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Multi-Feature Geometric Accuracy Optimization in FDM Additive Manufacturing via Taguchi Design and 3D Deviation Analysis

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Abstract

This study aims to evaluate the effect of Fused Deposition Modeling (FDM) 3D printing process parameters on the accuracy of printed objects. In this study layer height, building direction, print speed, and print temperature parameters are considered. Taguchi method is employed for planning and analysis of experiments. The RAISE 3D E2 3D printer is used to fabricate PLA test specimens with varying parameter settings. The build time, material consumption, and accuracy of the manufactured object are evaluated. The findings indicate that layer height is the main factor influencing printing performance, with optimal precision obtained at a 0.2 mm layer height under extreme printing conditions (0° build orientation, 40 mm/s print speed, and 225°C print temperature).

Keywords
3D printing, Fused Deposition Modeling, Printing time, 3D comparison, Accuracy.

1. Introduction and Literature review
Development of prototypes is a crucial step in the finalization of the product design. Currently rapid prototyping has been implemented instead of other prototyping techniques. Rapid Prototypes are developed by 3D printing technology it's wherein a physical model is directly produced from digital model by adding the materials layer by layer (Sumalatha et al., 2021),(Ameen et al., 2019b). 3D printing technologies have been also used for rapid tooling and manufacturing because of the advancements in materials and technologies (Levy et al., 2003). There are many technologies and methods that fall under the broad umbrella of 3D printing, and one of the widely used ones is FDM, which has been applied in several fields and applications due to its simplicity, reliability, and affordability(Ameen, 2024). Figure 1 shows the schematic of an FDM 3D printing process. The FDM technology operates by extruding heated polymer filaments through a nozzle to successively deposit layers onto a platform, therefore fabricating sections from a computerized model of the object(Ameen et al., 2019a).

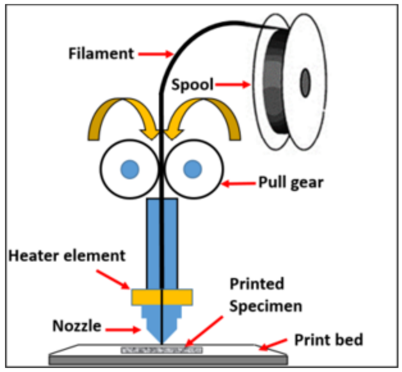


Figure 1. FDM Process Schematic (Ahmad et al., 2022)

Attention has been given towards optimizing the influence of design and process parameters on the performance of the FDM process. In order to optimize the support area, building time, and surface roughness, Aijun et al. [2010] proposed a methodology for selecting the fabrication orientation for fused deposition rapidly prototype models. Rapid prototyping systems' processing efficiency was increased by the suggested optimization strategy, which also clearly decreased costs (Aijun et al., 2010).Wang et al., (2007) assessed the tensile strength, surface roughness, and accuracy of dimension of parts produced via FDM, which were influenced by layer thickness, deposition method, support configuration, and build orientation. While layer thickness substantially influences the surface roughness, the results indicated that building orientation significantly affects tensile strength and dimensions accuracy. To attain an optimal surface finish and reduce fabrication time, Thrimurthulu et al. (2004) utilized a genetic algorithm to identify the optimal deposition orientation for the fused deposition modeling technique. Sood et al., (2010) used experimental design to explore the influence of FDM process parameters on the mechanical properties of the end product. Tensile and flexural impact strength are utilized to assess mechanical qualities, with influencing parameters including layer thickness, orientation, raster angle, raster width, and air gap. According to Pandey et al. (2007), the orientation of the part deposition has an impact on the prototype's cost, surface finish, dimensional accuracy, construction time, and support structure. Zonoobi et al. (2025) proposed a multi-objective optimization model for the parameters of the FDM process, that includes build orientation, layer height, infill density, temperature of nozzle , speed of printing, number of shells, infill pattern, and position of print, aimed at enhancing tensile strength, dimensional accuracy, and cost efficiency in manufacturing.

Nonetheless, 3D printing, particularly FDM process, continues to face difficulties in achieving consistent geometric accuracy across different feature types. Most previous studies evaluated the accuracy using a limited number of geometric characteristics. In contrast, the present study adopts a multi-feature geometric accuracy approach by assessing the printing performance of several representative geometric features, including cylindrical, spherical, triangular, and prismatic elements within a single benchmark specimen. This approach provides a more comprehensive evaluation of the printer's capability to reproduce complex geometries and justifies the use of the term "multi-feature geometric accuracy" throughout this work. Therefore, the Taguchi method is employed to optimize the FDM process parameters.

2. Material and Method

To assess the accuracy and performance of FDM 3D printing process benchmark specimen was designed using SolidWorks software. As illustrated in figure2, the benchmark specimen includes several common geometric features, such as, square, cylindrical, spherical and triangular shapes. These geometric features were specially selected because they represent the basic geometric features that are frequently observed in 3D printing and because they provide a thorough evaluation of the printer's capability to accurately replicate a range of forms. Unlike traditional accuracy studies that focus on a single feature or dimension, the proposed benchmark integrates multiple geometric features with different curvature characteristics and surface profiles. Consequently, the obtained RMSD value reflects the overall geometric reproduction capability of the FDM process across multiple feature categories rather than a single dimensional characteristic.

Through the inclusion of these essential geometrical features, the benchmark specimen guarantees that most of the crucial elements of FDM 3D printing performance are assessed.

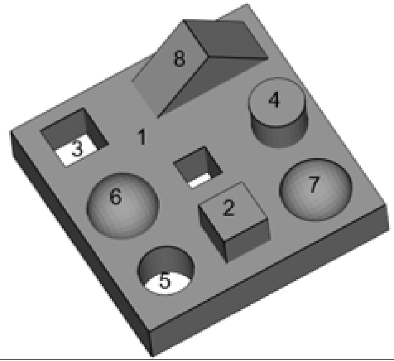


Figure 2. Benchmarking specimen for 3D printing accuracy test

The key FDM process parameters were considered in this study encompasses layer thickness (height), orientation of printing, speed of print and temperature of print. Table 1 lists these factors alongside their respective levels.

Table 1. Parameters and their levels in the FDM process

Parameter	**Parameter Levels**		
	1	**2**	**3**
Layer Height -A (mm)	0.1	0.2	0.3
Print Orientation - B (º)	0	45	90
Print Speed - C (mm/s)	40	60	80
Print Temperature D (°C)	190	205	220

This study uses Taguchi design to reduce the extensive number of tests, utilizing an orthogonal array to explore the whole parameter space with a reduced number of experiments. Objective Function in this study is, Smaller-the-Better (to minimize response).
S/N Ratio for this function:

$$S/N = -10 \log_{10}\left((1/n)\, \Sigma^{n}_{i=1} y_i^{2} \right) \qquad [1]$$

Where, n= Sample Size, and y= Printing time, Material consumption, or accuracy in that run.
The chosen orthogonal array for experimentation is the L9 array, as presented in Table 2. Consequently, a total of nine tests will be conducted.

Table 2. Matrix experiment with process parameters

Exp.#	**A**	**B**	**C**	**D**
Unit	(mm)	(º)	(mm/s)	(°C)
1	0.1	0	40	190
2	0.1	45	60	205
3	0.1	90	80	220
4	0.2	0	60	220
5	0.2	45	80	190
6	0.2	90	40	205
7	0.3	0	80	205
8	0.3	45	40	220
9	0.3	90	60	190

Based on the previously designed experimental matrix,the models were prepared on ideaMaker software, where the process parameters were adjusted. The designed specimens were then manufactured using the Raise3D E2 3D printer an, which works under the umbrella of FDM technology, with PLA plastic as the printing material. Figure 3 shows samples of manufactured specimens in different print orientation.

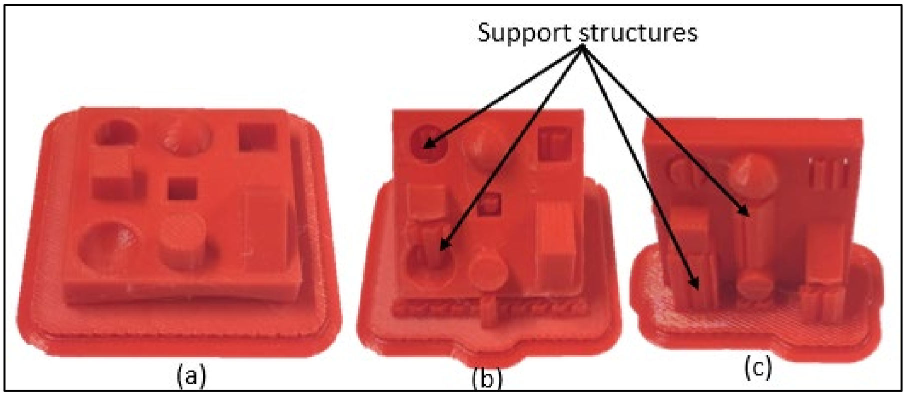


Figure 3. Manufactured specimen (a) 0º print orientation (b) 45º print orientation (c) 90º print orientation

The printing time (min) and the material consumption (g) were directly collected from the ideaMaker software after the experiment parameters are setting and the slicing process is done. Regarding the accuracy of the printed specimens, 3D comparison analysis was conducted in which the produced samples have been scanned utilizing the Creaform HandySCAN 700 3D scanner, as depicted in Figure 4. The scanned models were then compared with the CAD models using Geomatic software Control X as shown in figure 5. The reference model (CAD model) was aligned with the scanned model utilizing the Best Fitting Alignment method. To check the differences between the surfaces of the CAD models, 1500 points on the scanned model were aligned with their corresponding places on the reference model. The variation are defined as a negative deviation, signifying that the scanned model is smaller than the reference CAD model, and a positive variation, signifying that the scanned model is larger than the reference CAD model, as illustrated in figures 6 and 7. The root-mean-square variation (RMSD) had been used as an accuracy metric.

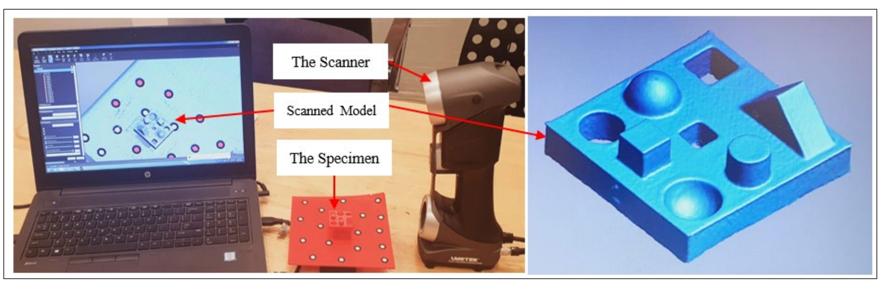


Figure 4. Scanning of the specimen

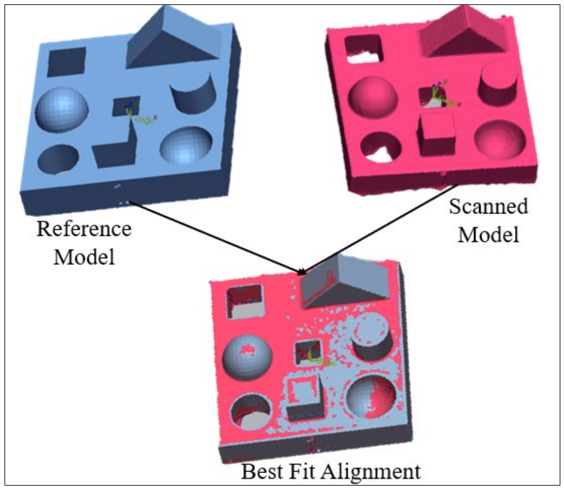


Figure 5. CAD Model and scanned model best fit alignment

Figure 5 illustrates the best-fit alignment procedure between the reference CAD model and the scanned specimen. This alignment minimizes the global deviation between the two datasets and establishes a common coordinate system before performing the deviation analysis. Accurate alignment is essential to ensure that the measured deviations are attributed to manufacturing errors rather than positioning differences. Figure 6 presents a typical 3D deviation map obtained from the comparison analysis.

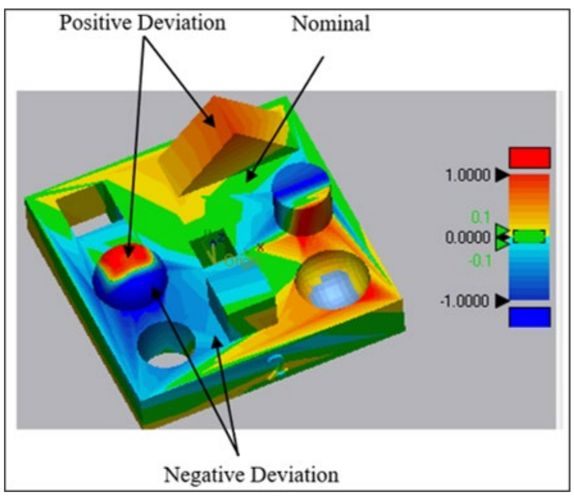
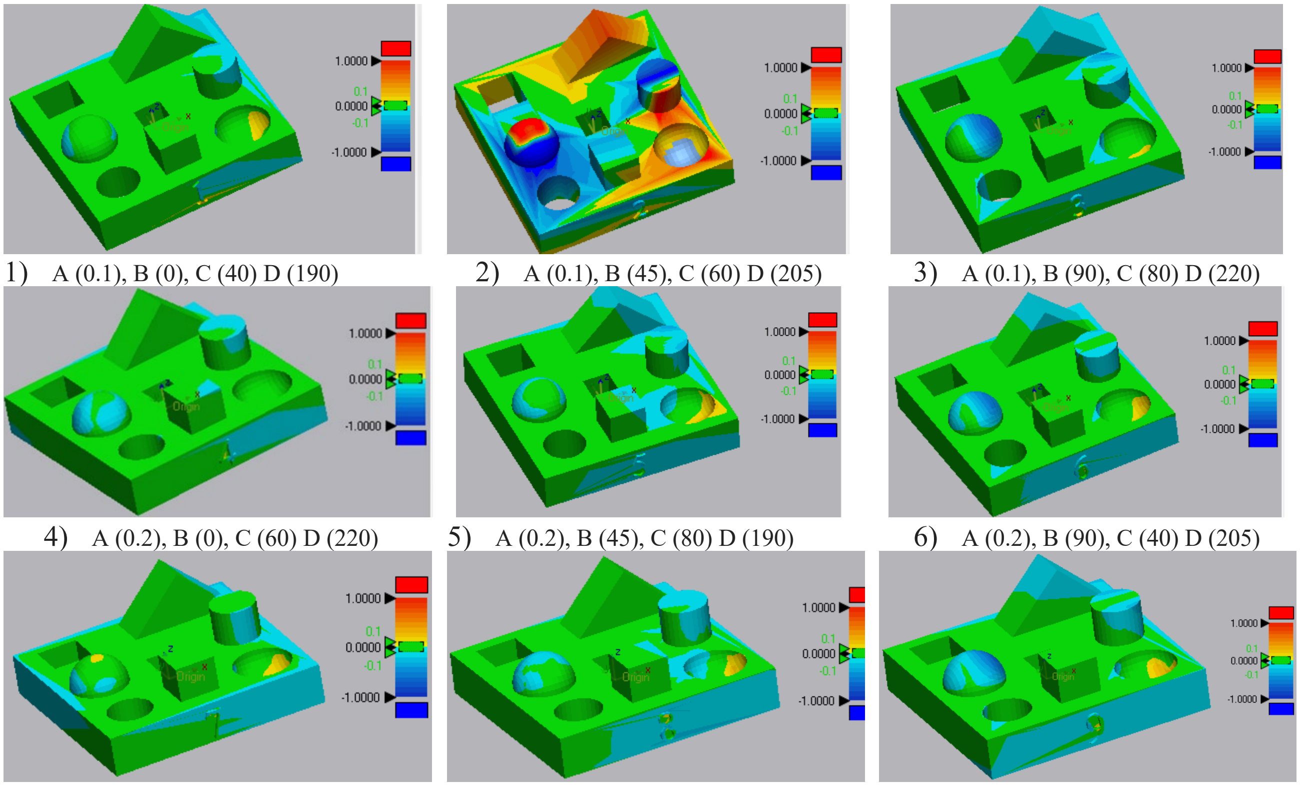


Figure 6. 3D comparison analysis results

The color distribution represents the local geometric deviations between the scanned specimen and the reference CAD model. Green regions indicate good agreement, whereas warm colors (yellow to red) indicate positive deviations and cool colors (light blue to dark blue) indicate negative deviations. The predominance of green areas demonstrates satisfactory geometric reproduction for most regions of the specimen.



1) A (0.1), B (0), C (40) D (190)
2) A (0.1), B (45), C (60) D (205)
3) A (0.1), B (90), C (80) D (220)
4) A (0.2), B (0), C (60) D (220)
5) A (0.2), B (45), C (80) D (190)
6) A (0.2), B (90), C (40) D (205)
7) A (0.3), B (0), C (80) D (205)
8) A (0.3), B (45), C (40) D (220)
9) A (0.3), B (90), C (60) D (190)

Figure 7. Comprehensive 3D Comparison results of Experiments 1–9

Figure 7 summarizes the deviation maps for all nine experimental runs. Considerable variation in deviation patterns can be observed among the different parameter combinations. Experiments 1, 3, 4, 6, 7, 8, and 9 exhibit predominantly green regions, indicating relatively high geometric accuracy. In contrast, Experiment 2 shows a larger proportion of red and blue regions, corresponding to increased geometric deviations and resulting in the highest RMSD value among all experiments. These observations are consistent with the quantitative RMSD results presented in Table 3.

3. Results and discussion

The printing time, material consumption and the accuracy error (RMSD) of each experiment are recorded and listed in table 3.

Table 3. Results of Experiments

Exp.#	**Printing Time**	**Material consumption**	**Accuracy (RMSD)**
Unit	(min)	(g)	(mm)
1	133	12.2	0.183
2	172	16.8	0.6752
3	127	11.7	0.1806
4	64	12.3	0.1493
5	90	16.9	0.1943
6	81	11.7	0.1572
7	44	12.1	0.1686
8	74	17	0.1835
9	49	11.7	0.1884

3.1 Descriptive Analysis

The presented results demonstrated that there are variations in printing time, material consumption, and RMSD corresponding to different process parameter settings. The printing duration ranged from 44 to 172 min, with an average of 92.7 min and a standard deviation of 39.8 min, indicating considerable variability in process times depending on the selected parameters. Regarding material consumption, the results remained comparatively consistent, ranging from 11.7 to 17.0 g, with an average of 13.93 g and a standard deviation of 2.26 g, demonstrating that material usage was only minimally influenced by changes in printing conditions. Concerning accuracy assessed via RMSD, the values varied from 0.149 mm to 0.675 mm, with a average of 0.230 mm and a standard deviation of 0.157 mm. The majority of experiments demonstrated high accuracy, with RMSD values below 0.2 mm, while Experiment 2 stood out as an anomaly with significantly increased error, likely due to suboptimal parameter configurations.

3.2 process parameters contribution

Due to the constraints of a limited experimental design (L9), ANOVA with the technique of Taguchi was utilized to quantify the percentage contribution. of each process parameter, rather than focusing on statistical significance testing as shown in table 4. The findings clearly demonstrate the comparative impact of each parameter on the chosen responses.

Table 4. Contribution analysis of process parameters for different responses

Parameters	Printing Time	Material consumption	Accuracy (RMSD)
A (%)	64.12	1.19	27.35
B (%)	24.73	95.22	28.48
C (%)	10.15	1.19	22.06
D (%)	00.99	2.39	22.12

Table 4 illustrates the contribution analysis of the FDM process parameters for the defined responses. Regarding printing time, layer height (A) is the primary parameter, accounting for 64.12% of the overall effect, followed by print orientation (B) at 24.73%. Print speed (C) shows a moderate impact, whereas print temperature (D) has a minimal effect. In relation to material usage, print orientation (B) is the most significant factor, contributing 95.22% to the overall effect, while the other parameters demonstrate negligible influence. Concerning accuracy (RMSD), layer height (A) and print orientation (B) show comparable influences, demonstrating that both parameters are crucial in regulating geometric precision. Print speed (C) and print temperature (D) also exhibit significant influence, underscoring the multi-parameter complexity of accuracy regulation in FDM.

3.3 Main Effects Plot for Means

The primary influences of process factors on printing duration (printing time) and material use (material consumption) and the accuracy error (RMSD) are shown in figures 8-10. Figure 8 illustrates the main effects of process parameters on the time of printing. It's clear the height of layer has the most significant influence on the printing time, as the height of layer increased the printing time decreased due to the reduce on the number of layers. Print orientation illustrates a moderate effect on the printing time, the orientation 45° results in longer printing time compared to the other orientations0° and 90° due to increased complexity of the toolpath and support requirements. Print speed shows a relatively low impact, where higher speeds slightly reduce the printing time. The limited impact of print speed on printing time can be returned to the inability to reach the required acceleration within the size of the test specimen and the printing conditions.

Similarly, print temperature has a slight impact on printing time because temperature primarily influences material fl ow and quality rather than printing time.

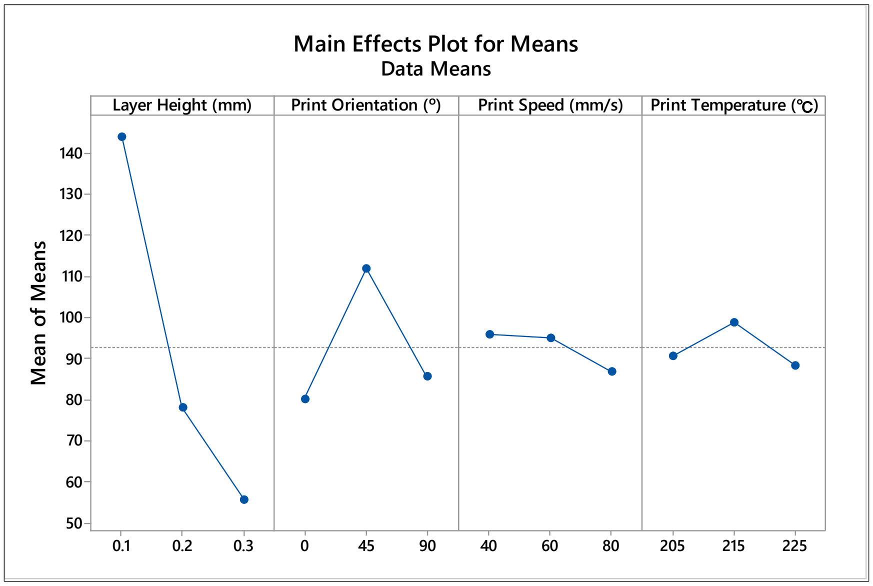


Figure 8. The main effects of process parameters on printing time

The steep slope associated with layer height confirms its dominant influence on printing time. Increasing layer height reduces the total number of deposited layers and consequently decreases fabrication time. The comparatively flatter slopes of print speed and print temperature indicate a weaker influence on this response.

Figure 9 shows that total material used remains almost constant with changing layer height, print speed and print temperature. The print orientation has effect on the used material due to the support structure requirement.

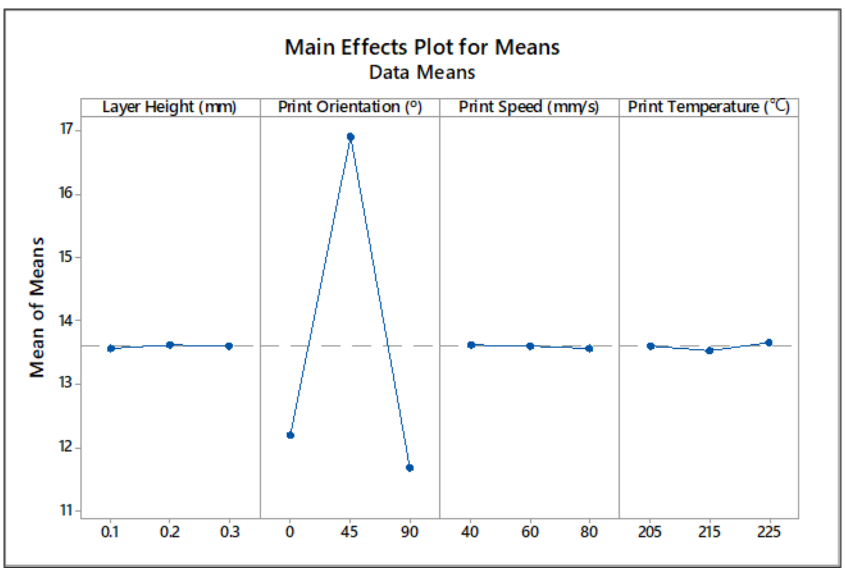


Figure 9. The primary impacts of process factors on how material is used

The nearly horizontal trends observed for layer height, print speed, and print temperature suggest limited influence on material consumption. Conversely, print orientation produces a noticeable variation due to differences in support structure generation and deposition strategy.

The main effects plot illustrates the impact of four 3D printing factors on accuracy error (RMSD), with lower values indicating more precision as shown in figure 10. Layer height exerts the most significant impact, with the minimal inaccuracy attained at 0.2 mm. The data for the remaining three variables Print Orientation, Speed, and Temperature indicates a non-linear "peak" pattern, wherein the intermediate values (45°, 60 mm/s, and 215°C) yield the most mistakes.

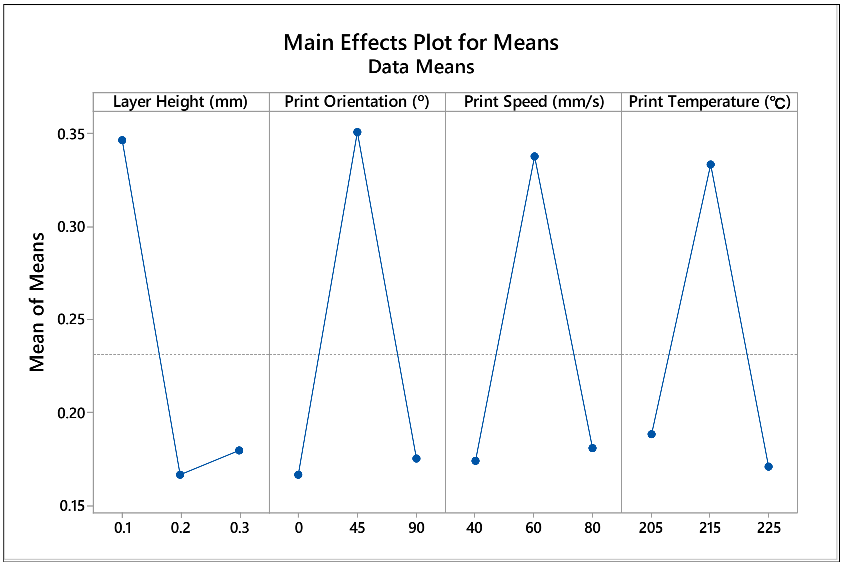


Figure 10. The primary influences of process parameters on the RMSD accuracy error

The main effects plot reveals that accuracy is influenced by all the parameters investigated. However, the minimum RMSD is achieved at a layer height of 0.2 mm, suggesting that moderate layer thickness provides a balance between staircase effects and process stability. The non-linear trends observed for orientation, speed, and temperature indicate the presence of interaction mechanisms that may influence geometric accuracy.

Therefore, to optimize print precision, one should eschew mid-range values and employ a 0.2 mm layer height along with extreme parameters such as 0° orientation, 40 mm/s speed, and 225°C temperature.

4. Conclusions

This study used the Taguchi technique to evaluate and improve the influence of FDM process parameters on printing time, consumption of materials, and accuracy (RMSD). From the experimental data and statistical analysis, the subsequent conclusions can be inferred:
Layer height is the most significant factor affecting printing time, contributing 64.12% to the overall impact. Augmenting layer height markedly lowers print duration by reducing the overall layer count.
Material consumption is mainly affected by print orientation, contributing 95.22% because to the different requirem ents for support structures.
Layer height, print orientation, print speed, and print temperature show comparable influences are crucial in regulating accuracy error (RMSD).
Different responses require different parameter combinations. However, when geometric accuracy is considered the primary objective, the optimal settings are A2-B1-C1-D3 corresponding to 0.2 mm layer height, 0° orientation, 40 mm/s print speed, and 225°C print temperature.

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References

Ahmad, M.N., Ishak, M.R., Mohammad Taha, M., Mustapha, F., Leman, Z., Anak Lukista, D.D., et al., Application of Taguchi method to optimize the parameter of fused deposition modeling (FDM) using oil palm fiber reinforced thermoplastic composites, Polymers, vol. 14, no. 11, p. 2140, 2022.

Aijun, L., Zhuohui, Z., Daoming, W. and Yang, J., Optimization method to fabrication orientation of parts in fused deposition modeling rapid prototyping, Proceedings of the 2010 International Conference on Mechanic Automation and Control Engineering (MACE), pp. 416-419, IEEE, 2010.

Ameen, W., Khan Mohammed, M. and Al-Ahmari, A., Evaluation of support structure removability for additively manufactured Ti6Al4V overhangs via electron beam melting, Metals, vol. 9, no. 11, p. 1211, 2019.

Ameen, W., Mian, S.H. and Alkhalefah, H., Design the support structures for fused deposition modeling 3D printing, Proceedings of the International Conference on Industrial Engineering and Operations Management, pp. 814-825, 2019.

Ameen, W., Design for 3D printing: Developing design rules for fused deposition modeling technology, Proceedings of the 14th Annual International Conference on Industrial Engineering and Operations Management, IEOM Society, 2024.

Chung Wang, C., Lin, T.-W. and Hu, S.-S., Optimizing the rapid prototyping process by integrating the Taguchi method with the Gray relational analysis, Rapid Prototyping Journal, vol. 13, pp. 304-315, 2007.

Changhui, L.I.U., Hao, L.I., Chunlong, Y.U., Xueru, L.I.A.O., Xiaojia, L.I.U., Jianzhi, S.U.N., et al., Balanced optimization of dimensional accuracy and printing efficiency in FDM based on data-driven modeling, Additive Manufacturing Frontiers, p. 200220, 2025.

Levy, G.N., Schindel, R. and Kruth, J.P., Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies: State of the art and future perspectives, CIRP Annals, vol. 52, no. 2, pp. 589-609, 2003.

Pandey, P., Reddy, N.V. and Dhande, S., Part deposition orientation studies in layered manufacturing, Journal of Materials Processing Technology, vol. 185, pp. 125-131, 2007.

Sood, A.K., Ohdar, R. and Mahapatra, S., Parametric appraisal of mechanical property of fused deposition modelling processed parts, Materials & Design, vol. 31, pp. 287-295, 2010.

Sumalatha, M., Rao, J.M. and Reddy, B.S., Optimization of process parameters in 3D printing-fused deposition modeling using Taguchi method, IOP Conference Series: Materials Science and Engineering, vol. 1112, no. 1, p. 012009, 2021.

Thrimurthulu, K., Pandey, P.M. and Reddy, N.V., Optimum part deposition orientation in fused deposition modeling, International Journal of Machine Tools and Manufacture, vol. 44, pp. 585-594, 2004.

Zonoobi, M.A., Haghshenas Gorgani, H. and Javaherneshan, D., Experimental investigation and multi-objective optimization of FDM process parameters for mechanical strength, dimensional accuracy, and cost using a hybrid algorithm, 2025.

Biography

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