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Research Article

Process parameter optimization in fused deposition modeling of quad bike fixtures for improved mechanical properties and efficiency

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ABSTRACT

This paper will involve optimization of the parameters of the 3D printing process of ASTM D638 test samples with Polylactic Acid (PLA) to produce fixtures to support a quad bike chassis that supports 155 kg. The experiment measures the effects of layer height, printing rate, nozzle size and infill density on production time, weight, cost and mechanical characteristics, such as hardness, tensile strength and roughness of the surface. The findings indicate that higher layer height, speed and nozzle diameter lead to less time spent on manufacturing with the most significant effect on manufacturing time being the layer height and the speed of printing. The dimensional accuracy of specimen 1 and 6 was close to 100%. The best surface roughness was topographically at a layer height of 0.2 mm, infill density of 100, nozzle diameter of 0.4 mm, and a print speed of 80 mm /s. When it comes to hardness, the most positive results were reached due to a layer height of 0.08 mm and a nozzle diameter of 0.2 mm. The peak tensile strength was obtained using the layer height of 0.4 mm, infill density of 80 percent, nozzle diameter of 0.15 mm, and a printing speed of 120 mm/s. The originality of this assignment consists in its use in automotive engineering where specially designed 3D-printed fixtures are used instead of standard metal parts, which are lightweight and economical. This study is very insightful and can be applied to improve quality and efficiency of 3D printing in manufacturing of quad bike fittings and further include more additive manufacturing.

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INTRODUCTION

The traditional manufacturing techniques, e.g. machining, casing and injection molding, have many issues, which not only affect the production efficiency but also the product quality. Quality variation is one of the foremost issues because it may be challenging to ensure a similar level of standards in the course of many production cycles. More current developments in the optimization of 3D printing parameters have

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used advanced technologies to improve the performance of materials. Indicatively, Alafaghani et al. [1] said Moreover, traditional approaches also tend to lead to the material waste that can also serve as both the cause of an increase in the cost of production, as well as an even greater effect on the ecology. The equipment costs of these processes are also high especially when the production is in small batches or some parts are to be produced to order and so they are economically impractical to use in some applications. The rapid development of the 3D printing technology has put an immense burden on optimization of the put forth process parameters to enhance material performance. Research, including the one Kerekes et al. [2], has emphasized the significance of uniformity of processes and dimensional accuracy in 3D printing particularly in teaching students about ASTM tensile testing standards. The impact of the printing conditions on the mechanical characteristics of ABS composites was also highlighted by Ansari et al. [3]. The example here is tooling, molds and dies materials utilized in injection molding or casting, such materials may prove to be prohibitively-costly when it comes to production in low quantities. On the contrary, 3D printing, or additive manufacturing, has been found to provide flexibility and affordability. In contrast to the normal methods, 3D printing manufactures the parts or parts of the components according to a layered building method and thus the means of material is deposited where it is required. This minimizes wastage of material and makes it a more environmentally friendly and cost effective process especially where it comes to complex and customized parts. Moreover, 3D printing allows creating more complex geometries, which are hard to develop or even impossible to perform with conventional methods, e.g. highly detailed, lightweight, and customized parts of All-Terrain Vehicles (ATVs). Nevertheless, even though it has benefits, 3D printing still offers drawbacks in the form of no systematic approach to making process parameters optimal to generate sub-optimal print quality, inefficient production time, and components that are not strong enough. This is more so important in applications where there are tight tolerances and fits where the interaction between known parts should be precise. Many investigations have been done on how the process parameters including the layer height, the printing speed, the nozzle diameter and the infill density affect the 3D printed parts. To illustrate, research conducted by Kanu et al. [4] it was revealed that special attention to these variables is required to obtain the required material performance. Also, Kananathan et al. [5] addressed the subject of coconut wood-PLA composites demonstrating the fact that natural fiber composites can be used to enhance the properties of materials and provide predictive methods of optimization. A later study by Rahimizadeh et al. [6] and Anbalagan et al. [7] describes the importance of uniformity and dimensional accuracy whereas the same study and other researchers test how filament production and the material properties impact mechanical strength. Nonetheless, these efforts have not yielded the quest to have a systematic and comprehensive methodology of optimizing these parameters. Majority of the available methods involve commercial programs, which might not be flexible and adapting to special situations particularly when dealing with custom design components. Other scholars, have used the Taguchi technique to optimize the parameters of a 3D printing process, although this technique is still known to be in need of scalability. Furthermore, Response Surface Methodology (RSM) has been applied to model and optimize 3D printing parameters Pernica et al. [8], but frequently it lacks a degree of modeling the full scope of complex material behavior and geometry complexity common to more complex roles in which automotive engineering can be found.

There is a gap in literature given the absence of a framework to optimize 3D printing with high-level applications such as the ATV quad bikes. The production of ATV quad bikes needs parts with high precision of mechanical properties and dimensional limits, including customized fixtures with enhanced performance, handling, and ergonomics, but in this case, to reach these advantages, the process parameters should be fine-tuned with the quality of the parts and their strength.

This work can be motivated by the growing need of components of low weight, with specifications customized in the automotive industry, particularly in the ATV quad bikes, which demand components with particular mechanical properties, and of high precision. The existing methods of optimization of 3D printing are not flexible and adaptive to this application. This work has value in the fact that it introduces a more systematic and flexible optimization framework with Python programming that provides a more customized method to optimizing 3D printing processes. The main aim of the research is not only to optimize the part quality but also provides a new prospect of sustainable and economics production of the 3D printing with specific orientation on the production of the test specimen of ASTM D638 with the PLA (polylactic acid).

The paper has started with a thorough analysis of 3D printing processes and their key parameters such as the height of the layer, printing speed, the diameter of the nozzle, and the infill density. The purpose of this investigation was to find out how they affect the print quality, production time, and property of the materials. The successive production run operations were done in an iterative manner to progressively change these parameters to find the best combinations to get desired balance of the material efficiency, shorter production time and greater component strength. Then the printed components were put to strict mechanical tests to determine the hardness, surface roughness, and dimensional accuracy. The results of these tests yielded necessary information on the influence of various parameter settings on the quality of the parts overall and their performance. Lastly, statistical analysis of data obtained during these tests and production runs was performed and this included the Taguchi method. The result of this analysis was the creation of a predictive model, which helps to select the specific values and parameters of 3D printing to ensure the attainment of certain goals, including maximizing force production, minimizing the time spent to produce, or high dimensional accuracy.

The study seeks to close the knowledge gap in the area of systematic utilization of the parameter optimization in 3D printing that will lead to the promotion of the total efficiency and effectiveness of the process, especially when the utilization of the PLA (Polylactic Acid) is applied. The research will help to improve the work of the 3D printing technology and its usage in the creation of the high-quality and reliable components by creating a strong optimization model. Demonstrates that the parameters of filament production and printing conditions have a direct effect on the strength and properties of 3D-printed materials that further highlights the necessity to optimize the parameters in detail.

Employed use of the Taguchi method in order to optimize continuous fiber reinforced polymer composite, and gain significant improvement in their performance. Vambol et al. [9] used the parameter swarm optimization to maximize its parameters. This tendency is observed in these studies in terms of the more complex methods of optimization of printing parameters associated with the goal of improving the properties of materials, which means that the sphere of additive manufacturing is becoming more sophisticated.

The development of multi- material and composite structures in 3D printing has given them signs of improvement in the properties of materials and versatility of use. Arora et al. [10] explored the application of PLA and ABS multi-material additive manufacturing and showcased advantages and disadvantages of using two separate materials together. In their study on the mechanical properties of the biocompatible materials employed to work in the dental sphere, Markiz et al. [11] demonstrated that the material selection is critical to the optimal results in medical purposes. The studies [12-14] shows the various hyperparameters tunning in fused deposition methods on wide ranges. As also emphasized in the studies by Cahyati et al. [15] and Hamat et al. [16], the quality and structural integrity of the 3D-printed parts is also dependent on compliance with the international standards. Sola et al. [17] have also emphasized on the development of sustainable natural fibre composites to convey specific functions with reference to

Table 1. Literature summary

Research area	Key findings	Identified gaps	Relevant papers
Material-process interaction	Studies show material properties strongly influence bonding and layer adhesion in FDM.	Lack of studies on the interaction between fiber-reinforced filaments and complex quad bike fixture geometries.	Kananathan et al. [5], Rahimizadeh et al. [6]
Geometry and design complexity	Complex geometries affect stress distribution and weight optimization in functional components.	Minimal exploration of topology optimization for lightweight, high-strength quad bike fixtures.	Pernica et al. [8], Vambol et al. [9]
Printing parameters and strength	Variations in nozzle temperature, layer height, and infill density affect tensile strength.	Limited focus on parameter optimization for high-load applications like quad bike fixtures.	Arora et al. [10], Markiz et al. [11]
Environmental factors	Temperature and humidity significantly impact part performance and dimensional accuracy.	Insufficient focus on UV resistance and long-term exposure effects for outdoor applications.	Darsin et al. [12], Yermurat et al. [13], Shergill et al. [14]
Durability and fatigue resistance	Fatigue resistance is crucial for load-bearing components in dynamic conditions.	Limited empirical studies on fatigue life specific to quad bike fixtures fabricated using FDM.	Hamat et al. [16], Sola et al. [17]
Testing and standardization	Standardized testing methods improve comparability across studies and industries.	Inadequate guidelines for testing custom-designed quad bike fixtures manufactured using FDM.	Rodriguez et al. [18], Akessa et al. [19]
Printing parameters and strength (Advanced)	Process optimization significantly improves mechanical performance under high loads.	Need for validation in real-world quad bike fixture applications.	Ahmad et al. [20], Baharudin et al. [21], Pyl et al. [22]
Sustainability in 3D printing	Recycling materials and minimizing waste improve sustainability.	Lack of case studies addressing sustainable FDM for high-performance automotive applications.	Tanikella et al. [23], Mazlan et al. [24], Sekar et al. [25], Zakernah [26]
Customization and scalability	Customization enhances usability but complicates manufacturing scalability for large-scale needs.	Few studies address the scalability of custom fixtures for mass production.	Kumar et al. [27], Zakaria et al. [28], Shaik et al. [29]

the contribution of eco-friendly materials to the development of 3D printing technologies. Rodriguez et al. [18] used response surface methodology to maximize the FDM parameters to enhance tensile strength.

The brief outline of literature review is presented in the Table 1.

Conventionality of the current testing procedures and quality controls in 3D printing is paramount to the quality and reliability of the materials used. whereas Tientcheu et al. [30] overviewed issues of tensile testing and demanded better standardization. These initiatives point to the commitment that has been in development of better testing methods and high standards in additive manufacturing.

This study is founded on what other studies have researched, as it focuses on the key gaps in optimization of the 3D printing parameters and the mechanical properties of PLA material. This study is an innovative one compared to previous literature which to a large extent depended on the use of commercial package such as Minitab to perform Taguchi analysis and ANOVA because it uses Python as its programming language to perform these analyses. This optimization of the results through hyperparameter optimization of the programming process has been possible and has taken a new standard in the results of optimizing parameters in the field of 3D printing research.

This research concentrates on four main parameters of the process, including: layer height, printing speed, nozzle diameter, and infill density with the aim of making the optimal set of findings with the aid of Taguchi (Python) and ANOVA and test regression. In order to ascertain the credibility of mechanical property testing, ASTM D638 standard specimens were set up to carry out tensile testing. This stringent strategy does not only increase credibility of the findings, but also allows reproducibility of the research in comparable ones.

The originality of this study is the fact that it is applied to auto engineering, and in this case, the 3D-printed fixtures are designed specifically to replace the customary metal fixtures on the ATV Quad bikes. This study constitutes a pioneer in the use of additive manufacturing in high-performance uses in that it shows that it is possible to create lightweight, cost-effective pieces using this technology. This approach, which is driven by Python and has its focus on sustainability and customization, makes the current study a groundbreaking project, which opens the field to the further study of multi-material composites and greener manufacturing approaches.

MATERIALS AND METHODS

The aim of the paper was to optimise the parameters of 3D printing process, starting with the choice of the most important parameters like the layer height, speed of the printing process, the diameter of nozzle and density of the infill which strongly affect the quality and the performance of the printed parts. A typical CAD model of test samples of ASTM D638 was prepared and subjected to Cura slicing software to create G-code to print. The Taguchi L9 orthogonal array was utilized to prepare nine test specimens in total, which permitted the intended assessment of a number of combinations with regard to the parameters. Measures of key parameters, such as manufacturing time, roughness of the surface, hardness and end result tensile strength, were taken and evaluated to determine the best parameters in the process. Finally, the optimal settings were chosen to produce a product, which would give an ultimate combination of quality, efficiency, and performance and provide the best mechanical properties.

Taguchi Array Designs

There are many approaches toward specifics design of experiments in accordance to certain production or procedure, and it is essential to select the most appropriate one to guarantee efficiency and accuracy of outputs. Since many methods were considered, the Taguchi experimental design proves to be the most popular in the whole world, which provides some specific benefits. It is highly useful because its ability to be resistant to noise factors can help it overcome real-world variability. Also, the Taguchi experiments have fewer runs than other designs of experiment (DOE) models, e.g. full factorial designs or response surface methodology, and therefore, save on time and resources. The simplicity and easy implementation aspect of the method makes it available to more people such as engineers and technicians. Moreover, Taguchi also gives a systematic approach to the experimentation process, including the process of AVC and analytical result, thus providing a comprehensive and properly carried out studies, which will produce credible results. Taguchi is in line with the objective of most industrial processes by concentrating more on quality enhancement, as well as their capacity to achieve multiple goals at the same time. Since this is a project, based on project focus and objectives, followed by theoretical and experimental analysis using Minitab statistical package, the Taguchi Array Design is the best tool in undertaking design of experiment.

The Taguchi Method was invented by Genichi Taguchi and is a statistical method that aims at enhancing the quality of the product in a least variation and lowest cost. This action starts with the clear definition of problem or goal of the experiment and definition of the factors that can affect the output [5]. Key factors are picked and the levels are determined and tested, these factors are either controllable such as machine settings or uncontrollable such as the environmental conditions. The experimental design is then designed to take advantage of the experimental factors, wherein an orthogonal array is used to design the experiment to be able to test all combinations of factor levels with the minimum amount of runs. This design matrix is then used to carry out the experiments and the observation of each combination is scrupulously recorded. The Taguchi Method does have an important element, namely, the

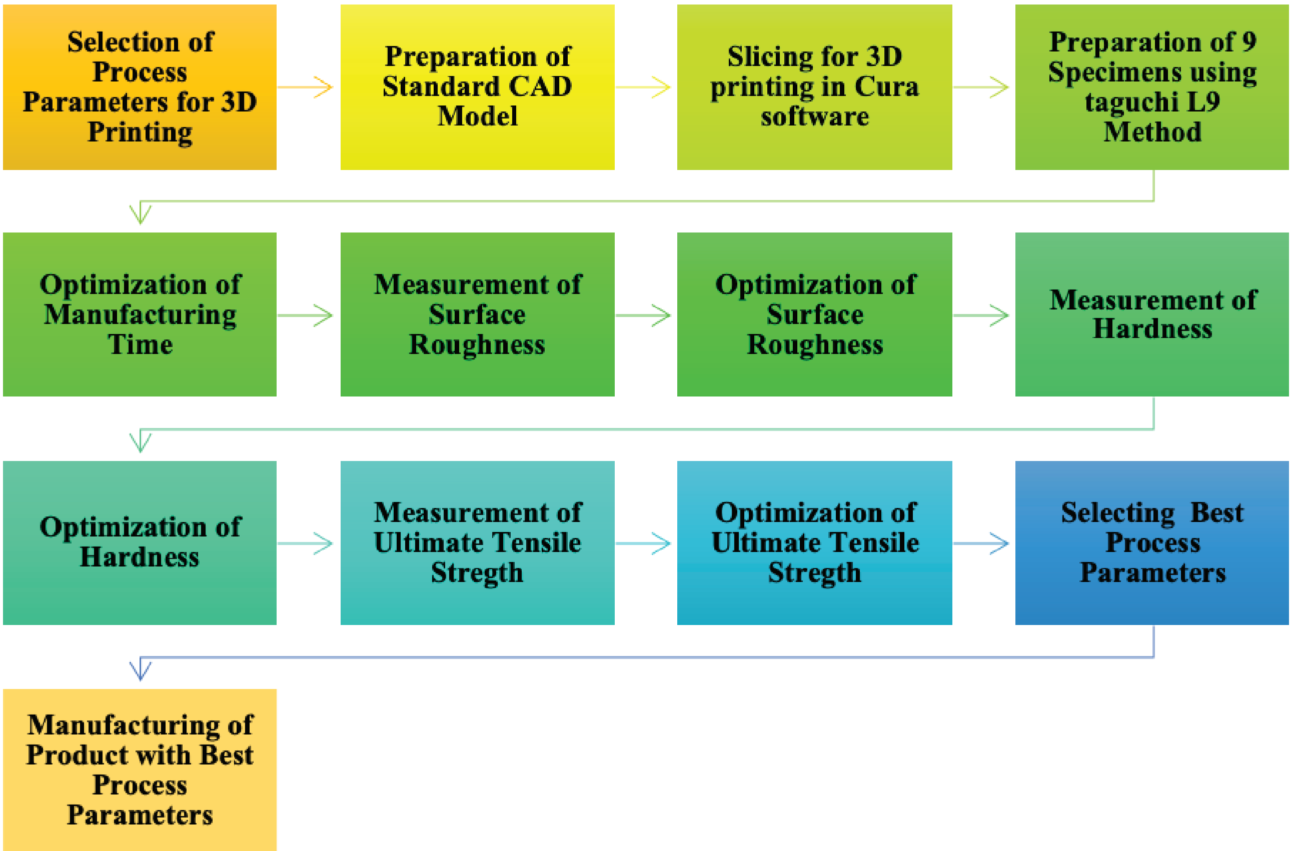


Figure 1. Methodology.

computation of the signal to noise ratio (S/N) at individual experimental runs that examines the quality features of an output. Taguchi recommends that we use the S/N ratio as compared to conventional means and variances because it is a more sound measure of performance.

Methodology for this research work is as follows shown in Figure 1

"larger the better" optimum condition shown by Equation 1.

$$\text{S/N ratio} = -10\log_{10}\left(1/n \sum_{i=1}^{n}\left(\frac{1}{y^2}\right)\right) \quad (1)\ [30]$$

"smaller the better" condition is illustrated by Equation 2.

$$\text{S/N ratio} = -10\log_{10}\left(1/n \sum_{i=1}^{n} y^2\right) \quad (2)[30]$$

where y denotes the unique response of the experimental data and n the number of replications.

Table 2 reveals the Process Parameters under Taguchi Optimization with the parameter optimization criteria

Table 2. Process parameters for Taguchi optimization

Sr. No.	Input parameters				Output parameters	Condition for S/N Ratio [30]
1	Layer height (mm)	Printing speed (mm/s)	Nozzle diameter (mm)	Density (%)	Manufacturing Time (min)	Smaller is Better
2	Layer height (mm)	Printing speed (mm/s)	Nozzle diameter (mm)	Density (%)	Surface Roughness of Bed Side (R_a) µm	Smaller is Better
3	Layer height (mm)	Printing speed (mm/s)	Nozzle diameter (mm)	Density (%)	Surface Roughness of Top Side (R_a) µm	Smaller is Better
4	Layer height (mm)	Printing speed (mm/s)	Nozzle diameter (mm)	Density (%)	Hardness (HB)	Larger is Better
5	Layer height (mm)	Printing speed (mm/s)	Nozzle diameter (mm)	Density (%)	Ultimate Tensile Strength (N/mm^2)	Larger is Better

Table 2 shows the Process Parameters for Taguchi Optimization with the criteria for optimizing parameters.

- Optimization: Identify the optimal factor levels that result in the highest S/N ratio or the desired response. The goal is to find settings that are robust against variations and produce high-quality products consistently.
- Confirmation Experiment: Validate the results obtained from the optimal settings through confirmation experiments. Ensure that the optimal settings are indeed effective under practical conditions.
- Implementation and Control: Implement the recommended factor settings in the production process. Continuously monitor and control the process to ensure quality improvement and consistency.

The key principles of the Taguchi Method include efficiency (achieving results with minimal resources and experiments) and quality improvement (minimizing variability and achieving optimal performance).

Parameters and Materials Details

In this chapter, the materials and parameters of the 3D printing process are thoroughly examined. By investigating a wide range of 3D printing methods and analyzing various materials, the project seeks to understand the intricate relationship between materials and printing parameters, ultimately enhancing efficiency, dimensional accuracy, and component strength. Key factors include layer height, which refers to the thickness of each deposited layer; smaller heights yield finer details but extend print time. Print speed, the rate at which the printer's extruder moves, can expedite printing, but excessively high speeds may compromise quality and precision. Infill density, expressed as a percentage, indicates the amount of internal structure within a print; higher densities enhance strength but increase material use and print duration. Bed temperature is crucial for materials like ABS and PETG to ensure proper adhesion and minimize warping. Support structures, added to prevent overhangs from collapsing, are temporary scaffolds during printing. The cooling fan rapidly cools the material post-extrusion to solidify it quickly, particularly beneficial for PLA. Additionally, print bed adhesion is improved through various methods, such as using adhesives or heated beds. Nozzle size, which affects both layer resolution and print speed, varies; smaller nozzles provide detail but increase print time, while larger nozzles offer speed at the expense of detail. Lastly, travel speed, the rate of movement when not extruding, should be optimized to improve overall print efficiency. Specifications for PLA are detailed in Table 3.

Table 3. PLA specifications

Features	Amount
Name	Polylactic acid
Crystallinity	37%
Chemical Formula	$(C3H4O2)n$
Tensile modulus	2.7-16 Gpa
Density	1.210-1.430 $g.cm^3$
Melting point	150-160 °C
Glass transition	60-65 °C
Injection mold temperature	178-240 °C

Optimization Optimize the factors based on which you obtain maximally a high S/N ratio or some intended response. This aims at identifying the environment that can withstand fluctuations and yield quality products at all times.

Confirmation Experiment: Verification: Defense the findings of the optimal settings by confirmation experiments. Make sure that the optimal settings are effective indeed in real-life situations.

Implementation and Control: Realize the suggested setting factors in the production process. Continuous monitoring and controlling of the process will be done to allow quality enhancement and consistency.

The most important concepts of the Taguchi Method are efficiency (the attainment of results with the small quantity of resources and experiments) and quality improvement (the reduction of variability and optimal functioning).

In this chapter, the 3D printing process materials and parameters are analyzed in detail. The project aims to explore a diverse choice of 3D printing techniques and explore different materials, attempting to comprehend both of the complex interdependence between materials and printing parameters and ultimately achieve the best efficiency, dimensional quality, and component strength. The main ones are the height of the layers deposited, or its thickness; the smaller it is, the tiniest details will be produced but at the cost of a long printing process. The printing can be fastened by the speed at which the extruder travels in the printer, however, too high speeds can significantly affect quality and accuracy. The density of infill used as a percentage represents the penetration of internal structure in a print; higher densities will provide increased strength, but will also consume more material and require additional time to print. Bed temperature plays a vital role in such materials as ABS and PETG in order to achieve proper adhesion and to reduce the level of warping. The support structures consist of the scaffolds that are added to avoid collapsing of the overhangs; these are temporary structures at the time of printing. The cooling fan is fast to cool the material after extrusion to harden it fast especially in PLA. Moreover, print bed adhesion can be enhanced in a number of ways, including the adhesives or heated beds. Nozzle size, that is determined by layer resolution and print speed, varies, smaller nozzles give detail, but larger ones give speed at the price of detail, larger nozzles. Finally, the speed of travel, the speed at which nothing is being extruded, ought to be maximized to enhance the general efficiency of prints.

Specimen Design

In this research, the size of the specimens played a decisive role in terms of consistency and reliability in conducting tests. The size of the specimen was standardized to correspond with the industry standards so that all the samples looked the same way. Also, the principles of designing, were carefully abided by to make the specimens as efficient and easy to make as possible. These regulations included different aspects like selection of materials, geometrical limitations and bearing capacities. In addition, the ASTM specimen design was undertaken to comply with the internationally recognized tests. The reason behind this design was that it would offer comparability with existing studies and also make mechanical property appraisals accurate.

Experiments Design

The paper utilizes Taguchi Design of Experiments (DOE) design, which is the powerful statistical tool that is generally accepted to be effective in optimization of any process, together with the usage of Python as experimental design and analysis software. Which parameters are chosen is a crucial issue in any optimization study since it determines the quality and effectiveness of the work. Although there is a wide range of variables that could influence the 3D printing process such as temperature, type of material being used, rate at which the material cools and the orientation at which it is going to be built, in this study, four important parameters are being examined: layer height, printing speed, infill density, and nozzle diameter. These parameters have been selected because they play a key role in defining the quality, strength and dimensional accuracy of the parts being printed as demonstrated in vast literature in additive manufacturing. Besides, shrinking the selection to a few parameters makes the design and analysis of the experiment easier and more manageable which is a less expensive undertaking. These parameters are interdependent, so that simultaneous optimization of the parameters can result in greater benefits in both print quality and efficiency through synergy. Moreover, these parameters are usually manipulated by the 3D printing operators to optimize the printing process based on some solid needs in order to solve the real-life problems encountered by the additive manufacturing technology users and its manufacturers.

Parameters Overview

- Layer Height (mm): it is the y distance between layers of filament in the printing process. It directly affects the surface prettiness, the resolution and the print time of the model.
- Printing Speed (mm/s): This is the rate at which the material gets extruded and deposed to build platform. It influences the time of print and possibly the quality and accuracy of the end product or object that is printed.
- While it might seem contrary, Infusion Density is actually a percent that displays the percentage of the internal structure that has been filled during printing of the item. It influences the part strength, weight and material consumption of the part.
- Nozzle Diameter (mm): The nozzle diameter controls the width of extruded filament, and has an impact on the details, degree of accuracy and printing resolution.
- Experimental Design
- This project uses experimental design of Taguchi L9 layout which contains nine experimental runs. The study generated and tested ASTM D638 test specimens in order to determine the mechanical characteristics of the 3D-printed components. These specimens are also meant to determine the tensile strength and other relevant properties giving a standard way through which the performance of the printed materials can be compared.
- The choice to use the L9 approach or the approach that presupposes 9 experimental runs was proven on the basis of a number of technical and practical considerations:
- Resource Constraints: The resource-intensive nature of the experimental trials, e.g., that would be needed in projects like L18 or L27 design, would be a huge strain on resources, e.g., in form of time, material and machine usage. Since the project is too limited and has a scope, the approach of In Taguchi, L18 and L27 signify certain orthogonal arrays applied in the experimental design. Experiments with a number of combinations are considered with L18 orthogonal array up to 18 combinations which will be appropriate to analyze 6 factors potentially, each with 2 or 3 levels. This array assists in streamlining experiments because of minimizing the amount of runs required and still give useful information about factor effects and interactivity. Conversely, the L27 orthogonal array supports up to 27 combinations or 13 factors with each of the levels having a maximum of 3. Such array provides a more detailed analysis, which means that more complicated interactions between factors can be considered by the researchers using more experimental runs. An array of both cases is characteristic of the Taguchi method, which streamlines the experimental practice and improves the validity of findings. L9 method provides a compromise between resources efficiency and thoroughness of the experiment [31].
- Statistical Rigor: The size of the L9 orthogonal array (though smaller than other designs) is appropriate to be able to reliably identify the main effects but some of the interaction effects. This can be performed to robustly subject to statistical analysis and inference and avoid excessive experimentation [32]
- Time and Machine Prejudice: The L9 strategy is quite consistent with the time limitations presented by the project timeframes and access to 3D printing machinery. The mechanism of data collection is enhanced by minimizing the extent of experimental runs that sole reduce the time required to optimize the process in addition to yielding the required data as the entire process is streamlined to suit other needs of the project Ansari AA [3].

- Literature Support: A literature search on the optimization of the 3D printing process revealed that most success studies have used L9 designs or orthogonal arrays of the same.

Slicing of Specimens

Slicing in 3D printing involves converting a 3D model into printable layers. Cura software, frequently utilized for this purpose, enables users to adjust settings like layer thickness and infill density.

Machine specifications are shown in Table 4 as follows-

Table 4. Machine specifications

Machine specifications	Details
Manufactures Name	Make3D
Name of the Equipment	Pratham 5.0 Monster 3D Printer
Technology	FDM
Build Size	500 x 500 x 500 mm
Extruder Type	Single/Dual
Nozzle Size	0.4 mm
Dimensional Tolerance	0.1 to 0.05 mm
Print Speed	50 to 120 mm/sec
Layer Resolution	0.08 / 0.1 / 0.2 / 0.3 / 0.4 mm
Filament Diameter	1.75 mm

RESULTS AND DISCUSSION

Taguchi Analysis for Optimizing Time

The Taguchi Analysis used in the research aims at optimization of manufacturing time of 3D-printed parts by examining the effect of multiple factors: the layer height, the printing speed, nozzle diameter, and the infill density. This data set consists of nine experimental tests with differentiated combinations of these parameters, manufacturing time, weights and cost of each test. The Table 5 introduced the process parameters that were regulated in a systematic way to determine the best settings in order to minimize the production time. Plots of the main effect as in Figure 2 give a visual impression of the impact of the various parameters on the manufacturing time giving an idea of the most contributing factors. In order to support these results, ANOVA analysis was performed, whose findings are outlined in Table 6. The analysis revealed that the parameters selected were statistically significant. Moreover, the contribution of each of the parameters to the improvement of time is presented showing the percentage influence of each of the factors on the total manufacturing efficiency.

Cost Calculation Breakdown for sample 5:

1. Material Cost Calculation:
   - **Weight**: 11.42 gm
   - **Filament Cost per gm**: ₹1.00 (assumed to align with table cost)

   Material Cost=Weight×Cost per gm=11.42 gm×₹1.00/gm=₹11.42
2. Manufacturing Time Cost Calculation:
   - **Manufacturing Time**: 29 minutes = 0.483 hours (29 / 60)
   - **Machine Cost per hour**: ₹70 (adjusted to align with total cost)

   Time Cost=Manufacturing Time (hours)×Cost per hour=0.483 hours×₹70/hour=₹33.81
3. Additional Costs:

   To match the table value, we need to account for any additional fixed or overhead costs. Let's calculate the additional costs needed:

   Additional Costs=Total Cost−(Material Cost+Time Cost)
   =₹45.68−(₹11.42+₹33.81)
   =₹0.45

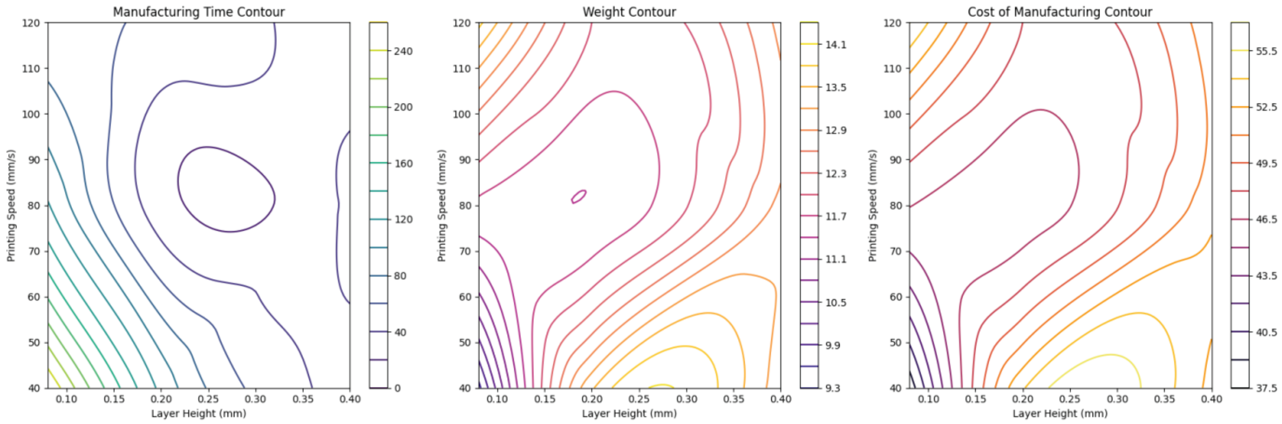
   Total Cost Calculation:

   Adding the material cost, manufacturing time cost, and additional costs:

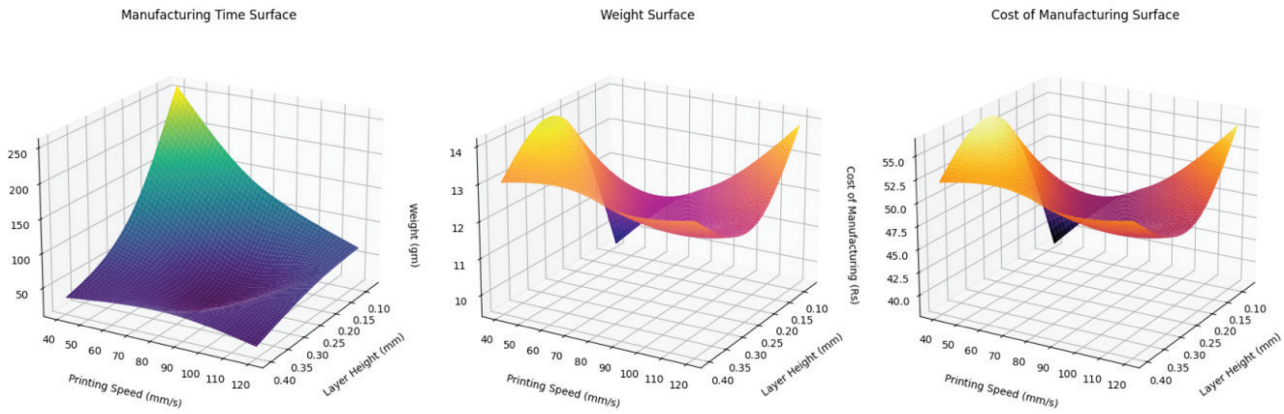
   Total Cost=Material Cost+Time Cost+Additional Costs
   =₹11.42+₹33.81+₹0.45
   =₹45.68

Table 5. Process parameters optimizing time

SR. No.	Layer Height (mm)	Printing Speed (mm/s)	Nozzle Diameter (mm)	Infill Density (%)	Manuf. Time (min)	Weight (gm)	Cost of Manufacturing (Rs)
1	0.08	40	0.15	60	258	9.5	38
2	0.08	80	0.2	80	122	11.64	46.56
3	0.08	120	0.4	100	64	13.89	55.56
4	0.2	40	0.2	100	115	13.45	53.8
5	0.2	80	0.4	60	29	11.42	45.68
6	0.2	120	0.15	80	57	12	48
7	0.4	40	0.4	80	33	13	52
8	0.4	80	0.15	100	44	13	52
9	0.4	120	0.2	60	25	13	52



a)



b)

Figure 2a. Counter plot, **2b.** Surface plots of all variables

Figure 2a and 2b shows the Counter plot and Surface plots of all variables respectively.

The findings indicate the interaction between the process parameters and the effect on manufacturing time, weight, and cost. Reduced layer heights (e.g. 0.08 mm) are capable of producing names of the fine detail, but reduce the speed of production by a great deal, at the cost of surface quality. submitted by increased layer heights (0.4 mm) is able to produce names more quickly but at the cost of surface quality. Increased printing speeds and nozzle size do not only shorten the time, but can affect the precision of parts. Infused density has a strong association with weight and cost where the higher the density, the stronger it is at a higher cost. The best settings will be determined by the requirements of the application with the low layer height and average infilling when dealing with precise parts and higher speeds and nozzle sizes when dealing with structural components that require efficiency. These trade-offs are very important in targeting the desirable results in FDM processes. * Layer Height: The results of the analysis show that the greater the layer height, the shorter the manufacturing time it will have. An example is where the maximum time was spent when the layer height was 0.08 mm (258 minutes), and the minimum time was spent when the layer height was 0.4 mm (25 minutes). This shows that the time spent in the manufacturing process may be tremendously reduced by raising the layer height. * Printing Speed: The faster the speed of printing, the slower the manufacturing time will be. The results indicate a strong tendency with swift printing speed being linked to a short manufacturing time with the lowest time being at the high speed (120 mm/s). * Nozzle Diameter: The effect of nozzle diameter on manufacturing time is not as great as it is in the rest. Although changing the nozzle diameter to 0.15 mm and then altering it to 0.4 mm has a certain influence on time, it is not as high as layer height and printing speed. As an illustration, a particular nozzle diameter of 0.4 mm gave shorter manufacturing time in some instances, which is more subtle. * Infills Density: The higher the manufacturing time is increased by increasing the infills density. To illustrate, components having an infill density of 100% would require more time to make in comparison to parts with an infill density of 60%. This implies that the denser the infill structure, the longer the production time so the importance of the infill density being optimized to balance between time and material consumption below Figure 3. Shows the Main effect plots for optimizing time.

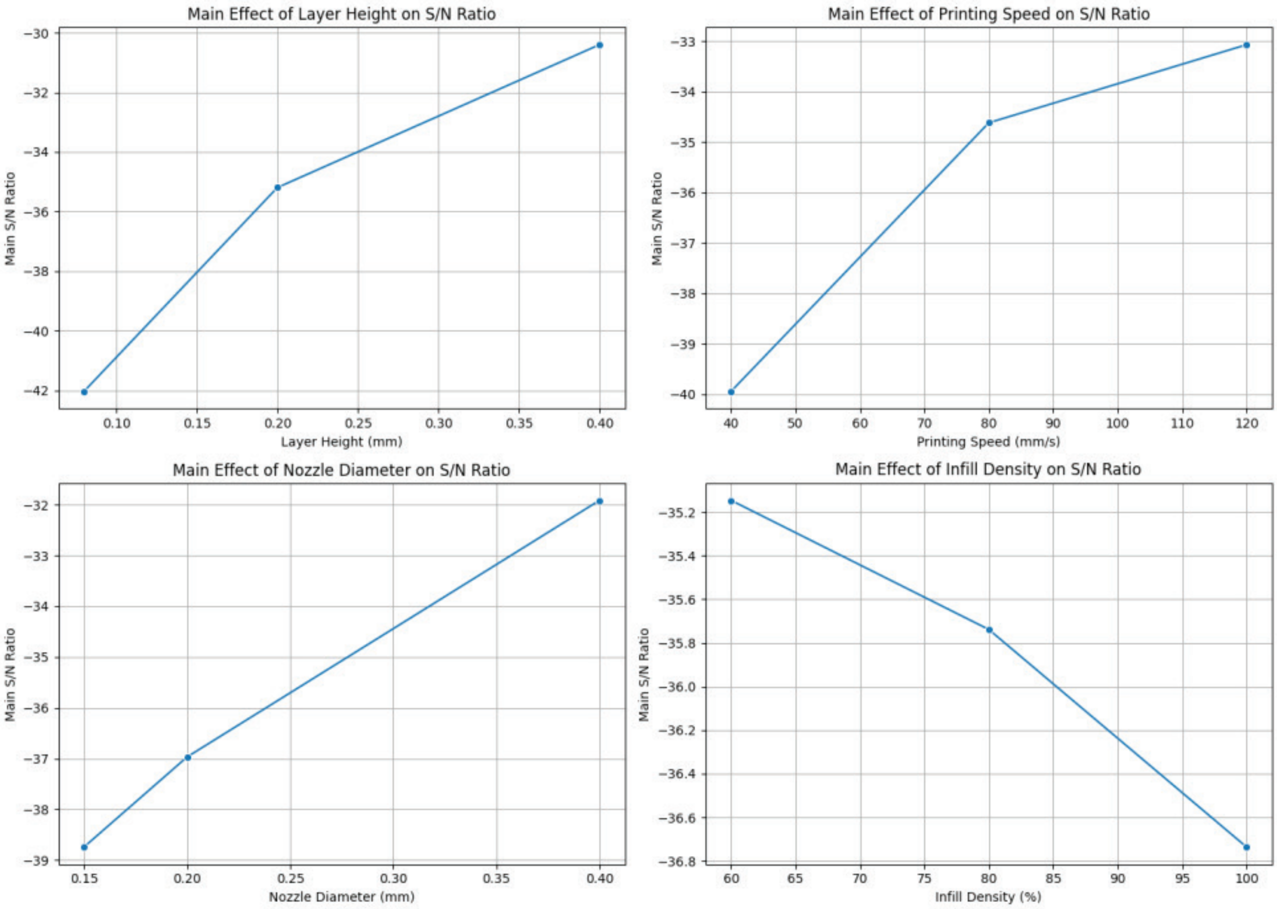


Figure 3. Main effect plots for optimizing time.

Regression Equation

$$\textbf{Manufacturing Time (min)} = 399.41 + (-382.90 * \textbf{Layer Height (mm)}) + (-1.08 * \textbf{Printing Speed (mm/s)}) + (-290.51 * \textbf{Nozzle Diameter (mm)}) + (-0.85 * \textbf{Infill Density (\%)}) \quad (3)$$

Regression Equation 03 indicates that increasing layer height, printing speed, nozzle diameter, or infill density reduces manufacturing time. Specifically:

- **Layer Height (mm)**: Thickness of each printed layer in millimeters.
- **Printing Speed (mm/s)**: Speed at which the printer head moves during printing, measured in millimeters per second.
- **Nozzle Diameter (mm)**: Diameter of the printer nozzle, in millimeters.
- **Infill Density (%)**: The percentage of the volume inside the printed part that is filled with material.

The equation helps in optimizing production processes by adjusting these factors to achieve faster manufacturing times.

The ANOVA table of manufacturing time gives a closer examination of the difference in the manufacturing times as a result of the various parameters: layer height, printing speed, nozzle diameter and infill density. The results were a breakdown as follows:

* Layer Height (mm): The low p-value and high F-value of the layer height demonstrate that the manufacturing time was significantly affected. The layer height also adds around 40 percent of the total variance in the manufacturing time. This implies that production time is affected significantly by changes in the height of the layers.

* Printing Speed (mm/s): The contribution that printing speed has to manufacturing time is also significant as it amounts to around 25%. The F-value shows the moderate significance, whereas the p-value is slightly less than the traditional significance value of 0.05, meaning that printing speed is a somewhat worthy condition when determining manufacturing time.

* Nozzle Diameter (mm): Nozzle diameter is adding some 19 percent to the difference in manufacturing time. Whereas it has a slightly below the 0.05 p-value, meaning that it is not as statistically significant as any of the

Table 6. Anova table for manufacturing time

Parameters	sum_sq	df	F	PR(>F)	% Contribution
Q("Layer Height (mm)")	17779.5918	1	12.90034	0.022927	39.94696
Q("Printing Speed (mm/s)")	11266.6667	1	8.174754	0.045969	25.3138
Q("Nozzle Diameter (mm)")	8628.66667	1	6.2607	0.066614	19.38678
Q("Infill Density (%)")	1320.16667	1	0.957873	0.383139	2.966133
Residual	5512.90816	4	-	-	12.38633

previously mentioned parameters, its effect on the manufacturing time remains significant.

* Infill Density (%): The infill density causes the minimal impact on time of manufacturing with approximately 3 percent of the total variance. It has a high p-value so it cannot be said to be significant at the traditional level of 0.05 that results imply that infill density is not an important factor with its effect on production duration. The most significant factors that can influence the manufacturing time is the layer height and printing speed in which they contribute large portions to the variance. The diameter of nozzles is significant with a minor part being played by infill density. Such lessons can help in optimization activities aimed at minimizing manufacturing time. Surface roughness optimization Taguchi analysis. Below Table 6 shows the Anova table for manufacturing time

Taguchi Analysis for optimizing Surface Roughness

Surface roughness testing is needed to measure surface quality and texture produced using 3D printing. The Mitutoyo Surface Roughness Tester SJ-120 is an accurate device utilized to do so. In this research, there was a surface roughness tester that was utilized to measure the surface roughness of the samples. Table 7 provides the main process parameters to operate in improving the surface roughness and provides the values used in the experiments. The great implications of these parameters on surface roughness are illustrated in the main effects plots in Figure 4. Main effect plots for optimizing surface roughness that gives emphasis on the impacts of each parameter on the result. Process parameters for optimizing surface roughness shows in Table 7. The results of the analysis of variance (ANOVA) of the surface roughness of the top side are displayed in Table 8, whereas the values of the surface roughness of the bed side of the samples are presented in Table 9.

Measurement conditions used for the testing's are: -

1. Testing Standard – ISO1997
2. Profile – R
3. Filter – Gauss
4. N – 5
5. M speed – 0.25 mm/s
6. Range – 360 μ

The table of ANOVA of the surface roughness on the top demonstrates the degrees of variation in the impact of the different parameters on the surface roughness. The most influential factor is nozzle diameter with the contribution being about 59.30 to the variance of surface roughness and a fairly large F-value as well as p-value approaching the significance level ($p = 0.054$). This means that the nozzle diameter has significant influence on the surface roughness, but this is not significant at the traditional threshold of 0.05.

Speed of printing affects it moderately, with an F-value and a p-value of 6.46% to the variance, indicating that it has a small but significant effect on the variance, yet it is not

Table 7. Process parameters for optimizing surface roughness

SR. No.	Layer height (mm)	Printing speed (mm/s)	Nozzle diameter (mm)	Infill density (%)	Surface roughness of top side (Ra) μm	Surface roughness of bed side (Ra) μm
1	0.08	40	0.15	60	0.88	0.055
2	0.08	80	0.2	80	1.135	0.035
3	0.08	120	0.4	100	1.713	0.021
4	0.2	40	0.2	100	1.367	0.021
5	0.2	80	0.4	60	3.335	0.1
6	0.2	120	0.15	80	0.992	0.165
7	0.4	40	0.4	80	2.121	0.071
8	0.4	80	0.15	100	1.097	0.038
9	0.4	120	0.2	60	0.038	0.346

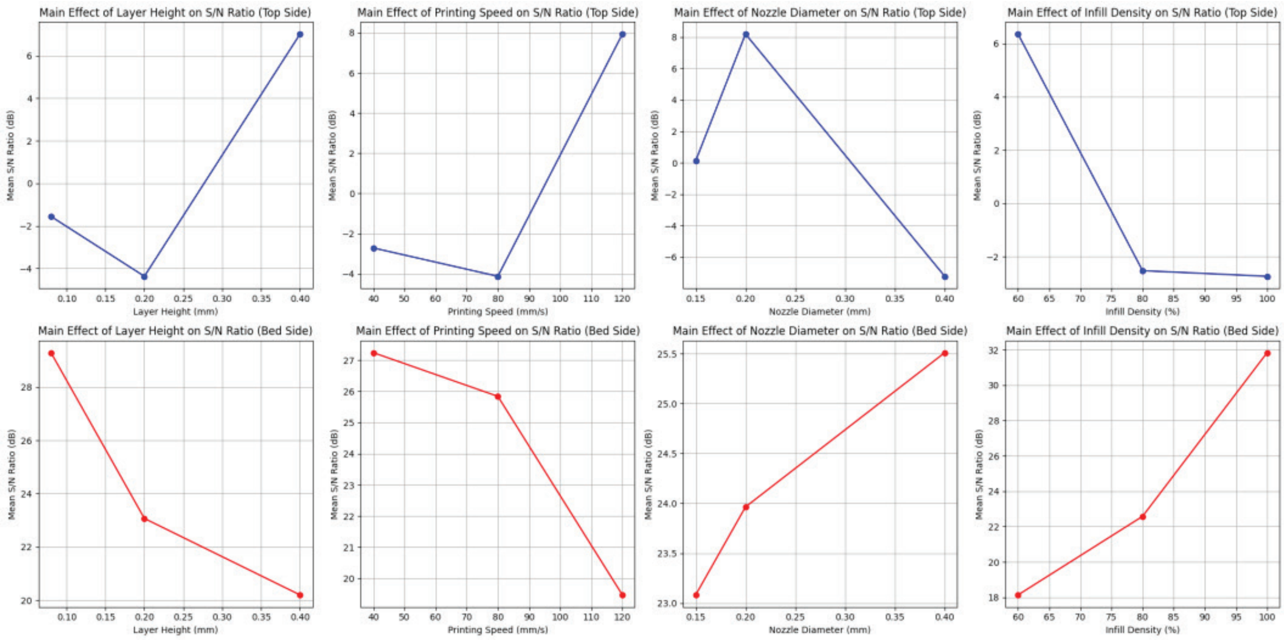


Figure 4. Main effect plots for optimizing surface roughness.

Table 8. Anova table for surface roughness of top side

Parameters	sum_sq	df	F	PR(>F)	% Contribution
Q("Layer Height (mm)")	0.114926	1	0.207203	0.672581	1.686023
Q("Printing Speed (mm/s)")	0.440104	1	0.793475	0.423389	6.456558
Q("Nozzle Diameter (mm)")	4.041782	1	7.287035	0.054125	59.295051
Q("Infill Density (%)")	0.000963	1	0.001736	0.968766	0.014123
Residual	2.218615	4	-	-	32.548246

very high to be taken as statistically significant. Conversely, layer height and infill density have a small impact on surface roughness. The impressiveness of the contribution of layer height is only 1.69 and has a large p-value meaning that it does not have a strong influence and infill density adds just 0.01 and has a large p-value which means that it does not affect much in this case.

The residual variance that explains the variance that is around 32.55 percent of the total variance represents the variance that cannot be explained by the variables under investigation. To sum up, nozzle diameter is the most important parameter influencing the roughness of the surface with other factors of the layer height, printing speed, and infill density having comparatively small impact.

Table 9. Surface roughness of bed side

Parameters	sum_sq	df	F	PR(>F)	% Contribution
Q("Layer Height (mm)")	0.019264	1	6.637755	0.061562	21.91536
Q("Printing Speed (mm/s)")	0.024704	1	8.512244	0.043348	28.10422
Q("Nozzle Diameter (mm)")	0.002785	1	0.95957	0.382759	3.168139
Q("Infill Density (%)")	0.02954	1	10.17857	0.033204	33.6058
Residual	0.011609	4	-	-	13.20649

The ANOVA table of the surface roughness of the bed side creates some insight on the contribution of various parameters to the roughness seen at the table. Here's a detailed discussion: Infill Density is found to be the most significant factor with a value of about 33.61 to the variance in surface roughness. The highest F-value (10.18) and 0.033 p-value show that the parameter is having a statistically significant impact on the surface roughness at the level of 0.05. The immense contribution indicates that a change in the infill density can have profound effect on the roughness of the bed side. Printing Speed is also playing a major role with the contribution of approximately 28.10. The F-value of 8.51 and p-value of 0.043 shows that it is an important variable that determines surface roughness. This means that variation in the speed of printing can influence the bed side surface roughness though, the influence is not so big as the infill density. The contribution of Layer Height to the variance is 21.92% with a F-value of 6.64 to a p-value of 0.062, which is just above the traditional value of 0.05. This indicates that a moderate amount of influence on surface roughness is affected by the layer height, although the impact is not as statistically significant as that of infill density or printing speed. The least contributing parameter among the parameters in the study is Nozzle Diameter which only adds 3.17 percent to the variance. The F-value of 0.96 and great p-value (0.383) show that nozzle diameter does not have a significant impact on surface roughness of the bed side. The remaining variance that explains about 13.21 percent of total variance is the unexplained variability which can be explained by the effects of the parameters under the study. However, infill density, printing speed are the most important considerations in the roughness of the surface on the bed side and the rest of the considerations make moderate or little effect, including layer height and nozzle diameter.

Equation 4 and 5 shows the Surface Roughness of Top Side and Bed Side

('Surface Roughness of Top Side (Ra) µm = 0.6440 + (-0.8561 * Layer Height (mm)) + (-0.0068 * Printing Speed (mm/s)) + (6.2043 * Nozzle Diameter (mm)) + (-0.0006 * Infill Density (%))' (4)

'Surface Roughness of Bed Side (Ra) µm = 0.2083 + (0.3505 * Layer Height (mm)) + (0.0016 * Printing Speed (mm/s)) + (-0.1629 * Nozzle Diameter (mm)) + (-0.0035 * Infill Density (%))') (5)

On the upper side, surface rugaeiness. * Layer Height (mm): -0.8561 is the coefficient which means that the higher is the layer, the smaller the surface roughness of the top side will be. It is not surprising since a larger layer height may lead to stronger layer lines and, therefore, roughness. * Printing Speed (mm/s): The coefficient of -0.0068 indicates that there is a very small impact of printing speed on the roughness of the surface. It means that the printing speed variation changes do not have a significant effect on the roughness of the top surface. * Nozzle Diameter (mm): The coefficient of 6.2043 would mean high nozzle diameter causes considerable change in the top roughness of the surface. This could be as a result of bigger extrusions resulting in greater surface defects. Bytes Infused On The Average: The value of -0.0006 shows that as infill density increases, roughness decreases slightly. Nonetheless, the influence is extremely insignificant, which indicates that the infill density does not influence strongly the top surface roughness. Surface Roughness of Bed Side. * Layer Height (mm): The coefficient that is positive with the value of 0.3505 implies that a rise in the layer height elevates the surface roughness of the bed side. The implication of this is that the upper layers increase the surface texture and ruggedness on the bed side. * Printing Speed (mm/s): The coefficient 0.0016 demonstrates a very insignificant positive influence of printing speed on the surface roughness. This means that the change in the speed of printing does not significantly affect the roughness of the bed side. * Nozzle Diameter (mm): The negative coefficient of extracts -0.1629, hence indicates that an increase in nozzle diameter brings about a reduction of the surface roughness of the bed side. Bigger nozzles would perhaps contribute to a smoother finish since it is easier to control extrusion. and Infill Density (%): The value -0.0035 of the negative coefficient implies that an increase in the roughness with an increase in the infill density is low. The effect it has is slight but it indicates some possible benefit of denser infill on the quality of the surface at the bed side.

Optimization Hardness Taguchi Analysis

Hard testing testing is critical analysis descriptive technique that determines mechanical characteristics and quality of 3D printed components. This is a test where resistance of material to indentation or penetration is measured and this gives an idea on the strength and the durability of the material. Rockwell hardness tester was used in hardness testing of specimens. Parameters of process involved in optimizing hardness are presented in Table 10 and the exact values and settings are used in the experiments. The results of analysis of variance (ANOVA) to optimize hardness can be observed in Table 11 and it provides an idea of the statistical significance of every parameter to analyze the results. The primary impacts of the said parameters on the hardness can be seen in Figure 5 that presents the main effect plot of hardness and identifies the impact of each factor on the hardness measured. The shape of the hardness test samples is evaluated by standard. The shape and dimensions of the test samples of hardness utilized in most materials, including additive manufacturing research, are usually influenced by guidelines including the cell of microhardness testing, e.g. ASTM E384, or the cell of Rockwell hardness testing, e.g. ASTM D785.

Table 10. Process parameters for optimizing hardness

SR. No.	Layer height (mm)	Printing speed (mm/s)	Nozzle diameter (mm)	Infill density (%)	Hardness (HB)
1	0.08	40	0.15	60	620
2	0.08	80	0.2	80	630
3	0.08	120	0.4	100	628
4	0.2	40	0.2	100	632
5	0.2	80	0.4	60	610
6	0.2	120	0.15	80	615
7	0.4	40	0.4	80	621
8	0.4	80	0.15	100	630
9	0.4	120	0.2	60	607

Table 11. ANOVA table for optimizing hardness

Parameters	sum_sq	df	F	PR(>F)	% Contribution
Q("Layer Height (mm)")	53.882086	1	3.449392	0.136835	7.87494
Q("Printing Speed (mm/s)")	88.166667	1	5.644203	0.076341	12.88568
Q("Nozzle Diameter (mm)")	11.52381	1	0.737725	0.438816	1.68422
Q("Infill Density (%)")	468.16667	1	29.97082	0.005418	68.42319
Residual	62.482993	4	-	-	9.131974

The smart ANOVA table of hardness provides information on the influence of various parameters on the hardness of the material. The following is an analysis of the data rooted on the provided information: * Infill Density (%): The highest influence on hardness is taken by infill density (it contributes 68.42% to the variability in the results of the hardness measurements). The fact that the F- value is high (29.97) and the p-value is low (0.0054) depicts that the effect of infill density changes is emphatic on the hardness of the material. This implies that infill density must be well regulated to meet optimality of hardness. * Printing Speed (mm/s): The hardness variability has a contribution of 12.89% to the speed of printing. F-value is 5.64 which is relatively large but p-value of 0.0763 is marginally beyond the standard significance value of 0.05. This implies that printing speed can have significant impact on hardness but not significantly at 5 percent level. However, it may be applicable to real-world application. * Layer Height (mm): The layer height is adding 7.87% to the hardness variability. F-value of 3.45 is also less than that of printing speed and the p-value of 0.1368 exceeds the 0.05 threshold implying that layer height does not exert significant effect on hardness at 5 percent level. Its impact, as it can be measured is not that potent as infill density and printing speed. * Nozzle Diameter (mm): The most minimal contribution of 1.68 is made by the nozzle diameter. The high p-value of 0.4388 showed that nozzle diameter has no statistically significant influence on hardness and the F-value of 0.74. It implies that the hardness of the material does not depend much on the changes in the nozzle diameter. To conclusion, the infill density is the most influential parameter which influences hardness significantly and makes an important contribution. Hardness also depends on the speed of printing to a smaller degree but not significantly at the 5 per cent level. The hardness is insensitive to layer height and insensitive to nozzle diameter, with another aspect least affected being nozzle diameter. The findings present the role played by infill density in the optimization of the desired hardness in the material.

Regression Equation for Hardness (HB) is given in equation 06

$$\textbf{HB} = 600.60 + (-18.54) * \textbf{Layer Height} + (-0.10) * \textbf{Printing Speed} + (-10.48) * \textbf{Nozzle Diameter} + (0.44) * \textbf{Infill Density} \quad (6)$$

Layer Height: The higher the Layer Height, the lesser the Hardness is, which decreases, by 18.54 HB used each millimeter. This implies that denser layers can make the material softer. * Printing Speed: Increasing printing speed reduces the Hardness by 0.10 HB units/mm/s, indicating that there is the possibility of using faster printing in terms of Hardness. Nozzle Diameter: Larger nozzle diameters found a decrease in Hardness of 10.48 HB units/millimeter, which underscores the fact that bigger nozzles provide soft prints. * Infill Density: A 1 per cent increase in Hardness is

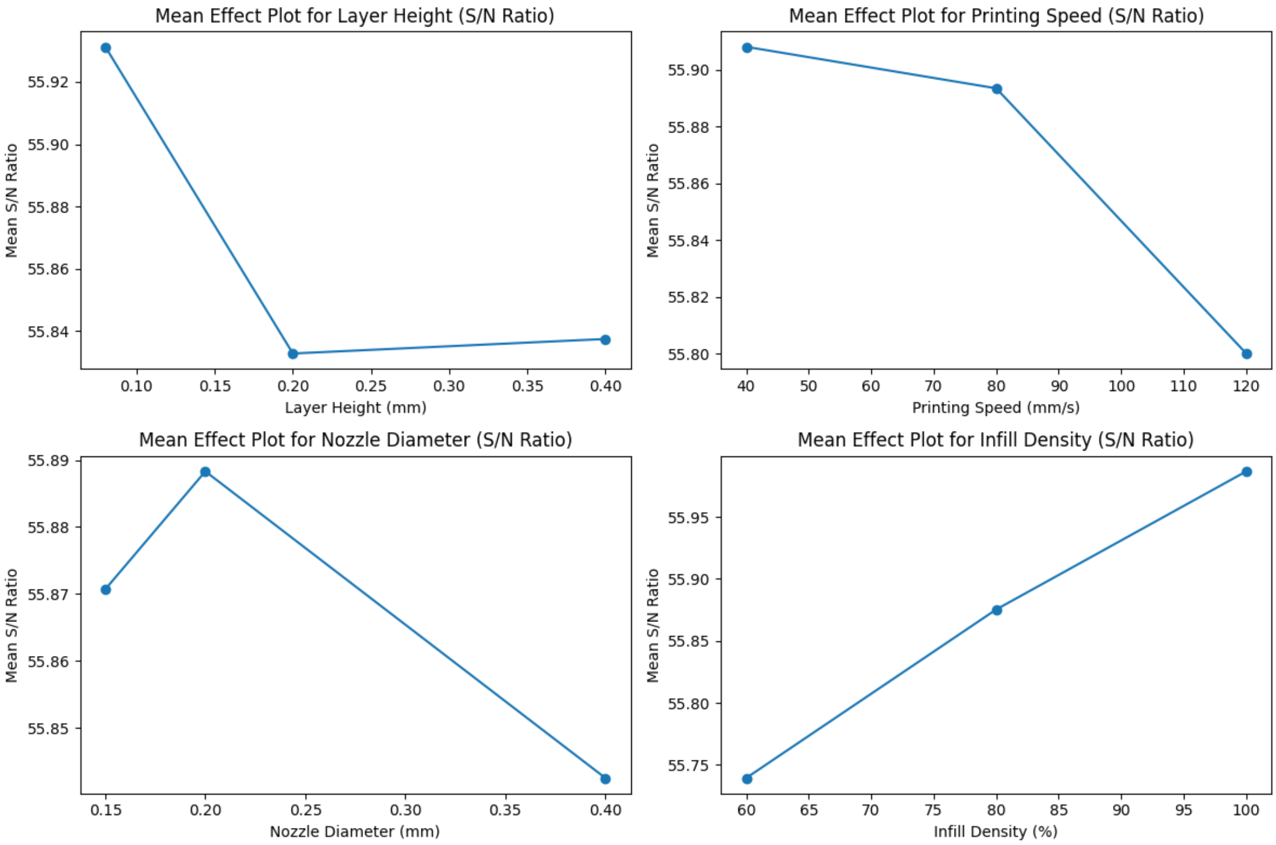


Figure 5. Main effect plot for hardness.

related to a 0.44 HB unit increase, that is, the denser is the infill, the harder is the specimen.

Taguchi Analysis for optimizing Ultimate Tensile Strength

Evaluation of tensile strength is an important test used to determine the mechanical properties and effectiveness of components that are manufactured through 3D printing. This test ensures the ability of a material to withstand tension or the pulling forces without breaking. Universal testing machine (UTM) is a versatile device that can be used to perform tensile strength tests on various forms of material, including those that are used in 3D printing. The prepared specimens were subjected to Tensile Testing with the help of a Universal Tensile Tester which was manufactured by Shanta Engineering. The reference samples that are to be tested are represented in Figure 6 and this shows a visual representation of the materials that are to be tested. Table 12 provides the process parameters of tensile strength optimization whereby the details of the conditions and variables are outlined to be implemented in the experimentation. Figure 7 below shows the main effect plot of ultimate tensile strength which illustrates the effect of each parameter on tensile strength. The outcomes of the analysis of variance (ANOVA) of ultimate tensile strength are presented in Table 13 that can provide a complete picture of the level of statistical significance and the impact of each parameter on tensile strength results. The testing system can take large loads of about 500 kg per unit, and hence can be used in numerous applications. It has a displacement resolution of 0.2 mm and this enables movement to be measured accurately. The column clearance is 380 mm and it offers a lot of space which can be used to test bigger specimens. Its cross head can be moved up to 900 mm with no grips or fixtures, which makes it flexible in the kind of testing of various kinds of samples. With an A.C. servo drive and variable speeds (1 mm/min to 500 mm/ min) are used, it can be adjusted to a large variety of testing requirements. The system needs 0.5 horsepower, which is not very high and can be used in the typical laboratory conditions. Figure 7 shows the Main effect plot for ultimate tensile strength

The ANOVA outcomes of Ultimate Tensile Strength (UTS) indicate that there is a substantial amount of information about the effect of different printing parameters on the material performance. The most powerful criteria is Layer Height (mm) that measures 90.41 percent of the variation in UTS. The F-statistic of this parameter is remarkably high (324.37) and the p-value of the parameter is extremely low (0.000056), meaning that the impact is very strong and statistically significant. The large percentage of

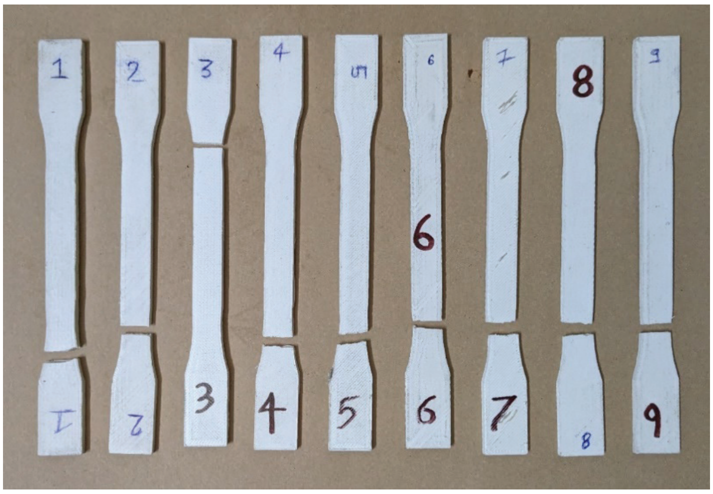


Figure 6. Tested standard specimens.

Table 12. Process parameters for optimizing tensile strength

Sr. No.	Layer height (mm)	Printing speed (mm/s)	Nozzle diameter (mm)	Density (%)	Ultimate tensile strength (N/mm^2)
1	0.08	40	0.15	60	14.23
2	0.08	80	0.2	80	17.81
3	0.08	120	0.4	100	19.62
4	0.2	40	0.2	100	24.22
5	0.2	80	0.4	60	25.86
6	0.2	120	0.15	80	32.13
7	0.4	40	0.4	80	35.71
8	0.4	80	0.15	100	41.96
9	0.4	120	0.2	60	41.67

Contribution points to its dominant position in the determination of UTS, where maximizing of the height of the layer is important in maximizing the strength of the material. Printing Speed (mm/s) has also an influence on UTS but to a smaller extent as it explains 7.35% variation. This parameter (F-statistic 26.39, p-value 0.006806) is statistically significant, which indicates that the changes in printing speed do affect UTS, but the effect is much smaller when compared to the impact of layer height. Conversely, there is little effect of Nozzle Diameter (mm) and Infill Density (%) on UTS. The nozzle diameter is insignificant in the change in UTS (0.80) and the F-statistic is 2.86 and the p-value stands at 0.166192. On the same note, infill density explains only 0.32 percent of the variation, F-statistic of 1.16 and p-value of 0.341904, which indicates that it contributes insignificantly to UTS. The remainder or the amount of UTS not covered by the parameters in this model is the residual variance that returns the amount of variability that is not taken care of in this model 1.11%. This left-over shows that although the model is able to explain a significant amount of variability in UTS, there might be other things or other sources of variation that are not represented in the analysis. In a nutshell, the height of the layers is the most essential aspect that enhances UTS and printing speed also counts in the matter. Nevertheless, nozzles size, and infill density have insignificant influence, and unused variance implies that a further study on the subject might be necessary to capture other factors that do not create an anthropomorphic difference in UTS.

Regression Equation of UTS is given in equation 07:

$$\mathbf{UTS = 5.24 + (69.62) * Layer\ Height + (0.08) * Printing\ Speed + (-7.99) * Nozzle\ Diameter + (0.03) * Infill\ Density} \quad (7)$$

- Layer Height significantly improves UTS, with each millimeter increase boosting UTS by 69.62 N/mm^2.
- Printing Speed has a minimal positive effect on UTS.

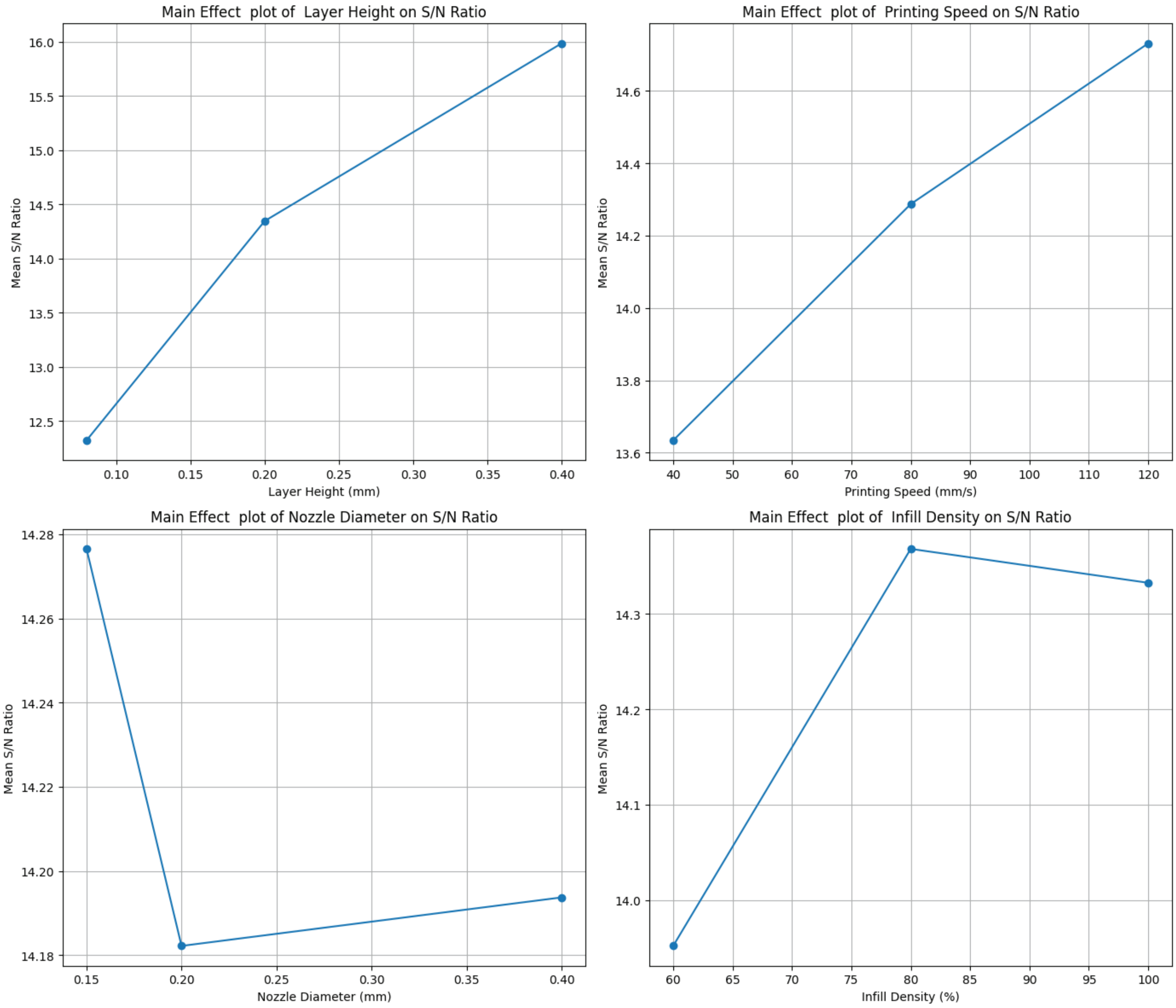


Figure 7. Main effect plot for ultimate tensile strength.

Table 13. ANOVA table for ultimate tensile strength

Parameters	sum_sq	df	F	PR(>F)	% Contribution
Q("Layer height (mm)")	760.0172	1	324.37385	0.000056	90.41041
Q("Printing speed (mm/s)")	61.8246	1	26.386617	0.006806	7.354554
Q("Nozzle diameter (mm)")	6.696021	1	2.857849	0.166192	0.796548
Q("Infill density (%)")	2.720267	1	1.161004	0.341904	0.323598
Residual	9.372115	4	-	-	1.114891

- Nozzle Diameter negatively impacts UTS; larger diameters decrease strength by 7.99 N/mm^2 per millimeter.
- Infill Density slightly increases UTS with each percent rise contributing 0.03 N/mm^2.

Layer height is the most influential factor, while nozzle diameter detracts from strength.

Dimensional Accuracy

Dimensional accuracy testing is crucial and first step in evaluating quality and precision of 3D printed parts. One common approach to perform this test is using a digital vernier caliper. The equipment used for this test is Mitutoyo Digital vernier caliper 300mm.

Table 14. Dimensional accuracy

3D Printed ASTM Specimen					% Accuracy			
SR. No.	Full length (mm)	Thickness (mm)	Parellel section width (mm)	Grip section width (mm)	Accuracy of full length (%)	Accuracy of thickness (%)	Accuracy of parallel section width (%)	Accuracy of grip section width (%)
1	172.9100	4.0900	13.0800	19.1350	99.9653	103.6670	100.6150	100.7110
2	172.9800	3.8466	13.3500	19.3400	99.9884	96.1667	102.6920	101.7900
3	172.7500	3.8644	12.8300	19.0750	99.8555	96.5833	98.6923	100.3950
4	172.8400	3.5866	13.0800	19.0650	99.9075	89.6667	100.6150	100.3420
5	173.0200	3.7200	13.1100	19.0200	100.0120	93.0000	100.8460	100.1050
6	173.1800	3.9933	13.4000	19.2950	100.1040	99.8333	103.0770	101.5530
7	172.9200	3.4600	13.2000	19.2900	99.9538	86.5000	101.5390	101.5260
8	173.0500	3.5833	13.3000	19.3150	100.0290	89.5833	102.3080	101.6580
9	172.8700	3.7100	13.1600	19.1300	99.9249	92.7500	101.2310	100.6840

The detailed measurements and results for dimensional accuracy are provided in Table 14**,** which lists the recorded values for each dimension.

The dimensional accuracy of the 3D printed ASTM specimens generally meets high standards, with full length and grip section width showing excellent consistency, ranging from 99.855% to 100.104% and 100.1053% to 101.6579%, respectively. However, thickness accuracy varies more significantly, from 86.5% to 103.6667%, indicating potential inconsistencies in the printing process. The parallel section width accuracy is fairly consistent, ranging from 98.69231% to 103.0769%. These variations suggest that while the overall printing process is reliable, improvements in calibration and process control are needed to enhance thickness consistency and achieve more uniform accuracy across all dimensions.

Using optimum settings and regression equations following parts are manufactured with the help of 3D printing for quad bike as shown in Figure 8.

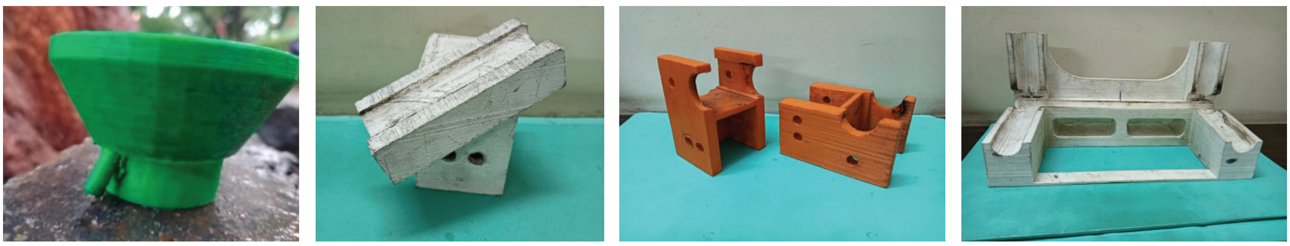
Figure 8 displays the 3D printed parts of the fixture for the quad bike, including: (a) the oil tank cap with funnel, (b) the fixture for the camber link assembly, (c) the welding fixture for the rear chassis' left and right mount position arm, and (d) the welding fixture for the rear chassis. This figure provides a comprehensive view of the various components designed and printed for the quad bike fixture.

Figure 9 shows the fixture positions for quad bike chassis during assembly.

Relations with the Current Research

The present research is closely related to several major spheres of current research and integrates fundamental knowledge from multiple domains. Previous studies by Kanu et al. [4] and Anbalagan et al. [7] highlighted the significant influence of environmental factors such as temperature and humidity on material efficiency, which must be carefully considered during the printing process. Furthermore, the work of Pernica et al. [8] and Vambol et al. [9] emphasized that complex geometries and manufacturability constraints play a crucial role in determining the structural performance of printed components.

In addition, Arora et al. [10] demonstrated that non-conventional printing conditions can lead to substantial variations in material behavior, affecting the final part quality. The multi-scale modeling approaches discussed



a) b) c) d)

Figure 8. 3D printed parts of fixture for Quad bike a) oil Tank Cap with funnel, b) fixture for camber link assembly, c) welding fixture for rear chassis' left and right mount position arm and d) welding fixture for rear chassis

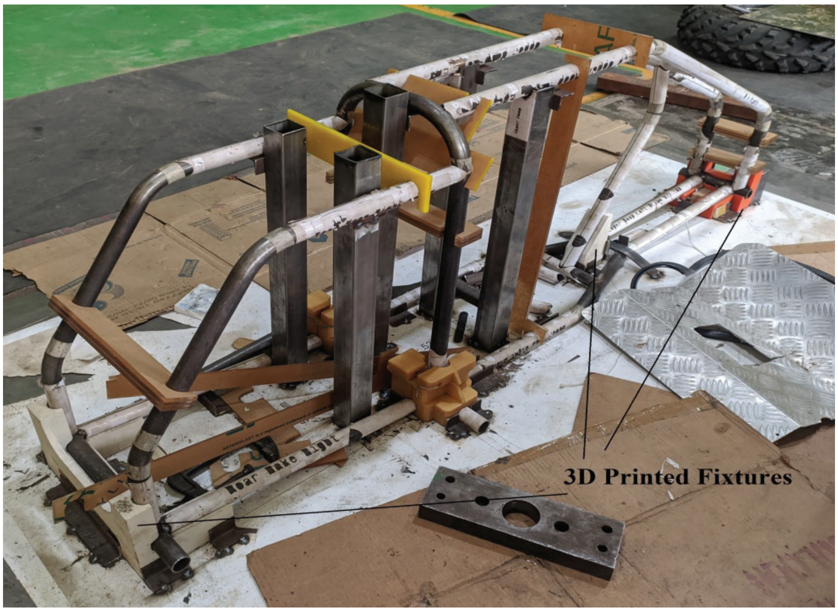


Figure 9. Fixture positions for quad bike chassis during assembly.

by Cahyati et al. [15] further support the need to integrate microstructural and macro-level performance analysis. Similarly, Hamat et al. [16] and Rodriguez et al. [18] contributed to the understanding of testing methodologies and practical manufacturability considerations.

The influence of printing parameters on mechanical properties has been extensively studied by Ahmad et al. [20] and Baharudin et al. [21], confirming that parameter optimization significantly enhances performance and consistency. Supporting this, Pyl et al. [22] investigated long-term durability and fatigue resistance, demonstrating the importance of material selection and process conditions in improving lifecycle performance. Sustainability aspects in additive manufacturing were addressed by Tanikella et al. [23], emphasizing the growing importance of recycling and environmental impact reduction.

Advanced modeling and simulation approaches proposed by Zakarneh et al. [26] further enhance predictive capabilities for material behavior. The importance of customization and user-specific design was highlighted by Kumar A et al. [27], showing its direct impact on performance optimization. Additionally, Zakaria S et al. [28] developed advanced testing procedures that improve the accuracy and reliability of material evaluation. Finally, Tientcheu SWT et al. [30] explored complex interactions between different materials and composites, confirming their significant influence on overall performance outcomes.

CONCLUSION

This paper has reviewed the effect of 3D printing parameters on manufacturing time, surface quality, hardness, and tensile strength through Taguchi and regression analysis using Python. The main conclusions are discussed as follows:

Manufacturing Time: Layer height, the speed of printing, and the nozzle diameter of the printing increased in significant amounts shortening manufacturing time. The impact was determined through regression analysis, and the major factors affecting it were the height of the layer and printing speed. The equation of manufacturing time indicates that it is strongly correlated with these aspects in a negative way.

Dimensional Accuracy: Both Specimen 1 and 6 had almost a perfect dimensional accuracy indicating the need to ensure accurate choices of parameters yield high-quality outputs.

Surface Roughness: The layer height of 0.2 mm, density of 100 percent, nozzle diameter of 0.4 mm, and printing speed of 80 mm/min the minimum level of roughness on the surface was attained. The regression analysis proved that the most important parameter that affects the roughness is layer height.

Hardness: The best hardness was attained using a layer height of 0.08 mm, nozzle diameter of 0.2 mm, 100% density and a print speed of 40 mm/min. The hardness equation stressed layer height and density, which is very crucial.

Tensile Strength: The maximum tensile strength was recorded when the layer height was 0.4 mm, the 80% density, nozzle diameter was 0.15 mm, and the print speed was 120 mm/min, which illustrates the trade-offs between the speed, structure strength and density.

The 3D-printed fixtures fabricated had a great impact on the welding accuracy of the Quad Bike chassis, and decreased the assembly time, which contributed to the overall stability of the product. This critical review highlights the significance of parameterizing the processes to implement the desired results, which should represent a powerful scheme of optimizing manufacturing tasks using FDM.

Constraints and Bondage.

The study has given meaningful information on optimization of the manufacturing parameters, though limited to some extent. The study is limited to the range of parameters under test that might not represent all possibilities of variation. Also, the study mainly addresses mechanical properties and does not consider all the other aspects including degradation of the material overtime or the effect of the environmental conditions under long term use.

Future studies would be able to build on these results by considering a wider selection of parameters and materials. The durability and performance of the optimized parameters in real-world applications is also long-term, but a more detailed analysis would be conducted to gain a clearer insight into their efficiency. Moreover, it might be possible to involve the use of more advanced modeling methods and simulations that will provide more profound understanding of the relationships between different factors and their influence on performance. The study may also be extended in future to discuss how young technologies and materials may be incorporated in order to widen the choice and application of the research results.

ABBREVIATIONS

ATV	All-Terrain vehicle
ANOVA	Analysis of variance
ASTM	American Society for Testing and Materials
CAD	Computer aided design
3D	Three dimensional entities
PLA	Polylactic acid

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AUTHORSHIP CONTRIBUTIONS

Authors' contributions- MP: conceptualization, PB: resources, methodology, investigation, visualization writing original and revised draft, KN: supervision and project administration, VW: investigation, visualization writing original and revised draft.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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