https://doi.org/10.24867/FUTURE-BME-2024-095 Original scientific paper

APPLICATION OF THE TAGUCHI METHOD FOR OPTIMIZING THE 3D PRINTING PROCESS FROM THE ASPECTS OF PRODUCTIVITY AND DIMENSIONAL ACCURACY

Dejan Bozic[1] [0009-0009-1095-8101], *Mijodrag Milosevic*[1] [0000-0002-8950-4867],
Zeljko Santosi[1] [0000-0003-3975-0864], *Stevo Borojevic*[1], *Borislav Savkovic*[1] [0000-0002-9037-2179],
Dejan Lukic[1] [0000-0002-1566-282X]

Abstract

This study uses the Taguchi method to optimize 3D printing conditions and identify key factors influencing fabrication time and dimensional accuracy. Three input parameters—printing speed, layer height, and infill percentage—were tested at three levels using Minitab software to analyze results via Analysis of Variance (ANOVA). 3D models were designed in CAD software, exported in STL format, and processed with software for 3D printing on a 3D printer using FDM technology. Dimensional accuracy was verified with a 3D scanner. Results showed that layer height significantly affected print time, with larger heights reducing it due to fewer layers. Infill percentage also influenced print time, with lower percentages speeding up fabrication. Although printing speed mattered, it wasn't statistically significant. This research offers valuable insights for optimizing 3D printing parameters, enhancing quality and efficiency in part production.

Key words: *Optimization, 3D printing, 3D scan, 3D modeling*

1. Introduction

This study investigates the optimization of 3D printing parameters using the Taguchi method to enhance part fabrication time and dimensional accuracy. By examining factors such as printing speed, layer height, and infill percentage, the research identifies significant influences on the printing process. Taguchi's method of experiment planning is a unique and very powerful technique for experimental analysis and optimization of products, processes, etc. (Vukman et al. 2023). Utilizing Minitab software for experimental design and Analysis of Variance (ANOVA), the study systematically analyzes these parameters. The findings aim to provide

[1] University of Novi Sad, Faculty of Technical Sciences, Serbia

insights into improving efficiency and quality in 3D printing applications, ultimately contributing to advancements in additive manufacturing techniques.

2. Literature review

Technologies such as 3D printing today fing a high position in terms of research and scientific contributions. A large number of papers concerning this technology are being published, and below is a brief overview of only a few papers that have dealt with this interesting topic. Polyamide (PA) is a key material in FDM 3D printing due to its excellent mechanical and tribological properties. This study investigates the impact of two parameters – nozzle temperature and layer thickness – on the performance of PA-printed parts. Increasing the nozzle temperature from 240°C to 260°C improves mechanical properties and reduces the wear rate, with little effect on the coefficient of friction (COF). Conversely, increasing the layer thickness from 0.1 mm to 0.3 mm reduces mechanical strength while increasing COF. Polishing significantly raises the COF of the printed parts (Wang et al., 2024). This study demonstrates the successful use of FDM technology for 3D printing complex combustible structures based on ammonium perchlorate/poly (lactic acid) (PLA) composites. Mechanical and thermal properties of filaments with 65% AP were tested, showing that structures can burn in a self-sustaining mode. The optimal extrusion temperature was found to be 180°C. Results indicate that the AP/PLA composite can be used to produce combustible structures without the need for solvents or special binders, allowing for the creation of complex geometries with high solid content (Monogarov et al., 2022). The study introduces a novel extruder for FDM 3D printers designed to produce continuous fiber-reinforced thermoplastic (CFRT) composites. This extruder can be mounted on existing FDM printers, eliminating the need for new chassis designs. Key challenges, such as fiber tension, surface preparation, and extrusion parameters, are addressed. Tests show that carbon fiber-reinforced PLA composites exhibit significantly higher tensile and bending strengths compared to pure PLA. Morphological analysis confirms strong fiber/matrix bonding, highlighting the technology's potential for high-performance applications in various industries. (Heidari-Rarani et al., 2019). This review examines methods for producing thermally conductive polymers or composites for FDM 3D printing. While FDM is popular for prototyping and manufacturing due to its affordability, polymers like PLA and ABS have low thermal conductivity. The review discusses enhancing conductivity using conductive fillers, modifying polymer crystallinity, and adjusting molecular orientation. It also explores 3D printing's ability to create advanced geometries and conductive networks, while addressing challenges like nozzle clogging. The review emphasizes the need for further research to develop high-performance thermally conductive filaments and improve processing techniques (Roudný & Syrový, 2022). The article examines advancements in Additive Manufacturing, with a focus on Fused Deposition Modeling (FDM) and optimizing tensile strength through parameters like infill density and extrusion temperature. It investigates ABS, PETG, and their composite, using Artificial Neural Networks (ANN) and a Genetic Algorithm-Artificial Neural Network (GA-ANN) hybrid tool for optimization. Results show that tensile strength is more affected by extrusion temperature than infill density, with optimal strength found in PETG at 240°C and 45% infill density. The study highlights the significance of parameter optimization for enhancing mechanical properties in FDM printing (Yadav et al, 2020). Fused Deposition Modeling (FDM) is a 3D printing process that constructs objects layer by layer. This study optimizes key FDM parameters—layer thickness, air gap, raster width, build orientation, raster angle, and contour count—to enhance tensile strength, surface roughness, and build time of PLA parts. Using Artificial Neural Networks, the study achieved high prediction accuracy (R = 0.9981 to 0.99837). Build orientation was identified as the most critical factor, with optimal parameters being layer thickness = 0.25 mm, air gap = -0.002 mm, raster width = 0.4048 mm, build orientation = 0°, raster angle = 90°, and 6 contours (Giri et al, 2021). Additive Manufacturing, a key innovation of the fourth industrial revolution, includes Fused Deposition Modeling (FDM), a popular method for 3D printing. This article reviews how parameters like layer thickness, infill density, speed, build orientation, and raster angle impact the mechanical properties of FDM parts. It examines their effects on tensile strength, flexural strength, and Young's modulus. Key findings identify optimal settings, such as a 215°C printing temperature for PLA and a 90 mm/s infill speed, for achieving the best mechanical performance (Doshi et al, 2022). Fused Deposition Modeling (FDM) is a 3D printing method where polymer is deposited layer by layer. This study examines how printing parameters—layer thickness, build orientation, and raster angle—affect the mechanical properties of PLA specimens, using the Taguchi method and L9 orthogonal array. Results show that layer thickness negatively impacts Ultimate Tensile Strength (UTS), with the highest UTS (46.65 MPa) at 0.1 mm layer thickness, 300° raster angle, and 450° build orientation. ANOVA reveals that layer thickness has the most significant effect on UTS compared to build orientation and raster angle (Lokesh et al, 2022). Manufacturing methods fall into three categories: formative, subtractive, and additive fabrication (rapid prototyping). Additive manufacturing, a modern approach that constructs parts directly from CAD data layer-by-layer, offers faster production and cost savings over traditional methods. Key processes include Vat Photopolymerization (SLA, DLP), Electron Beam Melting, Fused Deposition Modeling (FDM), Material Jetting, and Binder Jetting. FDM, which uses melted plastic to build parts, is particularly effective for biodegradable materials like PLA. However, further research is needed to optimize FDM parameters and explore materials such as PC and PC-ABS for broader applications (Patel et al, 2022). Today, various 3D printers are used, that is, there i a greater selection of different technologies for printing products. The most popular printer technologies are Fused deposition modeling (FDM) (Vasiljevic et al, 2022).

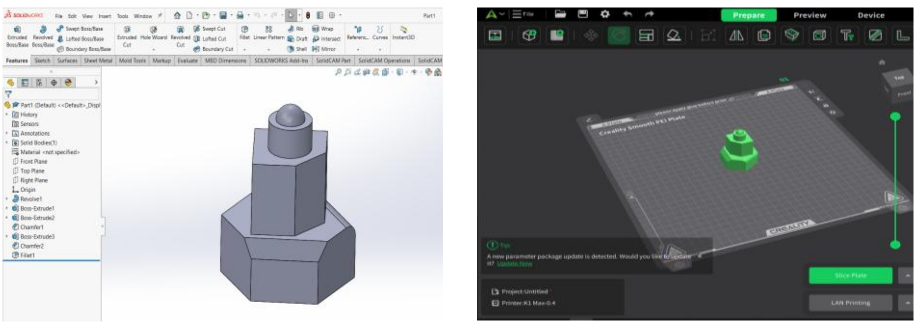
3. Experimental research

In this study, the Taguchi method was employed to analyze variations in the 3D printing process, aiming to optimize printing conditions and identify the factors most affecting part production time. The input parameters included printing speed, layer height, and infill percentage, each evaluated at three distinct levels. Table 1 summarizes the factors, and their corresponding levels used in the experimental design.

Table 1: Factors and factor levels

	Printing speed (mm/s)	**Layer height (mm)**	**Infil (%)**
Upper (+1)	400	0,3	80
Middle (0)	300	0,2	50
Lower (-1)	200	0,1	20

The experimental design was established using Minitab software, applying the Taguchi method to create factor combinations that optimize parameters while minimizing experimental trials, thus enhancing research efficiency. After printing the parts, results were analyzed with Analysis of Variance (ANOVA) in the same software to determine which factors significantly impact fabrication time. The 3D models were designed in SolidWorks 2022, which can export files in various formats, including STL for 3D printing. This compatibility enabled direct communication with Creality Print 4.3 software, facilitating the preparation for printing (Figure 1).



a *b*

Figure 1: SolidWorks 2022 (a) i Creality Print 4.3 (b)

The Creality K1 MAX 3D printer, which utilizes FDM (Fused Deposition Modeling) technology, was used for the fabrication of the samples, while a 3D scanner was employed to verify the dimensional accuracy of the parts. The printed parts were scanned to determine deviations from the nominal dimensions, and the data were further processed to quantify the accuracy of each sample (Figure 2).

a

b

Figure 2: 3D Printer (a) i scanning process (b)

This analysis provided a deeper insight into the impact of the selected factors on the 3D printing process, which can contribute to the optimization of parameters and the improvement of part quality in future experiments.

4. Results and discussion

Print Time: Layer height proved to be the factor with the most significant impact on print time. At higher layer height values (0.3 mm), the print time is considerably reduced, as fewer layers are required to produce the entire part. In contrast, a lower layer height (0.1 mm) necessitates more layers, significantly increasing the fabrication time. The infill percentage also has a notable impact. At a lower infill percentage (20%), the printing process is faster because less material is used. As the infill percentage increases, the fabrication time also rises due to the greater amount of material needed to fill the model's interior. Although print speed is intuitively important, it did not show a statistically significant effect on time, suggesting that other variables have a more dominant influence within this experimental range (Figure 3).

R-sq (Coefficient of Determination): 99.19%

This indicator suggests that 99.19% of the variability in print time can be explained by the model based on the variations in input factors (printing speed, layer height, infill percentage).

R-sq (adj) (Adjusted R-sq): 96.76%

The adjusted coefficient of determination reflects a high level of model accuracy, considering the number of factors relative to the sample size. The model demonstrates strong precision in explaining variations in print time.

R-sq (pred) (Predictive R-sq): 83.58%

This indicator indicates that the model possesses good predictive power, although it is somewhat lower compared to the explanation of variations observed in the available data.

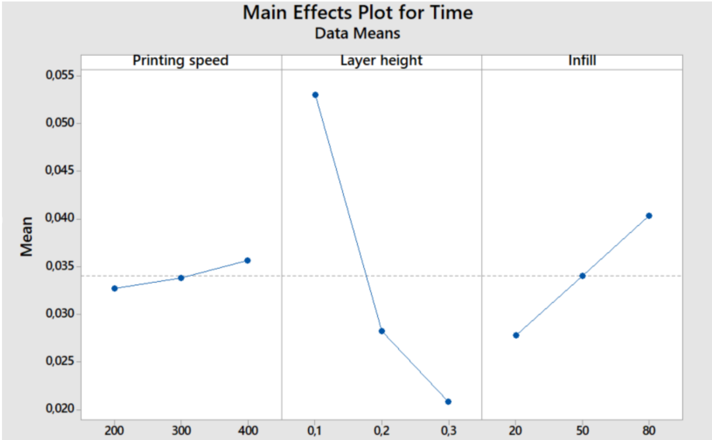


Figure 3: The Influence of Factors on Print Time

Mean distance: Layer height is again a key factor. A smaller layer height (0.1 mm) contributes to greater accuracy by reducing deviations from the specified dimensions, as thinner layers allow for a more precise representation of details. A larger layer height (0.3 mm) results in greater deviations, as thicker layers can affect the precision of geometry formation. The infill percentage has a moderate influence, with a lower infill percentage (20%) potentially leading to larger deviations due to less support for the internal structure of the model. Print speed has shown a certain influence on the average dimensional deviation, where a lower speed (200 mm/s) contributes to reduced deviation, while higher speeds (400 mm/s) lead to decreased accuracy (Figure 4).

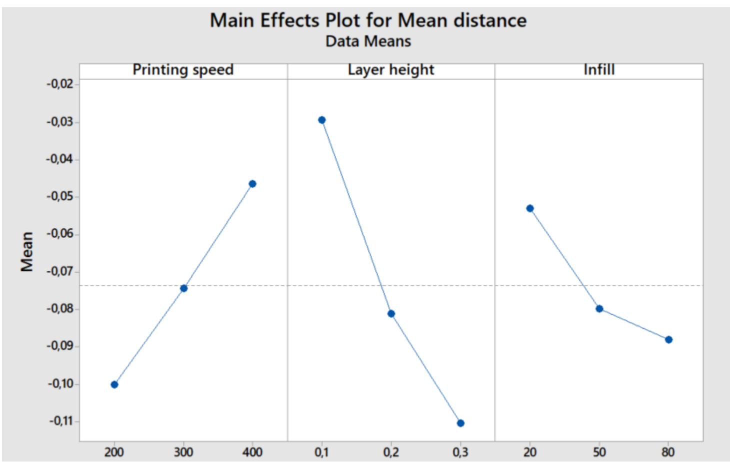


Figure 4: The Influence of Factors on Mean distance

R-sq (Coefficient of Determination): 98.40%

This high R-sq indicates that 98.40% of the variability in the mean dimensional deviation can be explained by the model.

R-sq (adj) (Adjusted R-sq): 93.60%

The adjusted coefficient of determination of 93.60% demonstrates that the model remains highly accurate, considering the number of factors in the experiment.

R-sq (pred) (Predictive R-sq): 67.61%

This indicator is somewhat lower, suggesting that the model for mean deviation has a more limited predictive power compared to the model for print time.

4. Conclusions

In this study, the Taguchi method was effectively utilized to optimize 3D printing parameters and assess their impact on fabrication time and dimensional accuracy. Key findings reveal that layer height significantly affects print time, with higher heights reducing time due to fewer layers required. Infill percentage also influences production time, while print speed showed minimal statistical significance. The models demonstrated a high coefficient of determination (R-sq) of 99.19% for print time and 98.40% for mean dimensional deviation, indicating strong explanatory power. Overall, these results contribute to enhanced understanding and optimization of the 3D printing process for future applications.

Acknowledgments

This research has been supported by the Provincial Secretariat for Higher Education and Scientific Research of the AP Vojvodina through the project “Trends of development and application of the Industry 4.0 model in SMEs” (No. 000435212 2024 09418 003 000 000 001) as well as supported by the Ministry of Science, Technological Development and Innovation (Contract No. 451-03- 65/2024-03/200156) and the Faculty of Technical Sciences, University of Novi Sad through project “Scientific and Artistic Research Work of Researchers in Teaching and Associate Positions at the FTS, University of Novi Sad” (No. 01-3394/1).

REFERENCES

[1] Doshi, M., Mahale, A., Kumar Singh, S., & Deshmukh, S. (2022). Printing parameters and materials affecting mechanical properties of FDM-3D printed Parts: Perspective and prospects. *Materials Today: Proceedings*, *50*, 2269–2275. https://doi.org/10.1016/j.matpr.2021.10.003

[2] Giri, J., Shahane, P., Jachak, S., Chadge, R., & Giri, P. (2021). Optimization of FDM process parameters for dual extruder 3d printer using Artificial Neural network. *Materials Today: Proceedings*, *43*, 3242–3249. https://doi.org/10.1016/j.matpr.2021.01.899

[3] Heidari-Rarani, M., Rafiee-Afarani, M., & Zahedi, A. M. (2019). Mechanical characterization of FDM 3D printing of continuous carbon fiber reinforced PLA composites. *Composites Part B: Engineering*, *175*, 107147. https://doi.org/10.1016/j.compositesb.2019.107147

[4] Lokesh, N., Praveena, B. A., Sudheer Reddy, J., Vasu, V. K., & Vijaykumar, S. (2022). Evaluation on effect of printing process parameter through Taguchi approach on mechanical properties of 3D printed PLA specimens using FDM at constant printing temperature. *Materials Today: Proceedings*, *52*, 1288–1293. https://doi.org/10.1016/j.matpr.2021.11.054

[5] Monogarov, K. A., Fomenkov, I. V., & Pivkina, A. N. (2022). FDM 3D printing of combustible structures: First results. *Mendeleev Communications*, *32*(2), 228–230. https://doi.org/10.1016/j.mencom.2022.03.025

[6] Patel, R., Desai, C., Kushwah, S., & Mangrola, M. H. (2022). A review article on FDM process parameters in 3D printing for composite materials. *Materials Today: Proceedings*, *60*, 2162–2166. https://doi.org/10.1016/j.matpr.2022.02.385

[7] Roudný, P., & Syrový, T. (2022). Thermal conductive composites for FDM 3D printing: A review, opportunities and obstacles, future directions. *Journal of Manufacturing Processes*, *83*, 667–677. https://doi.org/10.1016/j.jmapro.2022.09.026

[8] Vasiljevic, S., Rajkovic, D., Djordjevic, M., Kostic, S., Stanojevic, M. (2024). Application of innovative mechatronic systems in product design, development and production. *Journal of Production Engineering*, *27*(1), 13–21. https://doi.org/10.24867/JPE-2024-01-013

[9] Vukman, J., Milosevic, M., Antic, A., Bozic, D., Todic, V., Lukic, D. (2023). Optimization of high - speed machining parameters of thin - walled aluminium structures in the function of surface roughness, P*roceedings on Engineering Sciences*, *6*(3), 981-988. https://doi.org/10.24874/PES06.03.010

[10] Wang, C., He, Y., Lin, Z., Zhao, X., Sun, C., Guo, R., Wang, X., & Zhou, F. (2024). Mechanical and tribological properties of FDM-printed polyamide. *Tribology International*, *191*, 109198. https://doi.org/10.1016/j.triboint.2023.109198

[11] Yadav, D., Chhabra, D., Kumar Garg, R., Ahlawat, A., & Phogat, A. (2020). Optimization of FDM 3D printing process parameters for multi-material using artificial neural network. *Materials Today: Proceedings*, *21*, 1583–1591. https://doi.org/10.1016/j.matpr.2019.11.225