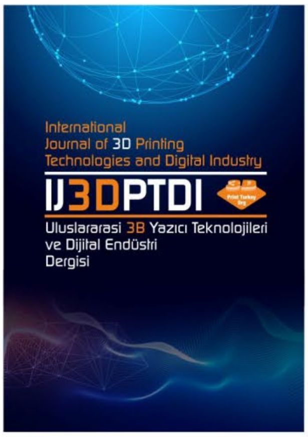

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3D PRINTER PARAMETER OPTIMISATION FOR PLA USING TAGUCHI AND GREY RELATIONAL ANALYSIS METHODS

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ABSTRACT

This study aims to increase measurement accuracy and print quality by using Fused Filament Fabrication (FFF or Fused Deposition Modeling (FDM)) and to examine the effect of parameters that cause variability. In this context, PLA (Polylactic Acid) filament was used, and printing parameters such as printing temperature, printing speed, layer thickness, fan speed, printing speed (outlines), and roof thickness were optimized with Grey Relational Analysis and Taguchi Design of Experiments. A total of 25 samples were produced at five different levels for each factor using Grey Relational Analysis and Taguchi Design of Experiments. The samples were evaluated using the intuitive quality scoring method, each scoring between 1 and 10. As a result of the research, we determined 215 °C printing temperature, 100 mm/s printing speed, 0.15 mm layer thickness, 90 mm/s fan speed, 15 mm printing speed (outlines), and 0.8 mm roof layer thickness as optimal printing parameters. This research aims to determine the effect of the production parameters on the measurement accuracy of parts produced by the FFF method and the values at which these parameters should be based on the overall quality analysis. Adopting the methodology used in the study of industrial applications aims to obtain the most optimal dimensions, improve production quality, and contribute to the broader use of FFF technology.

Keywords: FFF, FDM, Taguchi, Design of Experiments, Grey Relational Analysis, MEX

1. INTRODUCTION

Fused Filament Fabrication (FFF) is an material extrusion (MEX) based additive manufacturing method in which objects are produced layer by layer from 3D model data. This method allows complex parts to be produced quickly and efficiently [1]. This method enables the production of functional parts and prototypes using thermoplastics turned into filaments. Additive manufacturing has a principle based on production in layers during printing, and the 3D model is sliced on the software before printing. After the sliced process in the software, the values of the FFF process parameters are defined. The filament is melted at high temperatures and extruded onto the printing table through a nozzle. The extruder head moves in the X and Y planes to create the 2D shape of the sample, then starts moving in the Z plane and completes the 3D sample production with the layering process (Fig.1). Various thermoplastics (PLA, ABS, PETG) are widely available in the market for FFF production.

It is a more economical technology because it is low-cost. However, in addition to these advantages, there are also negative factors that should be considered. These factors include the chronic surface roughness problem that reduces the visual quality of the parts produced in FFF printers and the longer printing time than other 3D printers.

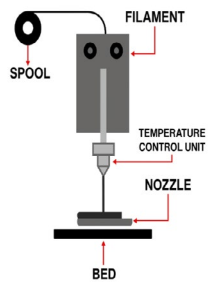

Figure 1. Schematic Representation of FFF Technology [2]

It enables the rapid production of complex and customized designs and offers a low-cost solution for small-scale prototypes. However, dimensional accuracy and surface print quality may fall short of expectations in large parts. Therefore, deviations in product sizing negatively affect the efficiency of the production process and the functionality of the final product and usually require additional processes to achieve the desired quality of the product. The critical factor for the FFF method is to make the correct parameter settings and to perform the 3D printer calibration properly. Toprak [3] in his study, examined process parameters such as infill density, layer thickness, and printing speed, which affect the tensile, yield strength, and weight of parts produced with the FFF method. Shakeri et al. [4] determined that infill density is the most important variable for the Grey Relation Degree. He examined the effects of parameters such as room temperature, printing temperature, layer thickness, and printing speed on five basic characteristic properties of the components. Singh et al. [5] examined the effects of different layer heights and extruder temperature combinations. They evaluated the effects of infill percentage and printing speed on three mechanical properties with the Grey Relational Analysis method. Shakeri et al. [6] examined the parameter effects on mechanical properties with Grey Relational Analysis and the Taguchi method. They determined that 60 °C and 270 °C were optimum values. John et al. [7] in their study, Taguchi and Grey Relational Analysis applied their relational analysis to cellular geometry, nozzle diameter, and output responses. Aslani vd. [8] examined previous studies according to FFF parameters such as number of shells, printing temperature, infill ratio, and printing model and selected PLA (Polylactic acid) filament as suitable. Altun et al. [2] aimed to increase printing quality in FFF technology and investigated the effects of parameters. While the increase in extruder temperature decreased the quality, it was found that the effects of other parameters were not linear. Baş et al. [9] Examining the production processes in FFF-type printers with fault tree analysis (FTA) revealed possible errors in detail.

For PLA, nozzle/printing temperature and printing speed have a marked influence on geometric accuracy and tensile response, with practical optima reported [10]. Broader DOE (Design of Experiments) frameworks such as RSM (Response Surface Methodology) capture the effects of layer height, bead width, and build orientation on mechanical behavior [11]. Multi-response optimization with Taguchi combined with Grey Relational Analysis (GRA) effectively consolidates dimensional and surface metrics into a single decision basis [12]. Other studies confirm the central role of layer height and speed on surface roughness and dimensional accuracy [13] and demonstrate PLA-focused Taguchi–GRA optimization in application-driven parts Tunçel et al. [14].

In this work, printing temperature, printing speed (infill), layer thickness, fan speed, outline (shell) speed, and roof layer thickness were chosen because they are among the most influential parameters on dimensional accuracy and surface quality according to previous work Altun et al. [2]; Solouki et al. [15]; Darsin et al. [16]. For example, Darsin et al. [16] reported that nozzle temperature and layer thickness contribute approximately 31.7 % and 25.5 %, respectively, to dimensional inaccuracy. Altun et al. [2] showed that layer thickness and nozzle temperature significantly affect surface roughness and mechanical properties in PLA prints. Similarly, Solouki et al. [15] demonstrated that combining high printing speed and large layer thickness leads to a loss of geometric accuracy and increased surface roughness.

Based on these findings, printing temperature and layer thickness were expected to have the highest impact on dimensional accuracy in this study. Fan speed and roof thickness affect surface smoothness by regulating cooling and top layer density. Infill and outline speed influence build time and visual defects such as oozing and ringing. Although generally considered an important parameter for preventing stringing, retraction distance was held constant because the calibration cube used in this study consists of continuous extrusion paths with minimal travel moves. Other factors, such as infill density and nozzle diameter, were kept constant to isolate the effects of the six selected parameters. PLA filament was selected as the material because it is the most widely used polymer in FFF printing, but the selected parameters are considered equally important for other common materials such as ABS and PETG.

In this study, parameter optimization was performed using Grey Relational Analysis and Taguchi Experimental Design in the FFF method. Printing temperature, printing speed, layer thickness, fan speed, printing speed (outlines), and roof layer thickness were determined as optimization parameters. The efficiency of FFF technology for specific criteria was analyzed using the Taguchi and Grey Relational Analysis methods.

Genichi Taguchi developed the Taguchi method in Japan in the 1960s [17]. This method provides a practical approach to creating experimental designs to examine complex problems and test and optimize quality values. The Taguchi method eliminates complexity by performing minimum experiments in experimental design processes. The simultaneous evaluation and optimization of all characteristics allow the determination of ideal performance values to achieve quality improvement goals. This method aims to achieve the best product quality and includes procedures such as system design, parameter design, and tolerance design to obtain robust processes and results [18].

The Taguchi method and Grey Relational Analysis are frequently preferred in engineering applications and provide effective results. Taguchi's method aims to improve product and process quality by minimizing the effects of parameters in optimization processes. At the same time, Grey's Relational Analysis determines the most appropriate solution by evaluating the relationships between alternatives in multi-criteria decision-making problems.

2. MATERIALS AND METHODS

2.1. Material and Equipment

The model used in the study is the "XYZ Calibration Cube" (Figure 2). This model is a good test sample for the 3D printer to be correctly calibrated and for the analysis of dimensional accuracy and measurement precision. The standard measurement value of the model is 20 mm. MakerBot Replicator 5th Generation 3D Printer was used to produce the sample, and the material used in the model is MakerBot brand PLA filament with a nozzle diameter of 0.4 mm.

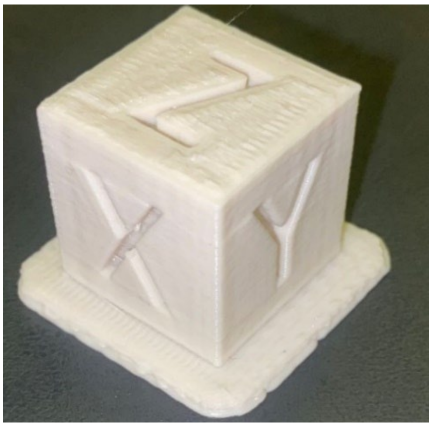

Figure 2. XYZ Calibration Cube Example.

2.2. Design of Experiments

In this study, measurement accuracy and visual quality assessment of test samples produced from PLA filament using the FFF method were performed. The aim was to determine the effect of fixed and variable parameters on measurement accuracy and quality variability. Taguchi Experimental Design was applied by selecting the L25 orthogonal matrix according to factor levels and number. Independent variables determined in the experimental design were printing temperature 205-225 °C, printing speed 80-100 mm/s, layer thickness 0.1-0.3 mm, fan speed 60-100 mm/s, printing speed (outlines) 15-35 mm/s and roof layer thickness 0.6-1 mm (Table 1). Dependent variables were determined as filling density 10%, retraction distance 0.5 mm, printing pattern Diamond Fill (Fast), and shell number 2. Other variables are the default parameters of the MakerBot Print slicer.

2.3. Intuitive Quality Value

Intuitive quality can be defined as the evaluation and measurement by users of a specific process or service according to its expected or perceived value in terms of performance, functionality, and visuality.

This study examined products produced with the FFF method and detected five printing defects. These defects were classified as follows: deformation on side surfaces, loss of detail, threaded appearance, scratches on the upper surface, and curled edge.

Each sample produced in the 25 experiments was evaluated separately regarding these detected defects. Four different decision-makers were evaluated on a 0-2 point scale. Each sample was scored for each defect type, and 10 points were obtained as an intuitive quality value. As a result of these evaluations, the products reached intuitive quality values ranging from 0 to 10 (Table 1).

2.4. Grey Relational Analysis

It is an analysis technique based on rating and classification in decision-making problems with multiple criteria and uncertainty. This method offers a more straightforward solution compared to mathematical analyses. The rated criteria take "0" or "1" target values; "0" means there is no correlation, and "1" means there is a correlation. This study determined the standard measurement value of the "XYZ Calibration Cube" sample produced in the x, y, and z planes as 20 mm. Four different decision-makers took the measurements of the samples with the help of calipers, and the average values of these measurements were calculated. In this context, measurement errors were determined for 25 different experiments. In addition, Grey Relational Analysis was performed to examine the relationship between the measurement precision of the process parameters and the visual quality variability in line with the purpose of the study, considering the intuitive quality values (chart) calculated for five different printing errors observed in the samples produced with the FFF method.

In studies [19-22] firstly, an m x n decision matrix is created, where m represents the alternatives and n represents the criteria. The Xi (k) value represents the criteria of the i. sample. Then, comparisons are made between the samples.

These processes are carried out in 5 steps using the following formulas:
Formula no. 1 is the best criterion; formula no. 2 is the lowest criterion, and formula no. 3 converts the average type criteria into normalization [22].

$$x_i(k) = \frac{x_i^0(k) - min\, x_i^0\,(k)}{max\, x_i^0(k) - min\, x_i^0\,(k)} \quad (1)$$

$$x_i(k) = \frac{max\, x_i^0(k) - x_i^0\,(k)}{max\, x_i^0(k) - min\, x_i^0\,(k)} \quad (2)$$

$$x_i(k) = 1 - \frac{|x_i^0(k) - x^0)|}{\max x_i^0(k) - x^0\,(k)} \quad (3)$$

After the normalization process, the absolute value table is created, and the Grey Relational coefficient matrix for different data series is created.

$$\varepsilon(x_0(k), x_i\,(k) = \frac{\Delta_{min} + \xi\Delta_{max}}{\Delta_{0i}\,(k) + \xi\Delta_{max}} \quad (4)$$

The Grey Relationship degree is calculated for each sample.

$$\Gamma_i = {}^1/_n \sum_{m=1}^{n} l_i\,(m) \quad (5)$$

3. Experimental Findings

3.1. Common Errors Seen in the Study

Baş et al. [9] , examined the errors encountered in the FFF method in detail. These errors include extrusion interruptions, surface deterioration, curling, dimensional errors, loss of detail, overheating, scratches, warping, support problems, curled edges, hole and gap problems, printing start problems, elephant foot, and infilling. Although there are many errors in the literature, five different errors were encountered in this study:

• Scratches on the Top Surface

Some scratches occur on the print due to excessive printing speed, printing temperature, and insufficient fan settings (Fig. 3). The formation of unwanted scratches at the top level can be prevented by reducing the printing speed and temperature. The hardening of the plastic can be prevented by reducing the fan speed.

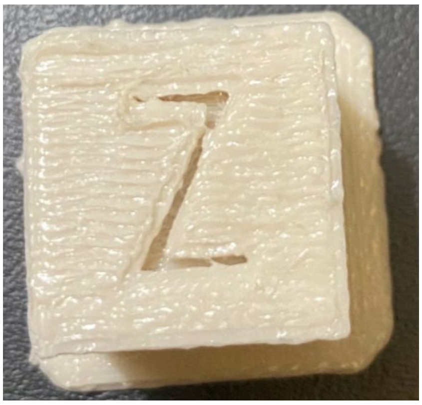

Figure 3. Scratches Error and Detail Loss Error on the Top Surface.

• Oozing
It is the emergence of a threaded and unclean appearance, different from the expected appearance in some recessed and voided designs. Threads occur in movements made without extrusion for a long time, at extremely high temperatures, or with low retraction speed. This problem is not observed in structures where the filament is continuously shed, i.e., without gaps (Fig. 4).

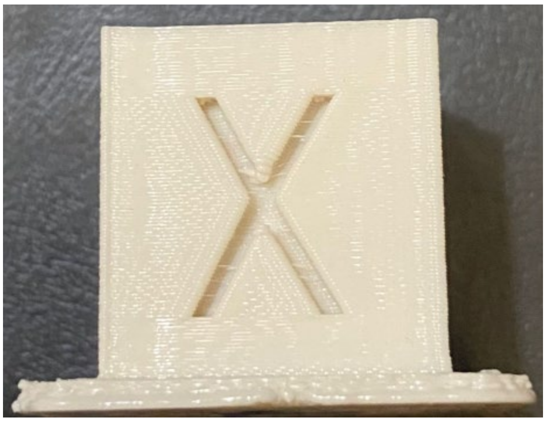

Figure 4. Oozing.

• Curled Edges
Curling is a common problem during printing. Layers usually have bends at their corners (Fig. 5). This problem can be observed when printing for a long time. These problems are the result of thermal stresses in the material being produced. A heated bed can be used to solve this problem, and fan cooling can be turned off.

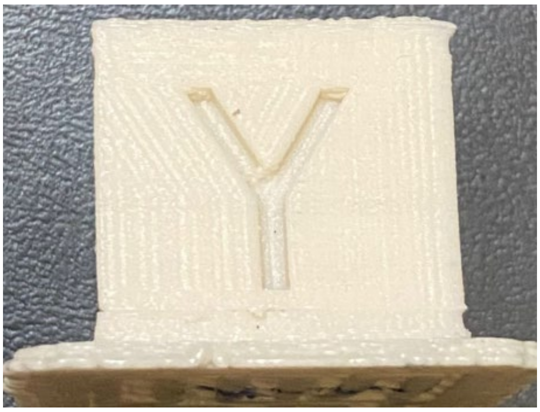

Figure 5. Curled Edges.

• Deformities on the Side Surfaces
During printing, problems like distinct lines and wavy patterns may occur on the side surfaces (Fig. 6). These problems are usually related to mechanical problems such as incorrect retraction distance, inconsistent extrusion, temperature changes, and vibrations in the printer.

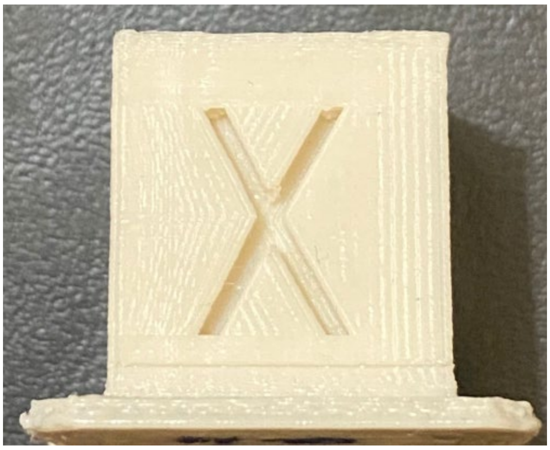

Figure 6. Deformities on the Side Surfaces.

• Loss of Detail
The thin and complicated parts of the product design do not contain the details desired by the 3D printer, are printed incompletely, or are not appropriately printed (Figure 3).

3.2. Taguchi Experimental Design Parameters and Intuitive Quality Assessment

In this study, 25 experiments were carried out using the parameters determined according to Taguchi Experimental Design (Table 1). S/N analysis was performed in the synthesis process. In the measurement precision, the "smaller is better" criterion was adopted to minimize measurement errors. The intuitive quality value adopted the "larger is better" criterion to maximize visual print quality [16]. Figure 7-10 shows x, y, z planes and intuitive quality value S/N analysis response reports.

At this stage of the synthesis process, the measurement errors and intuitive quality values of the samples were calculated. The experiment mainly investigates the effect of the parameter variability on the measurement precision and visual quality of the samples. Using the intuitive quality assessment method, five determined printing errors were considered and scored between 1 and 10, and the visual printing quality was evaluated.

Table 1. Taguchi Experimental Design, Measurement Errors and Heuristic Quality Values.

Experiment No	Printing Temperature (°C)	Printing Speed (mm/s)	Layer Thickness (mm)	Fan Speed (mm/s)	Printing Speed (Outlines) (mm/s)	Roof Solid Thickness (mm)	X	Y	Z	Intuitive Quality Value
1	205	80	0,10	60	15	0,6	0,20	0,30	0,44	2
2	205	85	0,15	70	20	0,7	0,27	0,37	0,01	7
3	205	90	0,20	80	25	0,8	0,37	0,38	0,01	8
4	205	95	0,25	90	30	0,9	0,28	0,38	0,20	9
5	205	100	0,30	100	35	1	0,24	0,36	0,05	8
6	210	80	0,15	80	30	1	0,22	0,39	0,06	4
7	210	85	0,20	90	35	0,6	0,32	0,44	0,02	5
8	210	90	0,25	100	15	0,7	0,25	0,29	0,02	6
9	210	95	0,30	60	20	0,8	0,15	0,27	0,02	7
10	210	100	0,10	70	25	0,9	0,21	0,41	0,67	1
11	215	80	0,20	100	20	0,9	0,23	0,35	0,15	7
12	215	85	0,25	60	25	1	0,26	0,40	0,07	7
13	215	90	0,30	70	30	0,6	0,23	0,36	0,02	7
14	215	95	0,10	80	35	0,7	0,20	0,44	0,58	2
15	215	100	0,15	90	15	0,8	0,09	0,25	0,10	7
16	220	80	0,25	70	35	0,8	0,23	0,41	0,12	5
17	220	85	0,30	80	15	0,9	0,11	0,31	0,01	8
18	220	90	0,10	90	20	1	0,14	0,32	0,60	1
19	220	95	0,15	100	25	0,6	0,14	0,39	0,13	7
20	220	100	0,20	60	30	0,7	0,22	0,45	0,03	8
21	225	80	0,30	90	25	0,7	0,20	0,36	0,12	7
22	225	85	0,10	100	30	0,8	0,19	0,40	0,29	2
23	225	90	0,15	60	35	0,9	0,28	0,43	0,15	4
24	225	95	0,20	70	15	1	0,19	0,41	0,04	6
25	225	100	0,25	80	20	0,6	0,20	0,40	0,16	7

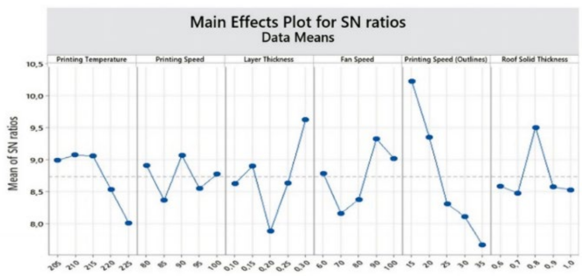

Figure 7. X-Plane S/N Report.

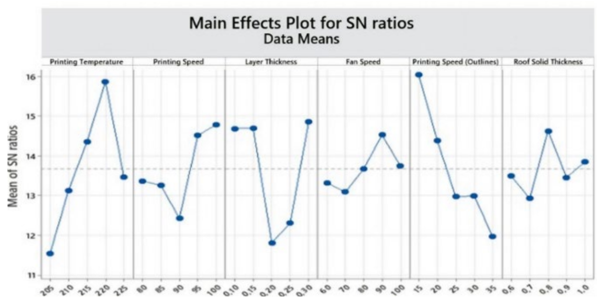

Figure 9. Z-Plane S/N Report.

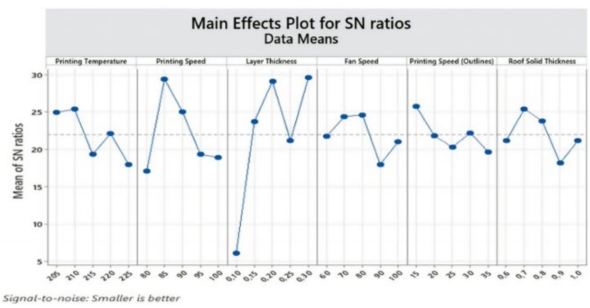

Figure 8. Y-Plane S/N Report.

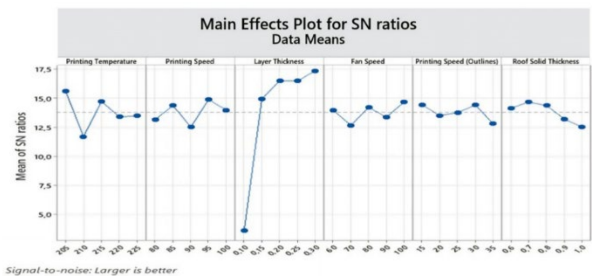

Figure 10. Intuitive Quality Value S/N Report.

3.3. Grey Relational Analysis Results

The measurement errors of the samples in the X, Y, and Z planes were calculated separately. The intuitive quality value was determined in the previous stages. In this direction, the Grey Relational Analysis Method was applied to evaluate the relationship between the four criteria, namely the measurement errors of the x, y, z planes and the intuitive quality value. The optimum parameter values obtained from the analysis are presented in the Table 2.

Table 2. Grey Relational Analysis Results

Experiment No	X	Y	Z	Intuitive Quality Value	Sorting
1	0,57	0,66	0,43	0,36	21
2	0,44	0,45	1,00	0,67	9
3	0,33	0,44	0,99	0,80	8
4	0,42	0,45	0,64	1,00	11
5	0,48	0,48	0,89	0,80	5
6	0,53	0,42	0,87	0,44	17
7	0,37	0,35	0,96	0,50	18
8	0,47	0,72	0,97	0,57	4
9	0,71	0,79	0,96	0,67	3
10	0,55	0,39	0,33	0,33	25
11	0,50	0,50	0,71	0,67	14
12	0,45	0,41	0,85	0,67	15
13	0,50	0,48	0,96	0,67	6
14	0,55	0,34	0,37	0,36	24
15	1,00	1,00	0,78	0,67	1
16	0,50	0,39	0,75	0,50	19
17	0,86	0,60	1,00	0,80	2
18	0,76	0,57	0,36	0,33	20
19	0,73	0,42	0,74	0,67	10
20	0,53	0,33	0,94	0,80	7
21	0,55	0,49	0,75	0,67	12
22	0,59	0,40	0,54	0,36	23
23	0,42	0,36	0,70	0,44	22
24	0,59	0,38	0,92	0,57	13
25	0,55	0,41	0,69	0,67	16

3.4. Discussion

The optimal parameter settings for each individual quality characteristic were determined by examining the Signal-to-Noise (S/N) ratio response tables (Figure 7-10), aiming for the highest S/N ratio in each case.

For the X-axis dimensions, the analysis suggests an optimal combination of 210 °C printing temperature, 90 mm/s printing speed, 0.30 mm layer thickness, 90% fan speed, 15 mm/s printing speed (outlines), and 0.8 mm roof solid thickness (Fig. 7).

Similarly, the optimal settings for the Y-axis dimensions exhibit some consistency with the X-axis results, recommending a printing temperature of 210 °C and a layer thickness of 0.30 mm. However, the optimal choices diverge for other parameters, favoring a 85 mm/s printing speed, 80% fan speed, and 0.7 mm roof layer thickness, while maintaining 15 mm/s for the outline speed (Fig. 8).

The optimization for the Z-axis dimensions showed a distinct preference for higher thermal and kinetic inputs. The highest signal-to-noise ratio (S/N ratio) was achieved with a printing temperature of 220 °C and a printing speed of 100 mm/s. Like the other axes, optimal settings included a 0.30 mm layer thickness, 15 mm/s outline speed, and 0.8 mm roof layer thickness, along with a 90% fan speed (Fig. 9).

Finally, the analysis concerning the Intuitive Quality Value suggested a different set of parameters. This characteristic was optimized at the lowest temperature setting (205 °C), a printing speed of 95 mm/s, and an outline speed of 30 mm/s. The optimal layer thickness remained at 0.30 mm, with a 100% fan speed and 0.7 mm roof layer thickness (Fig. 10). Similarly, in the study conducted by Altun et al. [2] , the effects of layer thickness, print temperature, fan speed, wall print speed, and retraction distance on print quality were evaluated intuitively using the 3DBenchy benchmark sample. Unlike our study, infill printing speed and roof solid thickness were added to the print parameters, and retraction speed was set as a fixed parameter. Furthermore, in our study, in addition to the intuitive scoring, we checked for measurement errors in the axes.

Since multiple parameters need to be evaluated, we should consider the grey relational analysis method. Using the Gray Relational Analysis method, the analysis of four criteria, namely X, Y, and Z measurement errors and visual printing quality, was carried out by keeping the weight values constant. The obtained results were tabulated and presented in Table 2, with a ranking column indicating the best (1) and the worst (25).

Optimum parameter values were determined as 215 °C printing temperature, 100 mm/s printing speed, 0.15 mm layer thickness, 90 mm/s fan speed, 15 mm/s wall printing speed, and 0.8 mm roof layer thickness (Table 3).

Table 3. Optimum Parameter Values

Print. Temp. (°C)	Print. Speed (mm/s)	Layer Thick. (mm)	Fan Speed (mm/s)	Print. Speed (Outlines) (mm/s)	Roof Solid Thick. (mm)	Intuitive Quality
215	100	0,15	90	15	0,8	7

The parameter values farthest from the optimum result were observed in Experiment 10 as 210 °C printing temperature, 100 mm/s printing speed, 0.10 mm layer thickness, 70 mm/s fan speed, 25 mm/s wall printing speed, and 0.9 mm roof layer thickness.

4. CONCLUSION

In this study, the Gray Relational Analysis method was applied to evaluate the relationship between the parameters determined by the Taguchi Method using FFF technology, measurement errors that may occur due to printing, and printing errors scored with the Intuitive Quality method. The relationship between the parameters and these errors was analyzed comprehensively.

Printing temperature, printing speed, layer thickness, wall printing speed, and roof layer thickness were determined as independent variables and a total of 25 samples were produced to analyze these variables. 20 mm was accepted as the standard value for X, Y, and Z planes. After printing, measurement errors were determined for each plane, and measurements were experimented with using vernier calipers. In addition, using the intuitive quality assessment method, five determined printing errors were considered and scored between 1 and 10, and the visual printing quality was evaluated. Optimum parameter values were determined as 215 °C printing temperature, 100 mm/s printing speed, 0.15 mm layer thickness, 90 mm/s fan speed, 15 mm/s wall printing speed, and 0.8 mm roof layer thickness

This work addresses apparent gaps by offering a reproducible, multi-objective calibration framework that improves dimensional accuracy (X, Y, Z) and overall surface quality using a Taguchi L25 and GRA approach. We also examine often overlooked parameters such as fan speed, roof solid thickness, and outline (shell) speed, together with the commonly studied printing temperature, printing speed, and layer thickness. Although the study focuses on PLA, chosen because it is widely used, the same parameter logic can be applied to other thermoplastics like ABS and PETG. It provides a practical baseline for future tests on different materials and geometries. For practitioners, the main benefit is actionable guidance with fewer trials: clearer priorities for process control and a ready-to-apply setting that improves both dimensional accuracy and overall surface quality.

As a result, parameter optimization in the FFF method was successfully achieved with the Taguchi method. The experimental approach used in this study constitutes a practical example of improving quality and minimizing unwanted errors in 3D printing made with the FFF method. The results show that carefully optimizing the printing parameters can achieve higher accuracy and visual quality. These findings provide an important basis for future studies, and process efficiency can be increased with parameter improvements.

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