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TOPSIS-Driven Optimization of FFF Process Parameters for Mechanical Strength Enhancement

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Abstract

In this study, the application of the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method for optimizing Fused Filament Fabrication (FFF) process parameters to enhance the tensile and flexural strength of Polylactic Acid (PLA) material-based 3D printed components is explored. This investigation delves into the intricate relationship between key parameters, such as layer height, print speed, infill density, print temperature, and nozzle diameter, and their impact on material strength. The experimental results reveal a significant improvement in both tensile and flexural strength, establishing PLA as an exemplary choice for manufacturing robust components suitable for diverse applications, ranging from prototyping to customized product development. The identified optimal settings, including a layer height of 0.23 mm, a print speed of 55 mm/s, print orientation at 45°, 100% infill density, and a print temperature of 220°C, contribute to the enhanced performance of the FFF technique. These findings contribute valuable insights for practitioners seeking to achieve superior mechanical properties in PLA-based 3D printed components.

Keywords: Fused Filament Fabrication process, TOPSIS, Multi Objective Optimization, Poly Lactic Acid

INTRODUCTION

In the discipline of additive manufacturing, more specifically in the context of the FFF technique, the primary focus lies in attempting to improve material performance and quality, a matter of utmost significance [1, 2]. The technique known as FFF, widely recognized for its remarkable adaptability and expansive range of practical implementations, heavily relies on the careful manipulation and regulation of diverse parameters in order to achieve the fabrication of three-dimensional objects through additive manufacturing [3–5]. Among these parameters, governing aspects such as orientation, print speed, infill density, nozzle temperature, and layer thickness play a pivotal role in determining the mechanical properties of the final printed components [6]. In order to address the problem of maximizing the strength enhancement in the FFF process, researchers and practitioners' resort to sophisticated methodologies, such as the TOPSIS [7]. The present methodology offers a systematic and data-centric framework for assessing and prioritizing various parameter configurations, with the objective of discerning the optimal settings for augmenting mechanical strength. The primary objective of this study is to enhance the Tensile Strength and Flexural Strength properties. Within the present context, the ensuing investigation undertakes an exploration cantered on the optimization of FFF process parameters, employing the TOPSIS methodology. The primary objective of this work is to explain the most advantageous arrangements that will

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result in materials possessing exceptional mechanical characteristics. By means of this comprehensive analysis, engineers and researchers are empowered to make judicious decisions that not only augment the calibre of components produced via FFF, but also pave the way for a plethora of applications across diverse industries, spanning from aerospace to healthcare and beyond. The investigation into the optimization of process parameters for strength enhancement in additive manufacturing through the utilization of the TOPSIS holds great potential for advancing the field and reshaping the capabilities of 3D printing technology. This study in novel ways employs the TOPSIS method to optimise FFF parameters, resulting in improved tensile and flexural strength in PLA-based 3D printed components. The identified settings, which consist of a 0.23 mm layer height and 55 mm/s print speed, showcase notable enhancement. The author primarily focused on flexural and tensile strengths. They present a novel approach that combines flexural and tensile strengths, which broadens the potential uses of PLA components. This can be beneficial in various fields, including prototyping and customized product development.

Related Work

M. Kamaal et al. [8] determine the process parameters for the FDM technique on the mechanical properties of carbon fibre PLA He evaluated the mechanical properties by using building direction, layer height, and infill percent as process parameter. TOPSIS is used to perform multi optimization to identify the optimal set of parameters that produce the maximum strength.

Vishwas M et al. [9] Study the effects of process parameters such as orientation, layer thickness, and shell thickness on tensile strength, manufacturing time, and dimensional accuracy for Nylon and ABS. They found that layer thickness has the maximum impact on dimensional accuracy and manufacturing time, whereas orientation has the maximum impact on tensile strength.

J.M. Chacon et al. [10] Study the influence of build orientation, layer thickness, and feed rate on the mechanical characteristics of PLA was investigated, and it was discovered that manufacturing cost is proportional to layer thickness and feed rate, i.e., printing time decreases as layer thickness and feed rate rise. As the feed rate is reduced and layer thickness is increased, flexural and tensile strength increases.

V. Durga Prasada Rao et al. [11] Study the impact of layer thickness, print temperature, and infill pattern on the tensile strength of Carbon Fiber PLA is being investigated. The maximum tensile strength was found to be 26.59 MPa for layer thickness 0.1, extrusion temperature of 225°C, and cubic infill pattern in a full factorial design of experiment.

Andhy Rinanto et al. [12] determines the best 3D printing parameters based on FDM technology to make products with high tensile strength, low energy consumption, and quick processing time Infill density, fill angle, and temperature are the parameters used. They employ the Taguchi technique for DOE and PCR-TOPSIS for optimization, and they find that infill density is the most important parameter.

Durgun and Erten [13] studied five distinct raster angles (0°, 30°, 45°, 60°, and 90°) for three different orientations (vertical, perpendicular, and horizontal) were used and evaluated for tensile strength, flexural strength, and surface roughness. The results reveal that the specimen built in horizontal direction with 0° raster angle offered optimal mechanical qualities as well as optimum production cost and time, and they also indicate that orientation has a greater impact on mechanical characteristics than raster angle.

Sakthivel Murugan R. and Vinodh S [14] used the grey based Taguchi technique to optimize the process parameter for FDM, and the results were compared to those of the analytical hierarchy process and TOPSIS.

Alsoufi and Elsayed [15] They measured the surface roughness in three different angular directions 0º, 45º and 90º during the investigation along with various independent process parameters of nozzle diameter (0.2, 0.3, 0.5 mm), layer height (0.1, 0.2, 0.3 mm). The results reveal that the layer height and nozzle diameter have a significant impact on surface quality, cost, and build time. They found that the optimum process parameter settings for surface roughness are 0.1-layer height and 0.3 nozzle diameter.

Ming-Hsien Hsueh et al. [16] evaluated and compared the mechanical and thermal characteristics of PLA and PETG in order to gain information on different printing speeds and temperatures. It was also discovered that the mechanical and thermal properties of PLA and PETG are increased at higher printing temperatures, and the effect of speed in PLA and PETG produces different results. It was also discovered that the mechanical properties of PLA are greater than PETG, but the thermal deformation is opposite.

Jasgurpreet Singh Chohan et al. [17] used ANOVA and Taguchi to investigate the combined impact of orientation angle, finishing time, and finishing temperature, and TOPSIS was used to do multi-criteria optimization. He discovered that when temperature rises, the percent change in surface roughness rises, whereas a 0-degree orientation angle produced maximum strength and a longer finishing time resulted in weight gain. Finally, the results of the ANOVA show that surface roughness is proportional to finishing time

TOPSIS Method

It is a multicriteria decision analysis method which help us to optimize the result which comes from different combination of input parameters. The aim is to develop analytical or numeric method that consider different options with different criteria [18]. TOPSIS is numeric method that helps in making decision from several criteria. This method may be applied in various circumstances with the help of simple mathematics. Furthermore, it is a very practical strategy that relies on computer assistance. The technology has been used for the past three decades, and there are numerous studies on its uses. TOPSIS' secret reasoning is that the best solution should be the shortest geometric distance away while the worst option should be the longest geometric distance away. Such a methodology enables for identifying a variety of trade-offs between criteria where bad performance in a part might be compensated by a strong(better) performance in other. This is a rather comprehensive type of modelling because we aren't keeping out other possibilities based on pre-defined thresholds [19]. Generally, the TOPSIS algorithms starts by creating a decision matrix that shows the optimum(correct) value for every criterion for every choice. After multiplying the values with criteria weights this by this way the matrix normalizes using the suitable normalizing procedure. Afterwards using distance measure, the positive and negative ideals solutions besides the distance between every alternative and these solutions are obtained [20]. Ultimately the alternatives are score based on how close they are to optimal answer. The TOPSIS method assists decision takes in developing solution to problems, in analysis, in comparing and ranking the solutions. When all the data is accessible for taking decision and can be then said its crisp numbers, the TOPSIS technique is used to solve problems. In the current study empirical data is obtained from experimental trials for different process parameter and its corresponding response, as shown in the Table 1.

THE STEPS OF THE TOPSIS METHOD

The various step involved in TOPSIS method can be visualized through Figure 1

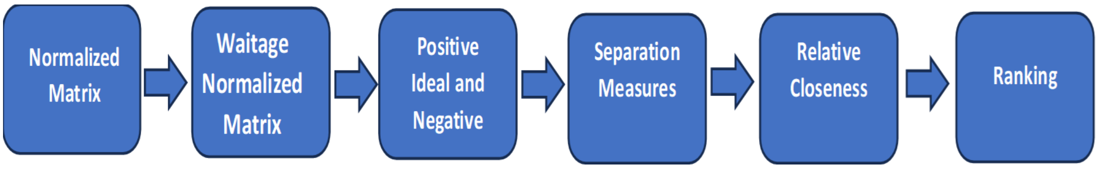


Figure 1. The steps of the TOPSIS method.

Table 1. Tensile and flexural strength at different process parameter.

S.N.	Print orientation	Print Speed (mm/s)	Infill density (%)	Print Temp. (°C)	Layer Height (mm)	Tensile strength (MPa)	Flexural strength (MPa)
1	90	50	40	210	0.2	0.175	6.7968
2	0	60	40	230	0.26	0.198	5.2439
3	135	55	60	220	0.23	0.168	6.6797
4	0	50	80	210	0.2	0.218	5.2146
5	90	60	40	210	0.26	0.168	6.533
6	45	55	100	220	0.23	0.263	7.6169
7	90	60	80	230	0.26	0.222	7.4411
8	45	55	60	200	0.23	0.164	5.7127
9	90	50	40	230	0.26	0.171	6.9138
10	0	50	40	230	0.2	0.186	5.0682
11	45	55	60	220	0.23	0.172	6.0642
12	45	65	60	220	0.23	0.177	6.0935
13	45	55	60	220	0.23	0.173	6.1228
14	90	50	80	210	0.26	0.227	7.4118
15	45	55	60	220	0.23	0.174	6.0642
16	0	50	40	210	0.26	0.216	5.3318
17	45	45	60	220	0.23	0.171	6.0056
18	45	55	20	220	0.23	0.119	4.1893
19	90	60	40	230	0.2	0.155	6.9138
20	90	60	80	210	0.2	0.235	7.8513
21	90	50	80	230	0.2	0.241	7.9099
22	-45	55	60	220	0.23	0.169	6.4451
23	0	50	80	230	0.26	0.256	5.8592
24	45	55	60	220	0.23	0.172	6.0349
25	0	60	80	230	0.2	0.229	6.1814
26	45	55	60	220	0.23	0.174	6.1228
27	0	60	80	210	0.26	0.244	5.6834
28	45	55	60	240	0.23	0.17	6.2986
29	45	55	60	220	0.23	0.17	6.3279
30	45	55	60	220	0.29	0.169	6.1521
31	45	55	60	220	0.17	0.173	6.6501
32	0	60	40	210	0.2	0.166	4.951

STEP 1: Normalize the Decision-matrix

The subsequent procedure involves the transformation of different attribute dimensions into non-dimensional attributes, thereby enabling the facilitation of comparisons across multiple criteria. The rationale behind this phenomenon originates from the fact that distinct criteria are evaluated using separate units of measurement. The process of normalizing values can be effectively executed through the utilization of a standardized formula, as presented below in Table 2 and also shown in Figures 2,3 & 4.

$$X_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^{2}}} \tag{1}$$

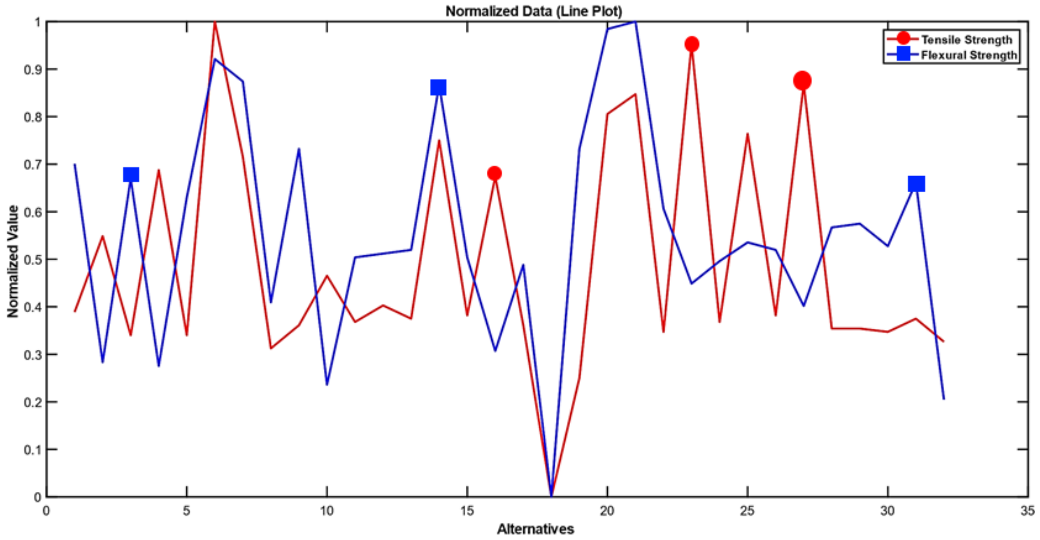


Figure 1. Normalized data as a line plot.

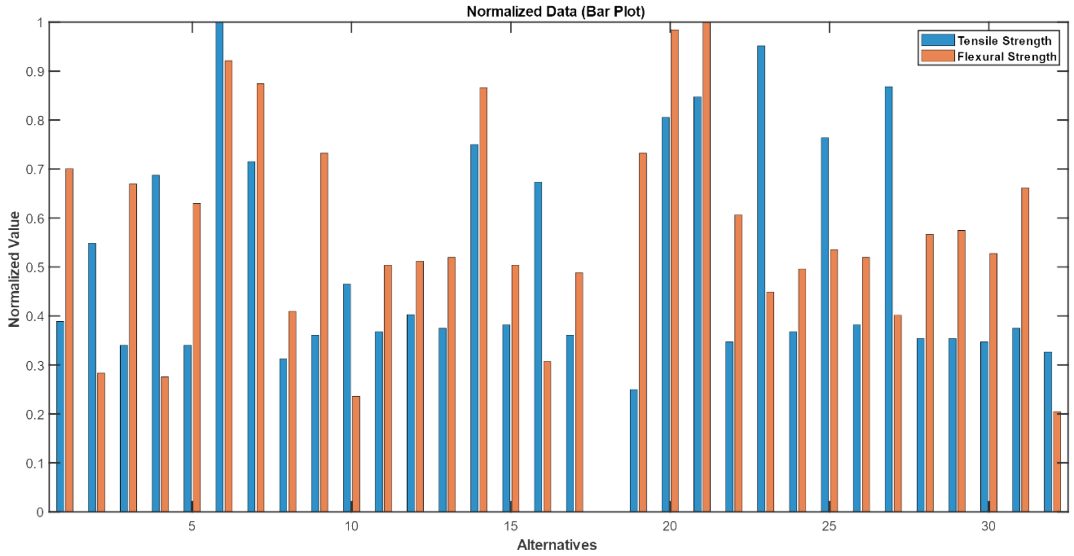
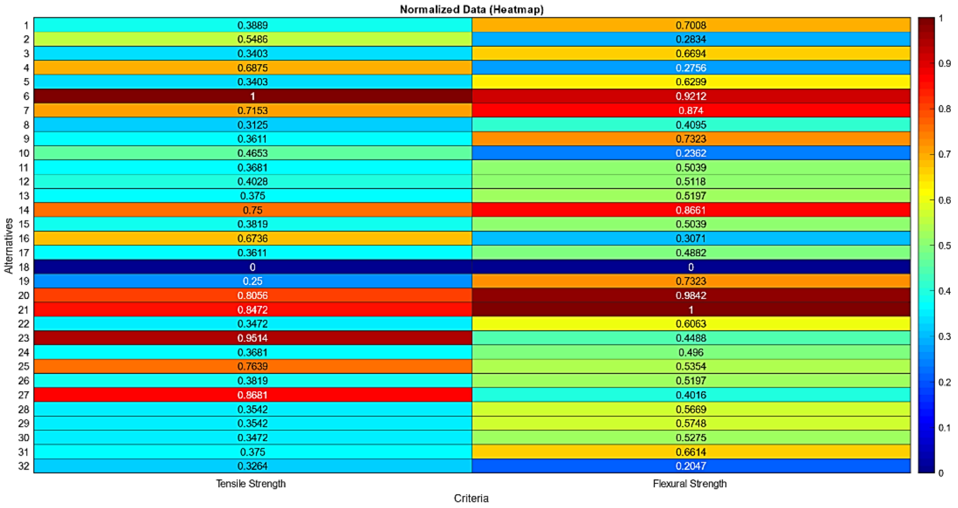


Figure 2. Normalized data (bar pot).



Alternatives	Tensile Strength	Flexural Strength
1	0.3889	0.7008
2	0.5486	0.2834
3	0.3403	0.6694
4	0.6875	0.2756
5	0.3403	0.6299
6	1	0.9212
7	0.7153	0.874
8	0.3125	0.4095
9	0.3611	0.7323
10	0.4653	0.2362
11	0.3681	0.5039
12	0.4028	0.5118
13	0.375	0.5197
14	0.75	0.8661
15	0.3819	0.5039
16	0.6736	0.3071
17	0.3611	0.4882
18	0	0
19	0.25	0.7323
20	0.8056	0.9842
21	0.8472	1
22	0.3472	0.6063
23	0.9514	0.4488
24	0.3681	0.496
25	0.7639	0.5354
26	0.3819	0.5197
27	0.8681	0.4016
28	0.3542	0.5669
29	0.3542	0.5748
30	0.3472	0.5275
31	0.375	0.6614
32	0.3264	0.2047

Figure 3. Normalized data (heatmap).

Table 2. Normalized decision matrix

Tensile Strength	Flexural Strength
0.3889	0.7008
0.5486	0.2834
0.3403	0.6694
0.6875	0.2756
0.3403	0.6299
1.0000	0.9212
0.7153	0.8740
0.3125	0.4095
0.3611	0.7323
0.4653	0.2362
0.3681	0.5039
0.4028	0.5118
0.3750	0.5197
0.7500	0.8661
0.3819	0.5039
0.6736	0.3071
0.3611	0.4882
0.0000	0.0000
0.2500	0.7323
0.8056	0.9842
0.8472	1.0000
0.3472	0.6063
0.9514	0.4488
0.3681	0.4960
0.7639	0.5354
0.3819	0.5197
0.8681	0.4016
0.3542	0.5669
0.3542	0.5748
0.3472	0.5275
0.3750	0.6614
0.3264	0.2047

STEP 2: Make a Decision Matrix that is Normalized and Weighted

Alternatives are compared using a weighted decision matrix that takes into account several factors that have varying degrees of significance. It is useful for ranking every option in relation to a set reference. The following formula is used to multiply Step 1 by the weight of the criterion. We give each component equal weight by multiplying it by 0.5.

$$V_{ij} = X_{ij} \times W_j \tag{2}$$

STEP 3: Find the Ideal Max and Min. Solutions

In this step we find the max and min of the above given criteria. TOPSIS algorithm finds the distance for each options using +ve and -ve ideals. As a result, the +ve and -ve ideal solution are calculated and shown in the Figure 5.

V+	0.2630	7.9099
V-	0.119	4.1893

STEP4: Distance for +ve and -ve Ideal Solutions

In TOPIS method no of distance matrices can be applied. TOPSIS calculates each alternative depending on how close it is to the +ve ideal and how far it is from the -ve ideal. As a result, the distances between each option and the positive and negative ideal solutions are calculated in this stage using the equations below.

$$S_i^- = \left[\sum_{j=1}^{m}\left(V_{ij} - V_j^-\right)^2\right]^{0.5} \quad S_i^+ = \left[\sum_{j=1}^{m}\left(V_{ij} - V_j^+\right)^2\right]^{0.5} \qquad (3)$$

STEP 5: Determine the Degree of Similarity of Alternatives to the Optimum Solution

At this point, each alternative's degree of closeness to the ideal solution is calculated using the equation below. If the relative closeness degree is close to one, the alternative is more closely aligned with the +ve ideal solution than the -ve ideal solution. It is now possible to rank the list of choices in descending order [19] as shown in the Table 3 and can visualized through Figure 6.

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \qquad (4)$$

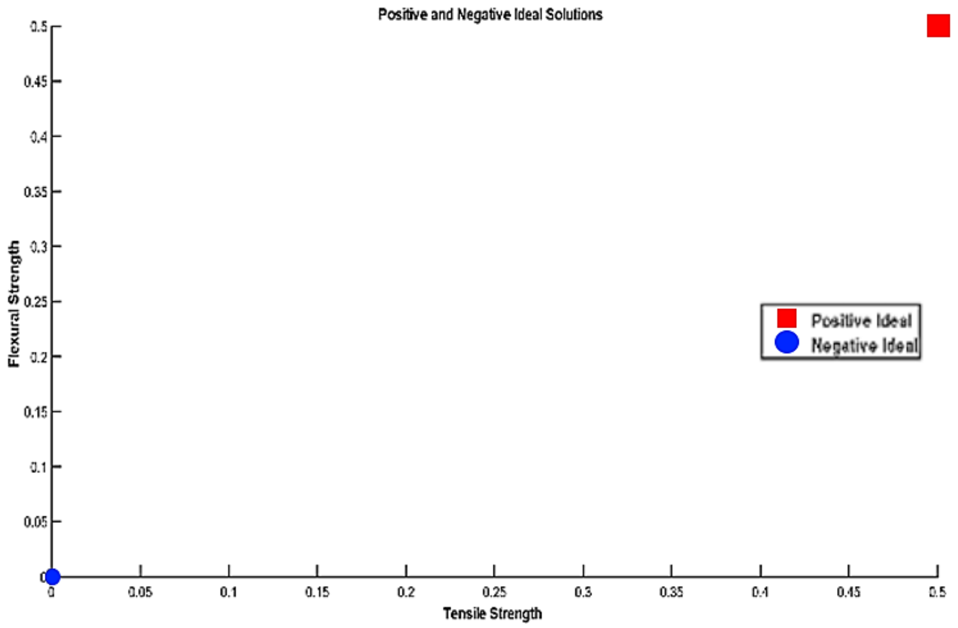


Figure 4. Positive and negative ideal solutions

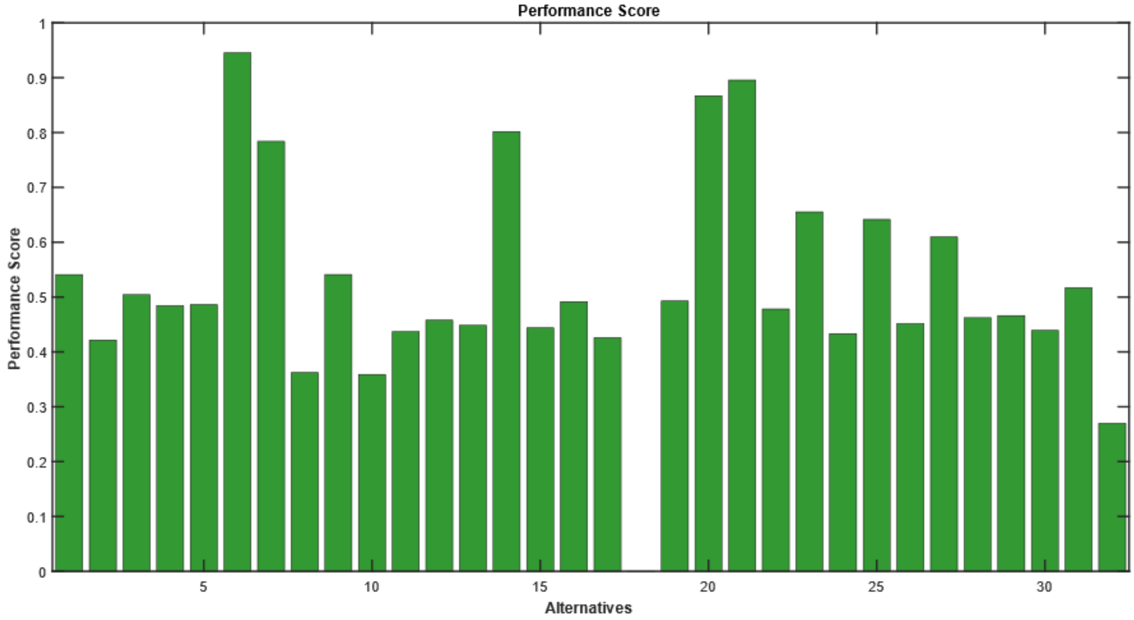


Figure 5. Performance score

Table 3. The computed TOPSIS and the final rank generated sequence.

S.No.	Tensile Strength	Flexural Strength	Si+	Si-	Performance score (Pi)	Rank
1	0.1944	0.3504	0.3402	0.40075	0.5409	10
2	0.2743	0.1417	0.4234	0.30875	0.4217	28
3	0.1701	0.3347	0.3690	0.37544	0.5043	12
4	0.3438	0.1378	0.3945	0.37034	0.4842	16
5	0.1701	0.3150	0.3782	0.35798	0.4863	15
6	0.5000	0.4606	0.0394	0.67983	0.9453	1
7	0.3576	0.4370	0.1557	0.56469	0.7839	5
8	0.1563	0.2047	0.4532	0.25754	0.3624	29
9	0.1806	0.3661	0.3464	0.40824	0.5410	9
10	0.2326	0.1181	0.4662	0.26091	0.3588	30
11	0.1840	0.2520	0.4017	0.31201	0.4372	25
12	0.2014	0.2559	0.3857	0.32564	0.4578	20
13	0.1875	0.2598	0.3941	0.32042	0.4484	22
14	0.3750	0.4331	0.1418	0.57286	0.8016	4
15	0.1910	0.2520	0.3963	0.31616	0.4438	23
16	0.3368	0.1535	0.3830	0.37015	0.4915	14
17	0.1806	0.2441	0.4093	0.30361	0.4259	27
18	0.0000	0.0000	0.7071	0.00000	0.0000	32
19	0.1250	0.3661	0.3982	0.38689	0.4928	13
20	0.4028	0.4921	0.0975	0.63594	0.8670	3
21	0.4236	0.5000	0.0764	0.65532	0.8956	2
22	0.1736	0.3032	0.3812	0.34934	0.4782	17
23	0.4757	0.2244	0.2767	0.52597	0.6553	6
24	0.1840	0.2480	0.4041	0.30884	0.4332	26
25	0.3819	0.2677	0.2606	0.46642	0.6416	7
26	0.1910	0.2598	0.3914	0.32247	0.4517	21
27	0.4340	0.2008	0.3064	0.47822	0.6095	8
28	0.1771	0.2835	0.3888	0.33423	0.4623	19
29	0.1771	0.2874	0.3866	0.33758	0.4661	18
30	0.1736	0.2638	0.4029	0.31578	0.4394	24
31	0.1875	0.3307	0.3554	0.38016	0.5168	11
32	0.1632	0.1024	0.5211	0.19264	0.2699	31

RESULT

The utilization of the TOPSIS approach facilitated the identification of the most appropriate or optimized parameters derived from numerous experiments, thereby enabling the determination of the optimal 3D printing parameter settings for the Fused Filament Fabrication technique. The present investigation was undertaken by collecting data subsequent to the execution of an experiment employing a combination of parameters, as per the design of experiment utilizing response surface methodology. The technique of TOPSIS was applied, wherein the values were normalized using a specific function and subsequently multiplied by the corresponding weighted matrix value, which was set at 0.5 for each factor, namely tensile and flexural strength. Through this approach, the minimum and maximum values for both factors were obtained. The current approach allows for the calculation of the spatial separations between positive and negative ideal solutions, subsequently allowing for the evaluation of the extent to which similarity has been attained. The obtained results are subsequently ranked based on their respective pi values, with higher pi values corresponding to higher ranks. Based on the findings of the TOPIS analysis, it has been determined that the experiment conducted on the sixth iteration yielded the optimal solution. This optimal solution was achieved by employing a layer height of 0.23 mm, a print speed of 55 mm/s, print orientation at 45°, an infill density of 80% and Print temperature of 220°C. The attainment of enhanced tensile and flexural strength concurrently necessitates the identification and implementation of optimal process parameters.

CONCLUSION

In this study, the ideal setting parameters in the Fused Filament Fabrication technique of PLA material in terms of flexural strength and tensile strength were determined. The method was controlled by five parameters: print orientation, infill density, print speed, layer height and print speed. TOPSIS approach was used to examine the best findings from all three quality responses at the same time. The study's findings revealed that the best settings to use were layer height of 0.23 mm, a print speed of 55 mm/s, print orientation at 45°, an infill density of 100% and Print temperature of 220°C.

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