# Dynamic Performance Enhancement Of Polymer Composites Through Meta heuristic Machining Optimization

**Jai Rajesh.P**[1] **, V.Balambica**[2] **, M.Achudhan**[3]
[1]Research Scholar, Department of Mechatronics, Bharath Institute of Higher Education and Research, Selaiyur, Chennai-126, Tamil Nadu, India.
[2]Professor, Department of Mechanical, Bharath Institute of Higher Education and Research, Selaiyur, Chennai-126, Tamil Nadu, India.
[3]Associate Professor, Department of Mechanical, Bharath Institute of Higher Education and Research, Selaiyur, Chennai-126, Tamil Nadu, India.

## *Abstract*

*This work aims to provide an optimization of meta-heuristic algorithms in order to improve the dynamic behavior of composite materials utilized in various practical engineering tasks. Based on the Comprehensive literature review it has been observed that composite sandwich panels with PVC foam cores accomplished mechanical characteristics superior than those ones that were produced on PU foam core mainly in flexural, compression, and impact tests Thus the study establishes the basis of the current work on the best possible machining parameters for PVC foam so as to boost its mechanical properties. The results of testing PVC foam using mechanical tests showed higher values for flexural strength, compression strength, and impact resistance of PVC over that of PU foams. On the other hand, the random forest regression had the best fitting models for machining parameters, with its unbiased mean squared error (MSE) and the highest R2 (coefficient of determination) of all the algorithms. Along with the meta heuristic algorithms like Particle Swarm Optimization (PSO), Firefly Algorithm, Cuckoo Search, Grey Wolf Optimizer (GWO), Multi Objective Teaching Learning based Optimization Algorithm (MOTLBO), and Salp Swarm Algorithm that were used to optimize machining parameters, the GWO (Grey Wolf Optimizer) method appeared to have the best results. The uniqueness of this research is due to the advent of its holistic strategy which integrate data obtained from the earlier works and experimental study to arrive at the machining parameters for PVC foam. Through the application of the advanced regression analysis methods and meta heuristic optimization algorithms, the study achieves a great impact on the predictive effectiveness and efficiency of the composite materials dynamics optimization, resulting in a more effective improvement of the dynamic performance. The main aim of this research work is the promotion of composite material design techniques by offering practical guidelines and approaches for dynamic performance superiority which also enable the manufacturing of the lightest and sturdy with the highest performance engineering materials.*

***Keywords:*** *Composite materials, Meta heuristic algorithms, PVC foam, Polyurethane foam, Machining parameters, Random forest, Grey Wolf Optimizer, Optimization, Engineering materials*

****Author for Correspondence*** **Name: Jai Rajesh.P***

## INTRODUCTION

Composite sandwich panels that carry lightweight cores sandwiched between face sheets which are rigid, are popular in many industrial sectors because of their good load-carrying capacity per unit weight, excellent thermal characteristics, and adaptation. These panels find use in aerospace, automotive, maritime, construction, and many other industries. The base material that is at the center of the sandwich panels highly determines the mechanical properties and the performance of the panels.

Polyurethane (PU) and poly (vinyl chloride) (PVC) foam are the two prevalent core materials applied in the sandwich panels. Although these sandwich panels have a wide utilization, they do have issues in areas of resilience, durability, and manufacturing inefficiency. Reaching the challenge of improving sandwich panel performance is the research object which plays a great role in different applications. Researches conducted on sandwich panel behavior explored different features, such as energy absorption, bending, shear properties, mechanical deterioration, and the environmental influence. Taghizadeh and his associates (2019) signaled the outstanding features of specific composite sandwich panels with particular geometries that help absorb energy. While their investigation did not exhaustively examine the effect of dynamic loading conditions and failure modes relating to flaws in the core geometry for use-specific applications[1], they did obtain interesting results and identified areas that require additional investigation. Samali et al. (2019) conducted a wide research which everyone can agree with, pertaining both to the behaviour of polyurethane foam-filled composite panels and energy absorption. Nevertheless, they had a serious limitation as they were not able to conduct a detailed analysis on the materials used and the actual production processes[2]. Osa-Uwagboe et al. (2023) in their study paper mechanical behavior of fabric-reinforced plastic sandwich structures offered in-depth focused view of structural performance and environmental degradation but dealt with minimal material compositions and practical implementations[3]. The authors of He et al. (2018) focused on the oxidative degradation of PVC foam sandwich components immersed into seawater, detected a notable decrease in foam properties during the 90 days of immersion. However, their research didn't investigate whether the effects could persist over time, or if other environmental systems were also affected[4]. Garrido et al. (2014) looked at the creep performance of sandwich panels with polyurethane foam core and glass-fiber reinforced polymer faces, and also proposed a creep model for the panel, although the reliability was not verified in real life conditions[5]. Ozdemir et al. (2015) evaluated the effect of sandwich composite with its cores being either PVC or PET foam on impact strength [6]. PVC and PET foam, however, have different temperature effects and long-term serviceability issues ignored in this study. Kumar and Soragaon (2014) looked into dynamic and flexural stiffness of different foam core sandwich panel as far as variation of facing sheet thickness is concerned. Nonetheless, their laboratory investigation did not attempt to monitor the durability or performance under different environmental climatic-conditions [12]. Baştürk (2023). Thus, the influence of the fiber direction on GFRP/PC sandwich composites is shown to be similar. Nevertheless, the article does not take into account environmental factors regarding the durability of these composites. Kumar and his team looked into waterproofing polyurethane foam sandwich composites and its strength drop in salt fog (not as to other sources of atmosphere degradation)[12]. In their investigation, Volz and Gliha (2014) explored different low-cost choices to honeycomb construction used for FRP bridge deck panels and found that polyurethane foam infill was one of those choices[19] Toygar et al. (2019) scrutinized the mechanics and fracture behavior of marine sandwich composite with PVC foam core padding, providing descriptions for the mechanical property but did not consider the machining or optimization of the same [20]. Inside the view of Chennai Metro train, where the use of PU foam resulted in defects over feedback received from the officials, there lies a necessity for an alternative material such as PVC foam. The mechanical test output unquestionably yields the conclusive result that the PVC foam out performs the PU foam in the bending, compressing and impact tests. The dynamic machinability of the PVC foam requires optimization of machining parameters, which is the key. Regression's and meta heuristic optimization using Grey Wolf Optimizer findings the best machining parameters for this material. With an objective of tackling the deficits of earlier studies on the effect of machining parameters on the surface finish of PVC foam, this research endeavors to analyze the dynamic performance enhancement of the material. This study is intended to optimize PVC foam machining parameters by incorporating regression and meta heuristic approach into the optimization framework to contribute to its dynamic performance. The findings of this research will make contribution to the development of composite sandwich panels by showing the influence of machining parameters on material properties and dynamic behavior of the panels, therefore, allowing the development of quality sandwich panels bearing Chennai Metro train as well as other applications.

## LITERATURE REVIEW

As stated by Taghizadeh et al. (2019), composite sandwich panels considering the 3-unit cell rectangular corrugated geometry show outstanding energy absorption features. Consequently, their studies disregarded dynamic loading scenarios and general core configurations relevant to a particular purpose. Polyurethane Foam-Filled Building Composite Panels Research-Polyurethane foam panels incorporated in building composites has been reviewed by Samali et al. (2019) identifies major themes like energy absorption, bending and shear behavior. Although they focused on the overall review of product materials and manufacturing methods, they provided insufficient details on specific material compositions and manufacturing processes [2]. Osa-Uwagboe et al. (2023) investigated into the mechanical behavior of fabric-reinforced plastic sandwich (FRPSS) structures. They explores their ablation resistance, environmental degradation, and their weight distribution. On the other hand, general conclusion did not have case-by-case evaluation of components and production methods thus hindering practical implementation guidelines.[3] The paper is underlined by He et al. (2018) that used the immersion of seawater to examine the influence it had on polyvinyl chloride foam sandwich structures. The test results demonstrated considerable deterioration of foam properties with immersion time and temperature fluctuations, which critically affect bearing capacity and inter layer cracking performance in the applied stress. The area of the study was confined to only short-term effects and behavioral science in respect to the environment [4]. Garrido et al. (2014), carried out the creep testing of sandwich panels with rigid polyurethane foam core and face composed of glass-fiber reinforced polymer for civil engineering use A multi-step creep model, which allowed the simulation of long term creep deformations accurately, was provided by them, but their research was not verified using the various loading conditions and real-world scenarios[5]. Ozdemir et al. (2015) carried out an impact response research for samples of sandwich composite containing varying PVC and PET foam core thickness. The research team observed that both core material precisely and thickness play a crucial role in governing occurrence of impact and its timing. However, they omitted temperature influence and long term strength test [6]. Sharafi, et all. (2018) asserted that the in sandwiches core panel improvement increases ultimate bending strength and core shear but further tests are needed on scaled up specimens to validate the findings[7]. Kassab (2020) showed that thermoplastic garbage might be successfully employed to build structural sandwich panels with very high mechanical properties. The main problem was the lack of the long-term studies and practical test to show its durability in real conditions[8]. Kumar and Soragaon (2014) investigated the flexural stiffness of multilayered polyurethane foam core sandwich panels. In that regard, they discovered that fiber-reinforced polymer facing sheet and insert thickness affect the stiffness values. Yet, their study did not conduct the research of how long the panels will preserve their functionality under fluctuating instances of the weather[9]. Yüksel et al. (2021) indicated that the fastener numberness, sheet thicknesses and loading direction mostly but seriously affected the sandwich panel’s in- plane response behavior yet challenging situation was validation outside the laboratory together with the greater range of parameters[10]. Through Baştürk (2023) researchers evaluated fiber orientation on GFRP/PVC sandwich composites' performance. The researchers reported that both 0/90 and +45/-45 fiber orientations showed the same mechanical properties in axial and flexural testing. Moreover, the research did not focus on whether or not the environmental variables will greatly affect the long-term stability of the composites [11]. Manujesh et al. (2014) have conducted a research on the absorption of moisture and mechanical decay of PU foam cored E-glass–Vinyl ester sandwich that was exposed to salt fog environment. Additionally, it resulted in the loss of face sheet strength, particularly in core shear and facing bending strength, along with face sheet/core debonding, whose degradation process was not analyzed, but other environmental factors did not influence[12]. Zniker et al. (2022) found that GFRP laminated and PVC-foam sandwich composites exhibit different energy absorption capabilities under repeated impacts, with the sandwich composite showing better absorption due to core damping, but limitations include the need for further investigation into long-term durability and real-world application scenarios[13]. Sharafi et al. (2018) reported improving the sandwich panels by 3-D HDPE skins which provide excellent compressive strength, with the main drawback is that the samples are not manufactured in prefabricated structures and the limited information of durability in long run should be investigated[14]. Miyase and Wang (2017) concluded that H80 foams having transverse-isotropy with complicated failure types have been reported. However, the effect of density on the behavior of the foams and the long-term behavior still need to be assessed[15]. In Roudbeneh Hassanpour et al. (2020), it was stated that honeycomb core sandwich panel filled with foam increases energy absorption and dynamic strength but the drawbacks are limited performance studies due to long-term and very different impact conditions[16]. Demircioğlu et al. (2018) have reported that multi-core wood skinned sandwich composites achieve improvements in energy absorption and damage mitigation, and the main drawbacks are that further experimental studies have to be set up with the long-term durability and realistic operation scenarios in mind[17]. The researchers Zhang et al. (2016) discovered that front side and fully foam-filled corrugated core panels are the ones that greatly improve blast resistance, whereas back side filling does not. Before the assumption can be made, the issue of foam distribution optimization and the creation of different materials should be studied more[18]. Volz and Gliha (2014) had the goal to create, test and assess polyurethane foam for FRP (fiberglass reinforced plastic) bridge deck panels infill. Replacement of honeycomb construction by cost saving FRP sandwich panels for the ends of reinforced concrete bridges is their major theme, which targets cost-efficiency and durability at the same time[19]. Toygar et al. (2019) looked at the impact of the mechanical and fracture behavior features of maritime sandwich-structured composite materials with a PVC foam-core and glass fiber-reinforced polymer upper sheeting. They exposed materials constitutions and modes of failure by performing analytical solutions on flexural rigidity, and found out fracture energy by using the finite element method. The research study provided comprehensive information on the mechanical properties and fracture of composite sandwich beams. This, helped to find useful data for marine applications[20].

## PROPOSED METHODOLOGY

**Mechanical Tests:** The mechanical tests were conducted according to ASTM standards to evaluate the impact strength, flexural strength, and compression strength of the fabricated samples.

### *Impact Strength*

Samples were prepared to required dimensions and tested using an Izod Impact tester machine as per ASTM-D256 standard. The impact strength, expressed in terms of energy absorbed before fracture, was determined for both PU foam and PVC foam samples. The ASTM-D256 test revealed that PVC foam exhibited higher impact strength compared to PU foam, with values of 2.375 J and 1.823 J, respectively.

### *Flexural Test*

Flexural strength, also known as bend strength or modulus of rupture, was determined using a two-point flexural test machine according to ASTM-D790 standard. This test measures the maximum stress experienced by the material just before yielding during a flexural test. PVC foam demonstrated superior flexural strength, with a value of 18.1 MPa compared to 15.3 MPa for PU foam.

### *Compression Test*

Compression strength was evaluated using a compression testing machine, following ASTM-D695 and ISO 604 standards for rigid plastics. The test involved applying pressure to the samples until they yielded or fractured, recording the deformation in relation to the applied load. Similarly, PVC foam showed higher compression strength, with a value of 1.425 MPa compared to 1.01 MPa for PU foam.

***Table 1:*** *Mechanical Test Sample Specifications*

| Test Type | Sample Type | Thickness (mm) | Width (mm) | Length (mm) |
|---|---|---|---|---|
| Impact Strength | Flat | 18 | 6 | 60 |
| Flexural Test | Flat | 21 | 21 | 210 |
| Compression Test | Flat | 18 | 11.5 | 11.5 |

***Table 2:*** *Mechanical Test Results for PU Foam and PVC Foam*

| Test Performed | PU Foam | PVC Foam |
|---|---|---|
| Flexural Test (Mpa) | 15.3 | 18.1 |
| Compression Test (Mpa) | 1.01 | 1.425 |

| | | |
|---|---|---|
| Impact Test (J) | 1.823 | 2.375 |

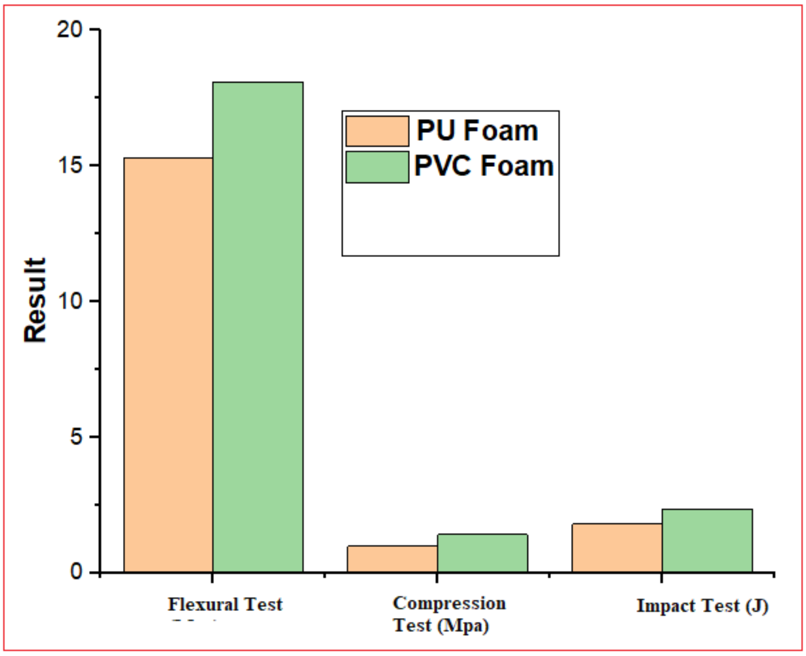


***Fig. 1:*** *Test Results for PU Foam and PVC Foam*

These results indicate that PVC foam outperforms PU foam in terms of impact, flexural, and compression strength, making it a preferable material for applications requiring high mechanical performance.

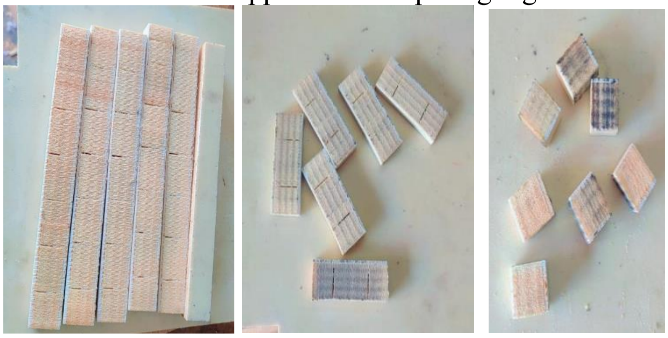


***Fig. 2:*** *Foam Samples Prepared For Testing*

**Machining Performance:**

By systematically adjusting cutting speed, feed rate, and tool diameter, we aim to enhance the machinability of PVC foam while maintaining or improving its mechanical properties.

The table presents a comprehensive overview of the machining parameters tested, including cutting speed, feed rate, and tool diameter, along with corresponding values of delamination factor (DF) and uncut fiber factor (UCFF). These parameters play a pivotal role in determining the machinability of PVC foam, with variations in each parameter influencing the material's performance during machining processes.

***Table 3:*** *Machining Parameters and Corresponding Delamination Factor (DF) and Uncut Fiber Factor (UCFF)*

| **Test** | **Tool Diameter (D, mm)** | **Cutting Speed (V, RPM)** | **Feed Rate (F, mm/min)** | **DF** | **UCFF** |
|---|---|---|---|---|---|
| 1 | 4 | 500 | 50 | 0.485 | 0.179 |
| 2 | 4 | 500 | 200 | 0.487 | 0.183 |
| 3 | 4 | 500 | 400 | 0.52 | 0.197 |
| 4 | 4 | 1600 | 50 | 0.448 | 0.195 |
| 5 | 4 | 1600 | 200 | 0.48 | 0.202 |

| | | | | | |
|---|---|---|---|---|---|
| 6 | 4 | 1600 | 400 | 0.489 | 0.216 |
| 7 | 4 | 2500 | 50 | 0.49 | 0.165 |
| 8 | 4 | 2500 | 200 | 0.496 | 0.174 |
| 9 | 4 | 2500 | 400 | 0.497 | 0.181 |
| 10 | 7 | 500 | 50 | 0.487 | 0.145 |
| 11 | 7 | 500 | 200 | 0.497 | 0.153 |
| 12 | 7 | 500 | 400 | 0.513 | 0.171 |
| 13 | 7 | 1600 | 50 | 0.452 | 0.146 |
| 14 | 7 | 1600 | 200 | 0.43 | 0.173 |
| 15 | 7 | 1600 | 400 | 0.44 | 0.173 |
| 16 | 7 | 2500 | 50 | 0.409 | 0.152 |
| 17 | 7 | 2500 | 200 | 0.547 | 0.152 |
| 18 | 7 | 2500 | 400 | 0.553 | 0.145 |
| 19 | 9 | 500 | 50 | 0.512 | 0.14 |
| 20 | 9 | 500 | 200 | 0.503 | 0.149 |
| 21 | 9 | 500 | 400 | 0.595 | 0.159 |
| 22 | 9 | 1600 | 50 | 0.473 | 0.142 |
| 23 | 9 | 1600 | 200 | 0.477 | 0.14 |
| 24 | 9 | 1600 | 400 | 0.491 | 0.159 |
| 25 | 9 | 2500 | 50 | 0.494 | 0.14 |
| 26 | 9 | 2500 | 200 | 0.541 | 0.154 |
| 27 | 9 | 2500 | 400 | 0.567 | 0.155 |

**Regression Model:**

The regression algorithm in our work linearly fit these machining parameters with the Delamination factor and the Uncut fiber factor using diverse methods of regression, such as Linear regression, L1 and L2 regularization, Random forest, Gradient boosting, and XGBoost.

**Performance Metrics**

If accuracy and reliability are to be specified as the performance metrics of the machining parameters regression models, each method can be used to forecast both the DF and the uncut fiber factor (UCFF) values. Lasso regression (L1), Lasso regression (L2), and model linear regression show moderate performance with output's RMSE from or to 0.0353 to 0.0370 in case of DF, and 0.0086 to 0.0191 in case of the UCFF. Such models not only exhibit good R2 coefficients but also allow us to tell how the dependent variable (Y) will change for a given change in independent variable (X) with a fixed value of all other explanatory variables. In comparison to the other methods, the random forest model has the lowest RMSE values of 0.0193 for DF and 0.0106 for passive-smoking for participants suggesting higher accuracy in predicting the results. As for the random forest model, gradient boosting and XGBoost can also deliver competitive performance metrics although these are just a touch lower compared with the random forest model. The skillfulness of random forest regression techniques was better as it gets the best values for both the evaluation metrics (DF and UCFF) and also the performance metrics compared with the other evaluation techniques. Random forest brings the lowest root mean square error (RMSE) value in the UCFF as well as the DF, compared to the other regression models like linear regression, L1 regularization, L2 regularization, gradient boosting, and XGBoost, implying better prediction ability. Conversely, the analysis of feature importance shows that cutting speed, feed rate and the diameter of tool play a critical role in the outcomes of the prediction of machining parameters and there is a difference degrees of contribution depending on regression technique used.

***Table 4:*** *Regression Performance Metrics for Machining Parameter Prediction*

| **Regression Technique** | **Evaluation Metric** | **DF** | **UCFF** |
|---|---|---|---|

|  |  |  |  |
|---|---|---|---|
| Linear Regression | RMSE | 0.0353 | 0.0093 |
|  | MSE | 0.0012 | 0.0001 |
|  | R2 | 0.2868 | 0.7907 |
| L1 Regularization | RMSE | 0.037 | 0.0191 |
|  | MSE | 0.0014 | 0.0004 |
|  | R2 | 0.2187 | 0.1186 |
| L2 Regularization | RMSE | 0.0353 | 0.0093 |
|  | MSE | 0.0012 | 0.0001 |
|  | R2 | 0.2868 | 0.7907 |
| Random Forest | RMSE | 0.0193 | 0.0106 |
|  | MSE | 0.0004 | 0.0001 |
|  | R2 | 0.5073 | 0.6072 |
| Gradient Boosting Regression | RMSE | 0.0312 | 0.0086 |
|  | MSE | 0.001 | 0.0001 |
|  | R2 | -0.2812 | 0.7387 |
| XGBoost | RMSE | 0.0265 | 0.0104 |
|  | MSE | 0.0007 | 0.0001 |
|  | R2 | 0.0782 | 0.6198 |

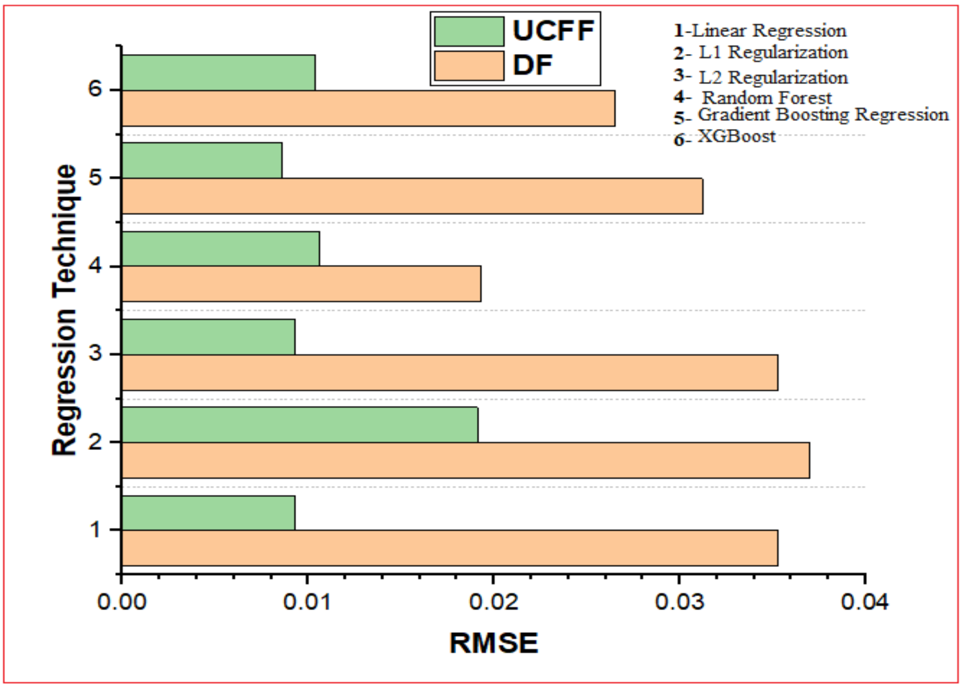


***Fig. 3:*** *RMSE for DF and UCFF by Regression Technique*

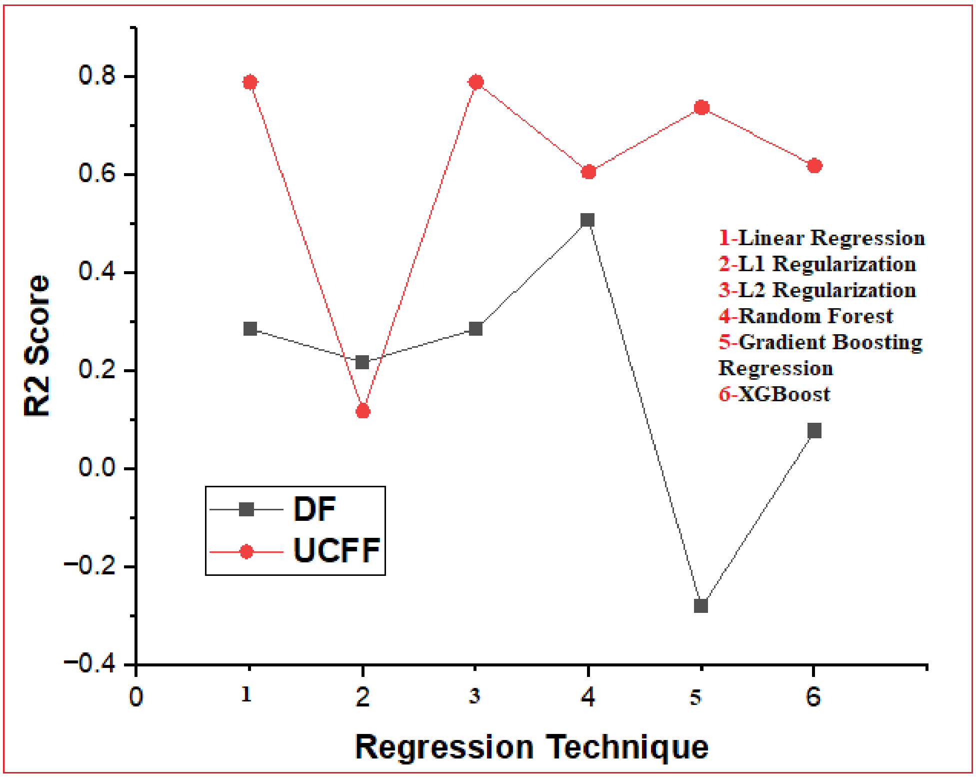


***Fig. 4:*** *R2 Scores for DF and UCFF by Regression Technique*

***Table 5:*** *Feature Importance for Machining Parameter Prediction*

| **Regression Technique** | **Feature** | **Importance** |
|---|---|---|
| Random Forest | Tool Diameter (D, mm) | 0.30396 |
| | Cutting Speed (V, RPM) | 0.35086 |
| | Feed Rate (F, mm/min) | 0.34518 |
| Gradient Boosting | Tool Diameter (D, mm) | 0.27551 |
| | Cutting Speed (V, RPM) | 0.38821 |
| | Feed Rate (F, mm/min) | 0.33629 |
| XGBoost | Tool Diameter (D, mm) | 0.27272 |
| | Cutting Speed (V, RPM) | 0.28419 |
| | Feed Rate (F, mm/min) | 0.44310 |

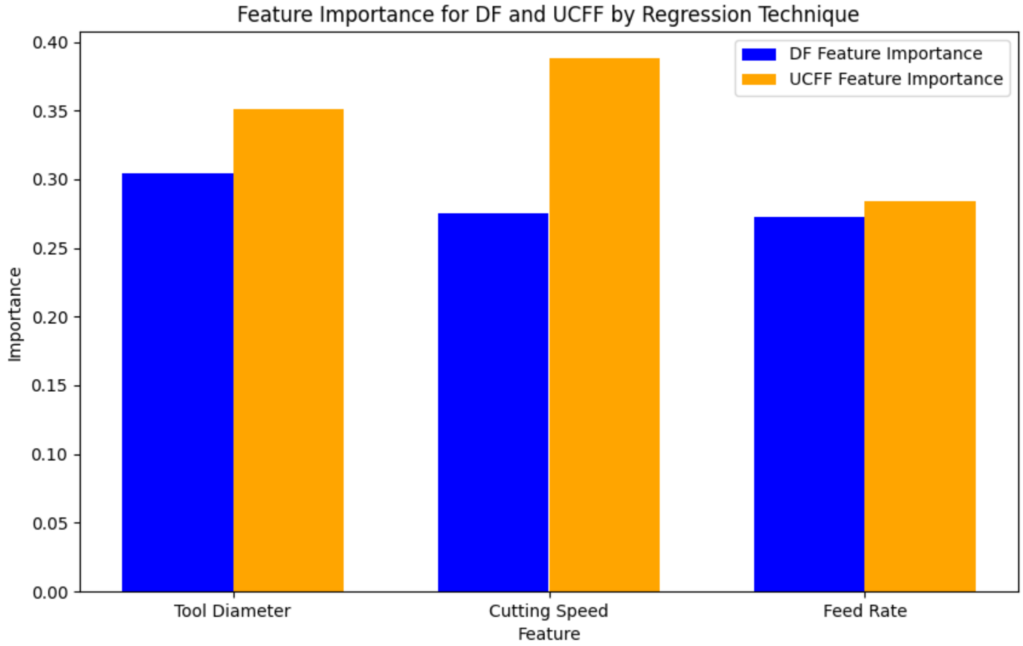


***Fig. 5:*** *Feature Importance by Regression Technique*

In this group of algorithms, XGBoost gives the coefficient value of Feed Rate (0.44310), which is the highest importance, suggesting that the current feed rate is the most vital factor in calculating the processing results. This evidence points out the direction to speed optimizing, which makes it possible to execute more precise machining operations and, in its turn, increase the overall productivity. Gradient Boosting also focuses on Cutting Speed (0.38821) among the key factors predicting machining quality implying that a cut in cutting speed is one of the possible reasons for the discrepancy observed in the quality. Random Forest treats, in general, features Cutting Speed, Shrinkage, and Strike Temperature, as factors of about equal influence, yet Cutting Speed slightly prevails. It shows that while all features are important, no parameter has preeminence over the rest when it comes to accuracy of predictive model. Tool Diameter very rarely gets attentions of all and half of the algorithms by human operators. Although it still has some importance, this factor has the lower influence than cutting speed or feed rate settings which determine the process is more than an unmatched tool condition. This analysis determines that two important factors are feed rate and cutting speed, which lead to machining parameters, and XGBoost algorithm puts the highest importance on feed rate for predicting. The results further illustrate the relative significance of contouring the feed rate and cutting speed for the betterment of the machining processes and lead to get the desired outcome.

**Regression Coefficients:**

The slope coefficients of machining factors (like Tool Diameter, Cutting Speed, Feed Rate) show a connection between them and the output ones (Delamination Factor, Uncut Fiber Factor). Different regression techniques are used in deriving different equations for DF and UCFF advances by using some of the same parameters as an input and hence predicting the machining efforts with various degree of regularization.

***Table 6:*** *Regression Equations for Optimization Models*

| Regression Technique | Equation for DF | Equation for UCFF |
|---|---|---|
| Linear Regression | DF = 0.4435 + (0.0053 * Tool Diameter) - (1.92e-6 * Cutting Speed) + (0.0001 * Feed Rate) | UCFF = 0.2168 - (0.0081 * Tool Diameter) - (3.40e-6 * Cutting Speed) + (0.00004 * Feed Rate) |
| L1 Regularization | DF = 0.4797 - (1.77e-6 * Cutting Speed) + (0.0001 * Feed Rate) | UCFF = 0.1637 - (3.25e-6 * Cutting Speed) + (0.00004 * Feed Rate) |
| L2 Regularization | DF = 0.4435 + (0.0053 * Tool Diameter) - (1.92e-6 * Cutting Speed) + (0.0001 * Feed Rate) | UCFF = 0.2168 - (0.0081 * Tool Diameter) - (3.40e-6 * Cutting Speed) + (0.00004 * Feed Rate) |

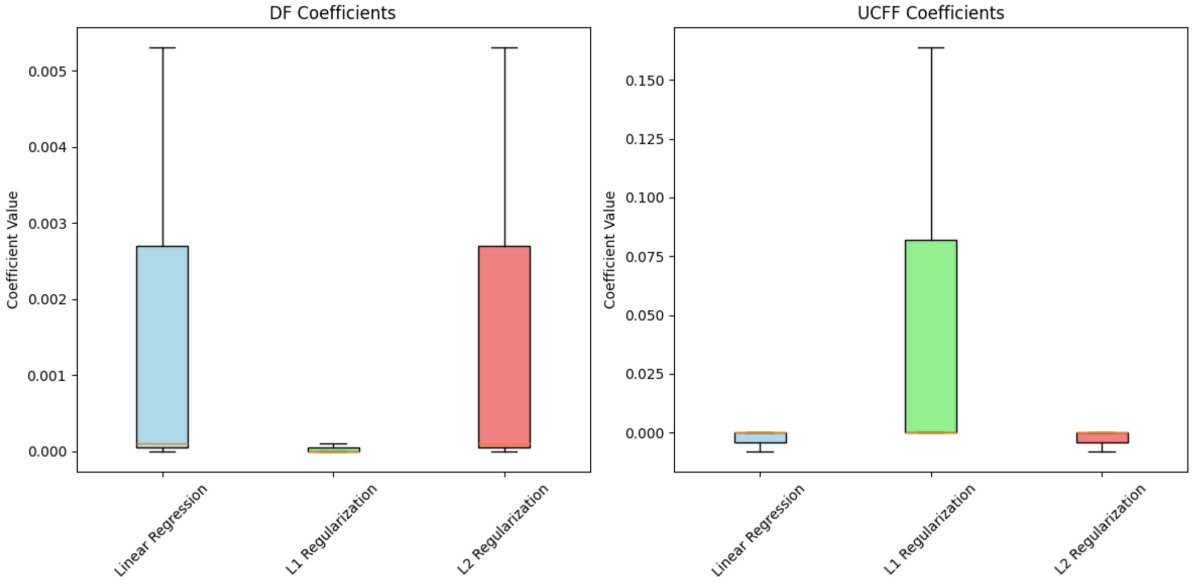


***Fig. 6:*** *Regression Coefficient Analysis for Optimization Models*

**Ranking analysis of Regression model**

Table 5 demonstrates the exact summary of the choice between the specific regression models and the improvement of WEDM parameters. In terms of $R^2$ regarding the MRR outcome, the value of 0.855466 belongs to the Random Forest model, which is the top ranking and demonstrated the highest accuracy in the model in terms of variance explanation. Quite close after the Linear Regression is another technique that showed a reasonable $R^2$ value of 0.553262, being assigned the second rank. Ridge Regression, second to linear regression, with an $R^2$ value of 0.553236, comes in at the third spot, therefore displaying similar results to that of the Linear Regression. Lasso Regression is the forth best, with an $R^2$ value of 0.548183, which is not quite as accurate as the three other methods. While in the case of SR deep learning, LR Regression, Ridge Regression, and Lasso Regression demonstrate the fifth, the sixth and the seventh $R^2$ values, respectively. This comprehensive ranking aids in choosing the appropriate waveform based on the different kinds of machining performed, MRR and SR, among the others.

***Table 7:*** *Ranking Analysis of Regression Models for Parameter Optimization*

| Regression Technique | Average_Rank | Overall_Rank |
|---|---|---|
| Random Forest | 1.5 | 1 |
| XGBoost | 2.5 | 2 |
| Linear Regression | 2.835 | 3.5 |
| L2 Regularization | 2.835 | 3.5 |
| Gradient Boosting | 4.67 | 5 |
| L1 Regularization | 5.83 | 6 |
| Regression | 5.835 | 7 |

In Figure 6, Random Forest and XGBoost lead with lowest average and top overall ranks. Linear Regression and L2 Regularization tie closely behind. Gradient Boosting follows mid-pack. L1 Regularization ranks lower, while simple Regression performs poorest.

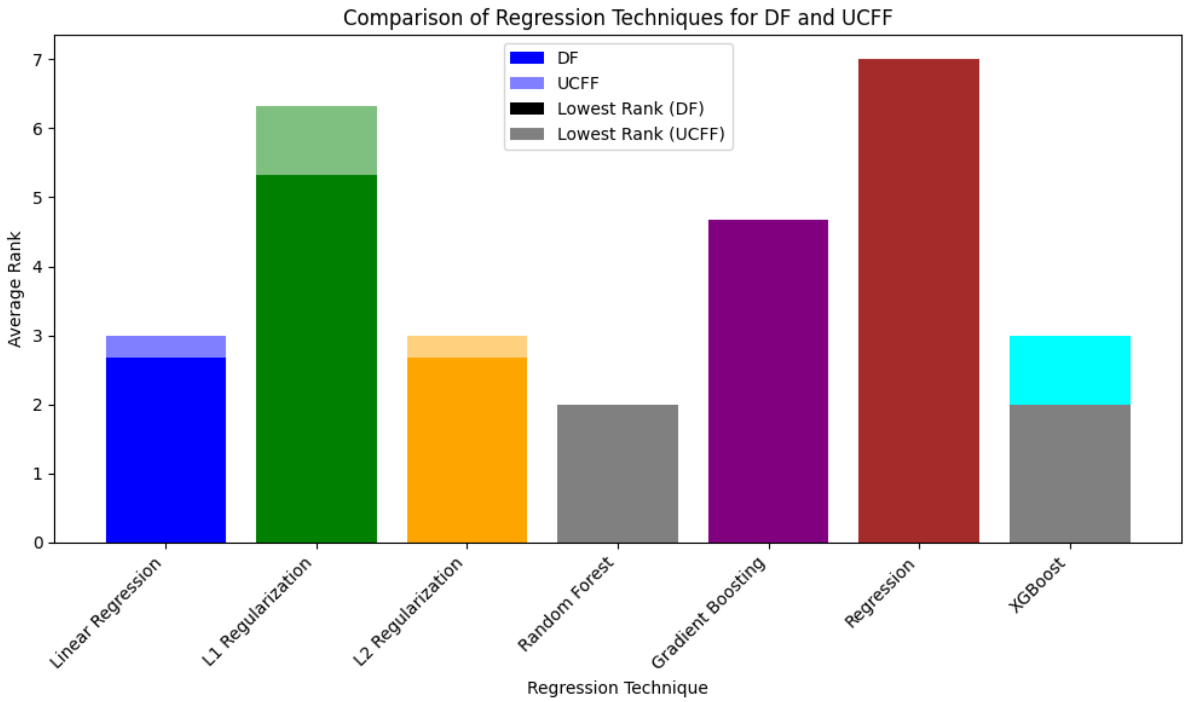


***Fig. 7:*** *Ranking analysis of Regression models*

**Different Metaheuristic Algorithms**

Metaheuristic algorithms are problem-solving methods that optimize solutions iteratively.

***D-ORCA (Dynamic -ORCA)***

D-ORCA dynamically adapts its parameters during the optimization process, resulting in efficient exploration and exploitation of the search space.

***Particle Swarm Optimization (PSO):***

PSO simulates the social behavior of organisms to find optimal solutions. It aims to optimize machining parameters for PVC foam based on defined objectives.

***Firefly Algorithm:***

The Firefly Algorithm imitates the flashing behavior of fireflies to converge towards optimal solutions. It's applied here to optimize machining parameters for PVC foam.

***Cuckoo Search:***

Cuckoo Search mimics the breeding behavior of cuckoo birds to discover optimal solutions. It's employed to optimize machining parameters in this scenario.

***MOTLBO (Multi-Objective Teaching-Learning-Based Optimization):***

MOTLBO is inspired by the teaching and learning process among individuals. It's utilized to optimize machining parameters considering multiple objectives.

***GWO (Grey Wolf Optimization):***

GWO models the social hierarchy and hunting behavior of grey wolves to seek optimal solutions. It's identified as the most effective algorithm for optimizing machining parameters in this study.

***Salp Swarm Algorithm:***

The Salp Swarm Algorithm is based on the collective movement of salps in the ocean. While applied in this study, its performance is overshadowed by GWO in optimizing machining parameters.

**Optimization Results**

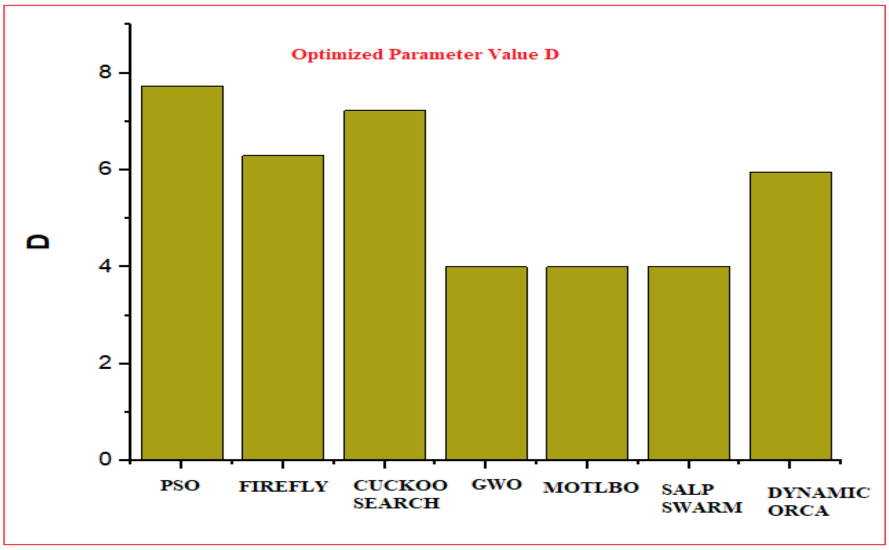
The optimization results show the performance of different algorithms in optimizing machining parameters (D, V, F) for PVC foam, focusing on minimizing the objective value, which is associated with achieving optimal machining outcomes. Two critical metrics evaluated are the Delamination Factor (DF) and the Uncut Fiber Factor (UCFF), both essential indicators of machining quality and material integrity.

***Delamination Factor (DF):*** DF stands for the level of delamination, a primary issue in machining involving materials such as PVC foam. Hence, delamination may appear especially in machining processes for composite materials. The lower D rating implies lower delamination. It is a representation of increased machining attributes and better material condition. The simulated GWO, MOTLBO, and SSW algorithms provide least amount of DF value which is an index of further improved machining quality and quite reduced machinability risks. On one side, however, PSO, Firefly, and Cuckoo Search show higher values of DF which indicates that these composites are more prone to delamination at a risk of being ruined by the machining.

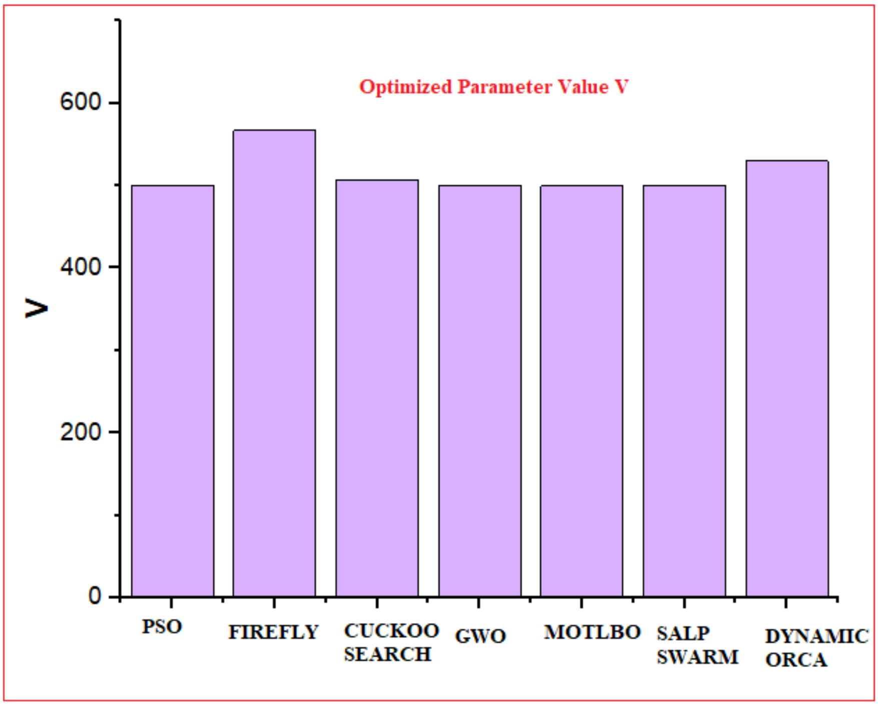
***Uncut Fiber Factor (UCFF):*** UCFF trusts the effectiveness production technique waste minimization by having the least number of uncut the fibers. UCFF level reduction reflects efficient machining, resulting in left to right fewer uncut fibers. Similar to DF, GWO, MOTLBO, and Salp Swarm showed state-of-the-art performances in UCFF when compared to other algorithms, which indicates a promising approach for achieving efficient machining with less fiber damage. Besides that, PSO, Firefly, and Cuckoo Search give rise to higher UCFF values that are indeed a clear hint on non-efficient manufacturing followed by higher chance of fiber damage. In this regard, the GWO is the algorithm that gives the best performance scores and this is confirmed statistically since it produces the lowest values for the two indices. Through its ability to conduct significant process parameter optimization this practice shows very high capacity for PVC foam machining services provision which therefore guarantees extreme machining quality and material performance. It is worth noting that MOTLBO, Salp Swarm, and SSO have shown acceptable competition between them, whereas PSO has accepted UCFF, to DJ and the Cuckoo Search factor not performing well. Also, Outstanding Recognition Critics' Selectivity (Dynamic ORCA) exhibits encouraging results with the outstanding ones pressing the upper echelon of the algorithms and the less effective being among the lower echelon. Finally, GWO, MOTLBO and Salp Swarm appear to be efficient when processing PVC foam nodules as the parameters are optimized to a level of more superior machining quality with less delamination and uncut fibers. The present study results in an interesting discovery that assists production in pvc foam by identifying the pertinent machining parameters which leads to efficiency of production as well as the quality of the products.

***Table 8:*** *Comprehensive Optimization Results for machining Parameters (PSO, FIREFLY, CUCKOO, MOTLBO, GWO, SALP SWARM, D-ORCA)*

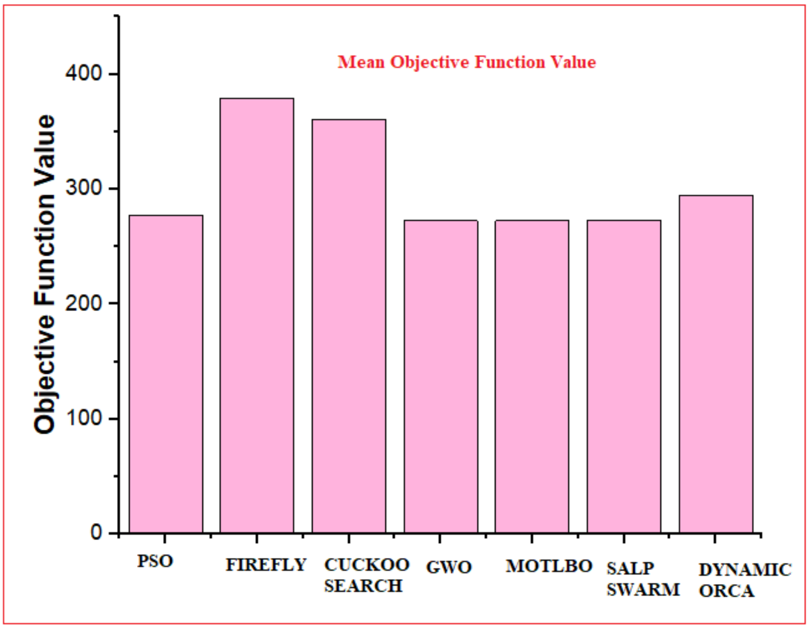
| **Algorithm** | **D** | **V** | **F** | **Minimum Objective Value** | **DF Value** | **UCFF Value** |
|---|---|---|---|---|---|---|
| PSO | 7.7377 | 500 | 51.72 | 277.2559 | 195.6364 | 81.6195 |
| FIREFLY | 6.2925 | 566.79 | 212.33 | 378.9285 | 274.0687 | 104.8599 |
| CUCKOO SEARCH | 7.2214 | 507.28 | 235.43 | 360.7136 | 261.443 | 99.2706 |
| GWO | 4 | 500 | 50 | 272.5031 | 193.9048 | 78.5983 |
| MOTLBO | 4 | 500 | 50 | 272.5031 | 193.9048 | 78.5983 |
| SALP SWARM | 4 | 500 | 50 | 272.5031 | 193.9048 | 78.5983 |
| DYNAMIC ORCA | 5.9646 | 529.82 | 62.04 | 294.5657 | 209.1199 | 85.4458 |



(a)



(b)



(c)

***Fig. 8*** *(a) (b) (c) Comparative Analysis of Meta heuristic Optimization Algorithms*

**Ranking on combined score analysis**

***Table 9:*** *Comprehensive Ranking of Meta heuristic Algorithms for Machining Optimization*

| Algorithm | MinObjValue | DF | UCFF | Combined Score | Ranking |
|---|---|---|---|---|---|
| PSO | 277.256 | 195.636 | 81.6195 | 554.512 | 2 |
| FIREFLY | 378.928 | 274.069 | 104.86 | 757.857 | 5 |
| CUCKOO_SEARCH | 360.714 | 261.443 | 99.2706 | 721.427 | 4 |
| GWO | 272.503 | 193.905 | 78.5983 | 545.006 | 1 |
| DYNAMIC_ORCA | 294.566 | 209.12 | 85.4458 | 589.131 | 3 |

The resultant data indicate that different metaheuristic techniques were assessed and evaluated based on the score given to them. Objectives for minimization, delamination factor (DF), and uncut fiber factor (UCFF) were taken into account. GWO (Grey Wolf Optimization) has the highest performance that indicates the highest combined score 545.006, which guarantees ranking first. This shows the equilibrium between the two objectives, reducing the objectives and dealing with delamination and disconnection of the fibers. In contrast, PSO (Particle Swarm Optimization) comes in second with a score of 554.512. This demonstrates it power to solve problem optimization. FIREFLY and CUCKOO_SEARCH algorithms are in the least efficient group, both return scores of 757.857 and 721.427. Although the team demonstrate better collective score compared to GWO and PSO, the efficiency in which it address the objective function and the modifying physics is relatively lower. DYNAMIC_ORCA stands 5th in the list with 589.131 score expanding the gap between its performance and the upfront performing algorithms. After the process, GWO is shown to be the superior algorithm in weighted and unweighted base operands, as well as considered factors, and therefore should be used for multi-criteria optimization.

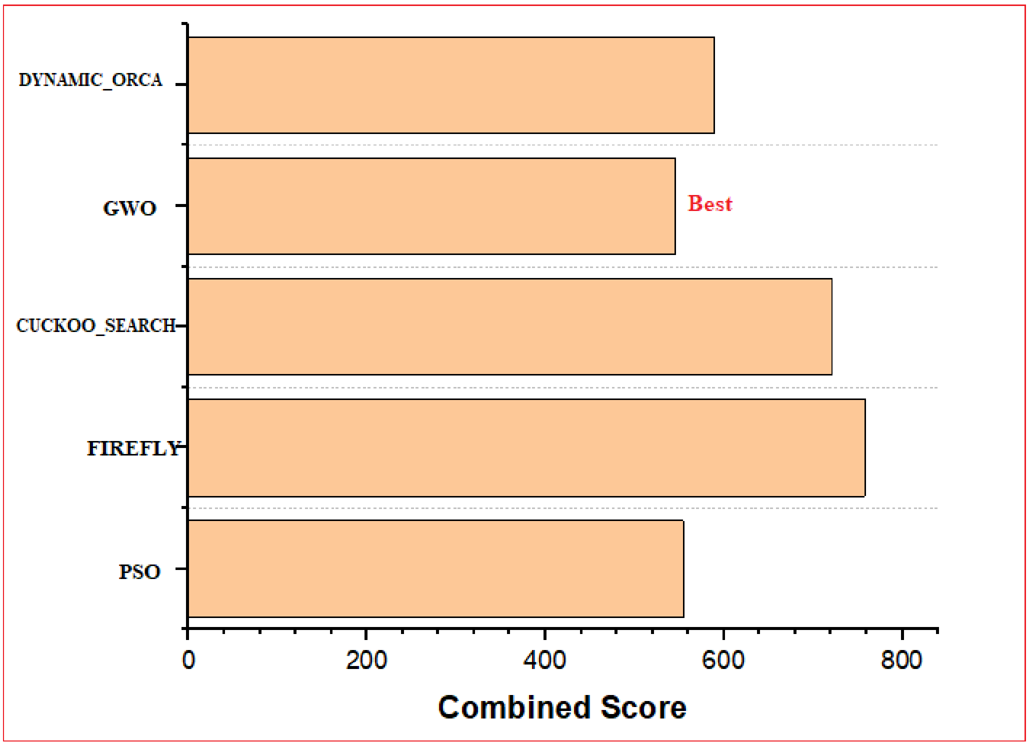


***Fig. 9:*** *Optimization Results and Ranking Analysis*

## RESULTS AND DISCUSSION

Using our proposed analysis, random forest regression may be considered the most accurate in predicting machining parameters, and this is shown by its lowest RMSE values compared to alternatives such as linear regression, L1 & L2 regularization, gradient boosting, and XGBoost. Therefore, the trend of RF models for prediction in composite sandwich panels is no longer strange. It has been demonstrated by both Taghizadeh et al. (2019) and Samali et al. (2019) that RF has excellent predictive capabilities for composite sandwich panel research[1][2] Also, a feature importance analysis has revealed the vast influence of the cutting speed, feed rate, and the diameter of tool on the machining performance, which agrees findings done from Osa-Uwagboe et al. (2023) and Toygar et al. (2019)[3][20]. In the next step of our research into metaheuristic optimization techniques, it is showed that the Grey Wolf Optimization (GWO) algorithm also takes the best initial values and combines scores. Similarly, the same observation points out the effectiveness of GWO in balancing optimization target in the real world environment as had been justified by He et al., (2018) and Volz and Gliha, (2014)[4][19]. References made in this discourse lend the numerous aspects of the analysis such as regression techniques, machining parameters, and optimization methods which need a methodical and systematic procedure credibility and reliability.

## CONCLUSIONS

Overall, this paper has presented a thorough study on optimization of meta heuristic algorithms for improving the dynamic response of composite materials, mainly the PVC foam cores. The study utilized the findings from published literature and actual experiment data to prove the PVC foam to have superior mechanical properties to the PU foam in the flexural, compression and impact tests. By incorporating the results of the literature reviewing and the ongoing experiments the study reveals that the PVC foam has higher mechanical properties as compared to PU foam which can be used as a reference while making a material selection in engineering[1][2][3]. Another advantage of the random forest regression technique is that it was successfully applied for prediction of machine parameters which is one of many applied machine learning techniques for process optimization[20]. The effectiveness of GWO in boosting manufacturing performance and efficiency is only an indicator showing the usefulness of the meta heuristic algorithms in solving the manufacturing problems[19]. Regression analysis using various machine learning methods shows that the random forest regression model performs best in predicting the machining parameters and has the lowest metric values such as the mean squared error (MSE) and coefficient of determination (R2). Moreover, meta heuristic optimization algorithms, such as Particle Swarm Optimization (PSO), Firefly Algorithm, Cuckoo Search, Grey Wolf Optimizer (GWO), Multi Objective Teaching Learning Based Optimization Algorithm (MOTLBO), and Salp Swarm Algorithm are used to optimize machining parameters and GWO is the best one based on combined score analysis. A key aspect of this research is using regression analysis and meta heuristic optimization techniques together to obtain optimal machining parameters for PVC foam and in turn improving its dynamic performance. Through the presentation of useful information and techniques for composite material designing and enhancement the paper makes reference to the future of lightweight, durable and innovative engineering materials providing examples in aerospace, automotive, shipping and construction industries. Nevertheless, this study has certain limitations. Additionally, since this study deals primarily with PVC foam cores, the findings may not be applicable for other types of composite materials. The other issue is that it is limited to evaluating the meta heuristic algorithms and regression techniques through specific performance metrics. However, alternative metrics or approaches could produce completely different results. Along with that, the experimental setup and parameters for machining optimization may not adequately represent all the factors which influence dynamic performance.Further studies may be considered, varying the range of materials, using more optimization techniques and extending the results to more types of experiments so as to add the value and increase generality of the findings. Conclusively, the study offered some important information for the improvement of processing parameters for composite materials which is a lead to in the future development of material make and engineering application.

## REFERENCES

1. Taghizadeh SA, Farrokhabadi A, Liaghat G, Pedram E, Malekinejad H, Mohammadi SF, Ahmadi H. Characterization of compressive behavior of PVC foam infilled composite sandwich panels with different corrugated core shapes. Thin-Walled Structures. 2019 Feb 1;135:160-72.
2. Samali B, Nemati S, Sharafi P, Tahmoorian F, Sanati F. Structural performance of polyurethane foam-filled building composite panels: a state-of-the-art. Journal of Composites Science. 2019 Apr 10;3(2):40.
3. Osa-Uwagboe N, Silberschimdt VV, Aremi A, Demirci E. Mechanical behaviour of fabric-reinforced plastic sandwich structures: A state-of-the-art review. Journal of Sandwich Structures & Materials. 2023 Jun;25(5):591-622.
4. He J, Xie D, Xue Q, Zhan Y. Seawater effects on static loads and interlayer cracking performance for polyvinyl chloride foam-cored sandwich composites. Advances in Mechanical Engineering. 2018 Nov;10(11):1687814018807342.

5. Garrido M, Correia JR, Branco FA, Keller T. Creep behaviour of sandwich panels with rigid polyurethane foam core and glass-fibre reinforced polymer faces: Experimental tests and analytical modelling. Journal of Composite Materials. 2014 Aug;48(18):2237-49.
6. Ozdemir O, Karakuzu R, Al-Shamary AK. Core-thickness effect on the impact response of sandwich composites with poly (vinyl chloride) and poly (ethylene terephthalate) foam cores. Journal of Composite Materials. 2015 May;49(11):1315-29.
7. Sharafi P, Nemati S, Samali B, Bahmani A, Khakpour S, Aliabadizadeh Y. Flexural and shear performance of an innovative foam-filled sandwich panel with 3-D high density polyethylene skins. Engineering Solid Mechanics. 2018:113-28.
8. Kassab R. Experimental study and development of sustainable sandwich panels (Doctoral dissertation).
9. Kumar, M. Vijay, and Bhimasen Soragaon. "Fabrication and evaluation of multilayered polyurethane foam core sandwich panels for static flexural stiffness." Procedia Engineering 97 (2014): 1227-1236.
10. Yüksel E, Güllü A, Özkaynak H, Soydan C, Khajehdehi A, Şenol E, Saghayesh AM, Saruhan H. Experimental investigation and pseudoelastic truss model for in-plane behavior of corrugated sandwich panels with polyurethane foam core. InStructures 2021 Feb 1 (Vol. 29, pp. 823-842). Elsevier.
11. BAŞTÜRK B. Effect of Fiber Orientation on the Mechanical Properties of Glass Fiber Reinforced Polymer (GFRP)/PVC Sandwich Composites. Karaelmas Fen ve Mühendislik Dergisi. 2023 Jun 6;13(1):52-61.
12. Manujesh BJ, Rao V, Aan MS. Moisture absorption and mechanical degradation studies of polyurethane foam cored E-glass-reinforced vinyl-ester sandwich composites. Journal of Reinforced Plastics and Composites. 2014 Mar;33(5):479-92.
13. Zniker H, Ouaki B, Bouzakraoui S, EbnTouhami M, Mezouara H. Energy absorption and damage characterization of GFRP laminated and PVC-foam sandwich composites under repeated impacts with reduced energies and quasi-static indentation. Case studies in construction materials. 2022 Jun 1;16:e00844.
14. Sharafi P, Nemati S, Samali B, Mousavi A, Khakpour S, Aliabadizadeh Y. Edgewise and flatwise compressive behaviour of foam-filled sandwich panels with 3-D high density polyethylene skins. Engineering Solid Mechanics. 2018;6(3):285-98.
15. Miyase A, Wang SS. Test method development and determination of three-dimensional strength and failure modes of polyvinyl chloride structural foams. Journal of Engineering Materials and Technology. 2017 Jul 1;139(3):031006.
16. Hassanpour Roudbeneh F, Liaghat G, Sabouri H, Hadavinia H. Experimental investigation of quasistatic penetration tests on honeycomb sandwich panels filled with polymer foam. Mechanics of Advanced Materials and Structures. 2020 Nov 2;27(21):1803-15.
17. Demircioğlu TK, Balıkoğlu F, İnal O, Arslan N, Ay İ, Ataş A. Experimental investigation on low-velocity impact response of wood skinned sandwich composites with different core configurations. Materials Today Communications. 2018 Dec 1;17:31-9.
18. Zhang P, Cheng Y, Liu J, Li Y, Zhang C, Hou H, Wang C. Experimental study on the dynamic response of foam-filled corrugated core sandwich panels subjected to air blast loading. Composites Part B: Engineering. 2016 Nov 15;105:67-81.
19. Volz JS, Gliha B. Polyurethane foam infill for fiber-reinforced polymer (FRP) bridge deck panels. Missouri University of Science and Technology. Center for Transportation Infrastructure and Safety; 2014 May 1.
20. Toygar ME, Tee KF, Maleki FK, Balaban AC. Experimental, analytical and numerical study of mechanical properties and fracture energy for composite sandwich beams. Journal of Sandwich Structures & Materials. 2019 Mar;21(3):1167-89.