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Fabrication and Process Parameter Optimization of a 3D Printer Using Response Surface Methodology

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Abstract

3D printing or additive manufacturing is a technology in which 3D objects are printed by depositing a thin layer of material layer-by-layer until a final product is produced. In this research work, it has been focused on the fabrication of a Portable 3D Printer for the manufacturing of sample parts by using Fused Deposition Modeling (FDM) process. The primary process parameters such as nozzle temperature, extrusion speed and fill density in addition to their interactions are studied. It has been observed that these process parameters influence the dimensional accuracy and extrusion time of the part produced by the process of FDM. The main objective of the research work is to create a reliable and cost efficient 3-D printer and to minimize the dimensional variation that usually occurs to plastic parts produced by 3D printers. Cartesian mechanism has been used where the print bed moves in the Z direction and the extruder moves in both the X and Y directions. The 3D printing filament that has been used is made of Poly Lactic Acid or Poly Lactide (PLA). The process involved 3D solid modeling to design, 3D printing with coated adhesive applied on the printing platform, measurement of dimensional variation of the printed parts and statistical analysis. Response Surface Methodology (RSM) based desirability analysis has been employed for optimization of FDM process parameters namely, nozzle temperature, extrusion speed and fill density. Mathematical models were developed and tested for accuracy and extrusion time using Design Expert 11 software for RSM application.

Keywords: Additive manufacturing, 3D printing, FDM, RSM, Optimization.

1 | Introduction

Additive Manufacturing (AM), contrast to traditional material removal or subtractive manufacturing is the process of manufacturing parts by adding layers in the third dimension. 3D CAD models are used to generate STL (standard triangulation) files containing the deposit layer data. AM is known for reduced supply chain costs, easier manufacturing design and green manufacturing initiatives. In AM, 3D-printing and rapid prototyping are used interchangeably to describe the process [1]. Fused Deposition Modeling (FDM) is a well-known additive manufacturing process for producing strong, robust prototypes [2]. The newer, more advanced manufacturing techniques are better able to deal with smaller, more complex, and custom product. Currently, FDM is used to produce models, visual aids, and prototypes as well as functional parts, such as drill grids in the aerospace industry.

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The application of the FDM process in manufacturing functional parts is still limited due to various drawbacks such as uneven surface, poor mechanical properties, and low accuracy. FDM has a bright future in a variety of industrial and medical fields. Many unsolved problems, such as reproducibility, post-processing, and the low-volume production, persist [3]-[5]. These drawbacks decrease its comparability across traditional manufacturing processes [6]. Reproducibility, ability to produce the replicas of the same part under same conditions with high dimensional accuracy, is one of the major challenges in AM. Several FDM parameters have a big impact on the final pieces. All of these variables affect the bonding between and within layers. Choosing the best process parameters can produce the desired properties. Choosing the best thermoplastic polymer for the part's intended use is also critical [7]. Dimensional precision, mechanical qualities, building time, and surface roughness have all been improved in 3D printers. The right FDM parameter selection can lead to excellent process performance. Research and our desired outcome determine the parameters for this work procedure. Air gap, build orientation, extrusion temperature, infill density, infill pattern, layer thickness, and number of shells are some of the most common process parameters (post-processing parameter). Innumerable studies have looked at the effects of process parameters on dimensional accuracy and mechanical properties. Surface roughness tends to increase with the increament of layer thickness and also with the increamnet of nozzle speed was investigated by Gurminder Singh et al. [8]. In order to get the best surface roughness, various efforts have been made using the traditional optimization approach. To achieve the best surface quality, the optimum process parameters can be found using a variety of optimization techniques, including conventional and non-conventional techniques. In order to optimize the response, the Response Surface Methodology (RSM) uses mathematical and statistical methods to model and analyze a process and to determine the influence of factors (independent variables) and their interactions in order to establish the best circumstances for a dependent variable of interest [9]. RSM studies aim to understand the response surface topography, including local maximum, minimum and ridge lines, and locate the most appropriate response region [10] and [11]. Srinivasan et al. [12] states that RSM is the method that can be used when many input variables affect a process's performance or quality. The input variables are called factors by researchers, and the response quality is called response. The RSM field uses experimental methods to link response and process variables. RSM has many advantages over conventional methods. It takes fewer experiments to study the effects of all variables and find the optimal combination. The interaction (where one factor's behavior is affected by another's level) between factors can be determined [12]. The effects of layer thickness and build orientation on 3D printed part tensile strength were studied by Rai et al. [13]. The number of experiments was determined using the Box-Behnken Design (BBD) of RSM, and the results were analyzed using ANOVA and regression analysis. The results showed that layer thickness reduces tensile strength. Srivastava et al. [14] optimized layout plans for various FDM parameters and spatial orientations. The full factorial central composite design was used. The FDM process parameters contour width, raster width, air gap, raster angle, slice height, and orientation were optimized using RSM.

According to a review of past potential studies, most studies only considered one or two factors at a time, and only a few studies considered three factors at a time. We used a full factorial design of experiment with three factors: nozzle temperature, extrusion speed, and fill density. With both main effects and interaction effects, we want to see if the significant factors remain the same. The key goals of this research are to build a FDM 3D printer, utilize Design Expert software to design an experiment, evaluate the influence of controllable process parameters and their interactions on dimensional accuracy and extrusion time, and apply RSM to optimize the process parameters. The findings of this study will determine the appropriate levels of components that can be employed to generate more precise AM products.

2 | Development of the 3D Printer

Selecting one of the additive manufacturing processes is the first step in building a 3D printer. The FDM process was chosen because it is clean, easy to use, and environmentally friendly. It is possible to print complex forms and intricate pieces. Because it is primarily utilized by people, FDM is at the very beginning of the market. When compared to other 3D printing technologies, FDM is a more economical option. For X, Y, and Z axis movements, a Cartesian mechanism is chosen after evaluating different factors such as fabrication cost, design simplicity, synchronization, and precision. The bed moves in the Y axis, while the extruder travels in the X and Z axes in this setup. The bed should be minimal in weight with the purpose of maintaining precision. Two stepper motors are used for Z-axis movement, one for X-axis movement, one for Y-axis movement, and one for Extruder filament movement in this system. This mechanism uses a single motor to control lead screws, which are coupled to the Extruder's Z-axis movement. Because the print volume is quite large, using only one motor would produce an interruption in the action. The build volume has been set at 200x200x250 mm3. *Table 1* displays the 3D printer's general parameters, whereas *Fig. 1* depicts the completed built 3D printer.

Table 1. Specification of the fabricated 3D printer including hardware and software.

Elements	Specifications
Frame	Aluminium Channel (1 inch X 2 inch) [53cm, 45cm, 43 cm]
Controller	Ramps 1.4 Shield Arduino Mega 2560
Stepper Motor Drivers	A4988 with heat sink
Stepper Motor	NEMA 17 Stepper Motor 4 Wire Bipolar
Lead Screw	T8 Trapezoidal Lead Screw L8mm Thread 8mm Pitch 300mm
Smooth Rod	M8 500mm
Linear Ball Bearing	LM8UU 8mm Linear Ball Bearing
Timing Belt	2 meter GT2 6mm Open Timing Belt
Pulley	20 teeth Pulley 5mm Bore
Flexible Coupling	5mm*8mm*25mm
Extruder	V6 J-Head Hot End Bowden Extruder
Firmware	Marlin
Slicing Software	Slic3r
Heat Bed	PCB Heat Bed MK2B
Power Supply	12 volt 20 amp Power Supply

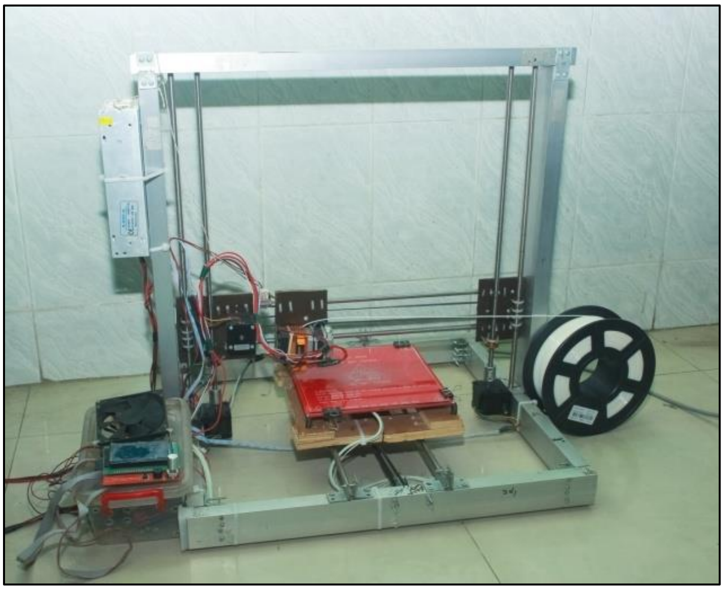

Fig. 1. Final assembly of 3D printer.

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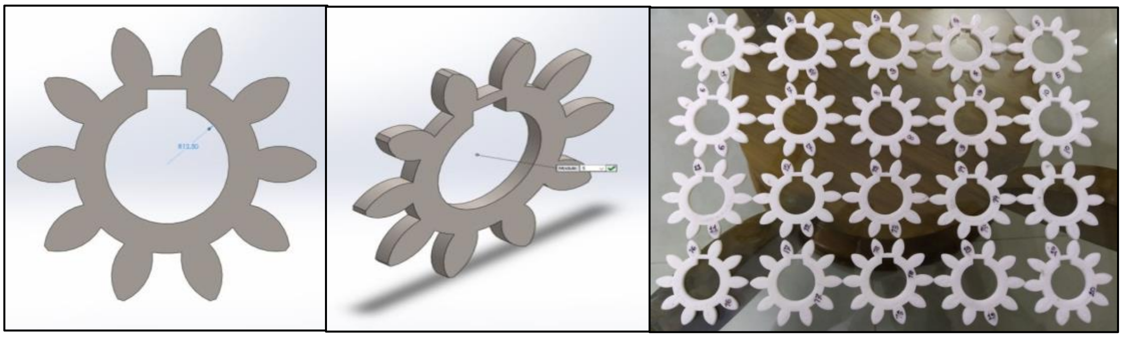
3 | Experimental Design

In the experimental design, response surface method was adopted to study the relationship between the process parameters and the output response and the mathematical model that can predict the output response from the actual process. The calculations for the RSM model development was carried out by utilizing the Design-Expert 11 software. The range and level of parameters are shown in *Table 2*. To develop the empirical model for dimensional accuracy and extrusion time, experiment was implemented in accordance with CCD. The CCD has an embedded factorial design which consists of fourteen non-centre points and six centre points for curvature estimation. *Table 3* shows the experimental data for 20 runs with three control factors and two response variables [15].

With the help of SOLIDWORKS software 3D solid model of a Spur Gear is modeled and then converted to STL file which is indicated in *Fig. 2*. STL file is imported to Slic3r software. Control factors listed in *Table 2* are set as per shown experiment plan in *Table 3*. The parts per experiment are fabricated by the use of our 3D printer. PLA is the material used for fabricating the designed part. The average of the three readings of Gear Bore is taken to be the representative value respectively. Digital Slide Calipers was used to measure the dimensions and the response time was taken from the 3D printer display.

Table 2. 3D printer parameters and their levels.

Symbol	Parameter	Unit	Low	High
A	Nozzle Temperature	°C	220	240
B	Extrusion Speed	%	30	40
C	Fill Density	%	20	30



a b c

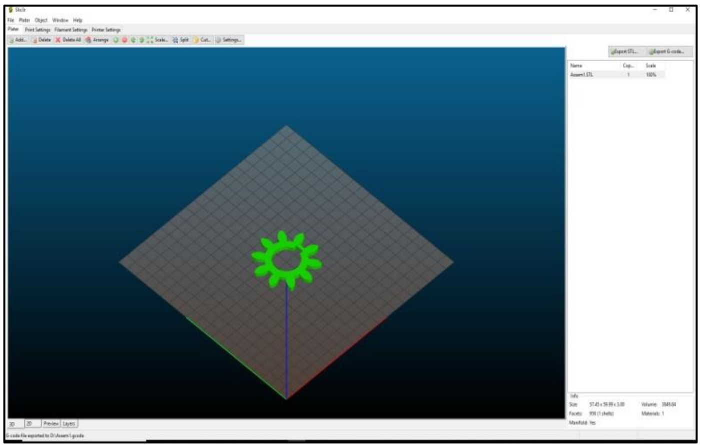


Fig. 2. a. Dimension of the test specimen; b. 20 3D printed spur gears; c. conversion of CAD model into G-code through Slic3r software.

Table 3. Experimental data for input process parameters and response variable.

Run	Factor 1 A: Nozzle Temperature (°C)	Factor 2 B: Extrusion Speed (%)	Factor 3 C: Fill Density (%)	Response Gear Bore Diameter (mm)	Response Extrusion Time (Min)
1	230.000	35.000	25.000	24.7001	42.06
2	220.000	40.000	20.000	24.6706	36.23
3	230.000	26.591	25.000	24.7214	53.12
4	230.000	35.000	25.000	24.6936	42.06
5	230.000	35.000	25.000	24.6981	41.24
6	230.000	35.000	17.691	24.6916	41.33
7	230.000	35.000	25.000	24.7346	41.32
8	246.818	35.000	25.000	24.699	41.56
9	220.000	30.000	20.000	24.8046	48.15
10	230.000	35.000	34.309	24.6848	41.56
11	240.000	40.000	20.000	24.6991	36.05
12	240.000	40.000	30.000	24.7072	37.33
13	230.000	43.409	25.000	24.7069	34.49
14	213.182	35.000	25.000	24.6379	41.29
15	220.000	40.000	30.000	24.6524	36.28
16	230.000	35.000	25.000	24.7014	41.09
17	240.000	30.000	30.000	24.7259	48.19
18	230.000	35.000	25.000	24.6512	41.57
19	240.000	30.000	20.000	24.8963	47.35
20	220.000	30.000	30.000	24.6357	48.53

4 | Results and Analysis

4.1 | Dimensional Accuracy

ANOVA has been done as shown in *Table 4* to observe the influence of the process parameters which are nozzle temperature (A), extrusion speed (B) and fill density (C) on output response which is gear bore diameter. As per the ANOVA test the calculated "F value" of the second-order model is 3.11 implies the model is significant. There is only a 4.57% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant. In this case A, B, C and BC are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. The "Lack of Fit F-value" of 3.82 implies the Lack of Fit is not significant relative to the pure error. There is an 8.37% chance that a "Lack of Fit F-value" this large could occur due to noise. The R2 value is close to 1, which is desirable. The adjusted R2 value is particularly useful when comparing models with different number of terms. Adequate precision compares the range of the predicted values at the design points to the average prediction errors. Ratios greater than 4 indicate adequate model discrimination. In this particular case, the value is 7.478 indicates an adequate signal as it can be seen in *Table 4*. Equation in *Table 5* is valid and can be used to predict the gear bore diameter.

Table 4. ANOVA for main and interaction effects on average gear bore diameter.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0480	9	0.0053	3.11	0.0457	significant
A-Nozzle Temperature	0.0099	1	0.0099	5.79	0.0370	
B-Extrusion Speed	0.0094	1	0.0094	5.47	0.0415	
C-Fill Density	0.0109	1	0.0109	6.37	0.0302	
BC	0.0135	1	0.0135	7.91	0.0184	
Residual	0.0171	10	0.0017			
Lack of Fit	0.0136	5	0.0027	3.82	0.0837	not significant
Pure Error	0.0036	5	0.0007			
Cor Total	0.0651	19				
Std. Dev.	0.0414	R^2		0.7370		
Mean	24.71	Adjusted R^2		0.5002		
C.V. %	0.1675	Predicted R^2		0.5235		
		Adequate Precision		7.4776		

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Table 5. Final equation in terms of actual factors.

Gear bore Diameter	=
+25.84549	
+0.002694	Nozzle Temperature
-0.046391	Extrusion Speed
-0.063026	Fill Density
+0.001646	Extrusion Speed * Fill Density

Fig. 3 shows the trace or perturbation plot. The perturbation plot compares the effects of the various factors in the design space. The intersection of the lines is at the reference point (where, X=0.00) and the actual conditions for the factors at the side point are as indicated in the figure. For an instance, in case of factor A, any shift to the right of the reference point (or towards the +1.00 of the deviation from the reference point axis) i.e. as the nozzle temperature (A) increases, the gear bore diameter increases. However, in case of extrusion speed (B) and fill density (C), gear bore diameter tends to decrease with a shift from the reference point to the right. Comparisons of the predicted results and the experimental results of the gear bore diameter were also performed. The experimental and predicted values were compared as shown in *Fig. 4*. For a good fit, the points are located in the vicinity of the fitted line, with narrow confidence bands. Points on the left or right of the plot, furthest from the mean, have the most leverage and effectively try to pull the fitted line towards the point. Points that are vertically distant from the line represent possible outliers. *Fig. 4* shows that the points that have been plot are mostly close to the fitted line so the model that had been generated can be considered as a good prediction in estimating the predicted gear bore diameter values.Fig. 3. Perturbation plot of factors in measuring the dimensional accuracy.

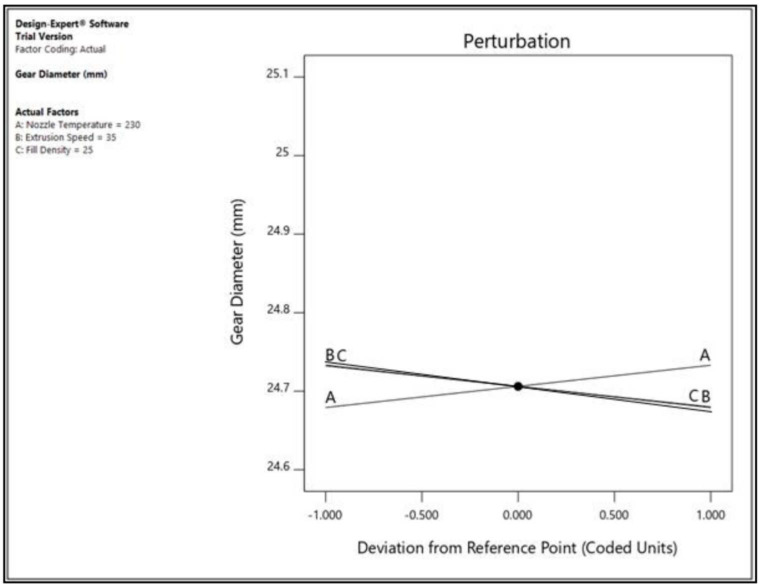

Fig. 3. Perturbation plot of factors in measuring the dimensional accuracy.

The response surface plot is a good tool to estimate the region of optimum response, which is basically similar to the 3-D wire frame plot. *Fig. 5* represents the gear bore diameter as a function of nozzle temperature (A) and extrusion speed (B). In this case, feed (C) was kept at '20' level value. The plot for Figure 5 shows that the gear bore diameter decreases as extrusion speed increases and gear bore diameter decreases with the decrease of nozzle temperature. The response surface plot is a good tool to estimate the region of optimum response, which is basically similar to the 3-D wire frame plot. *Fig. 6* represents the gear bore diameter as a function of extrusion speed (B) and fills density (C). In this case, nozzle temperature (A) was kept at '230' level value. The plot for *Fig. 6* shows that the gear bore diameter decreases as fill density increases and gear bore diameter decreases with the increase of extrusion speed. The interaction between extrusion speeds and fill density also appear to have a dominating effect on gear bore diameter.

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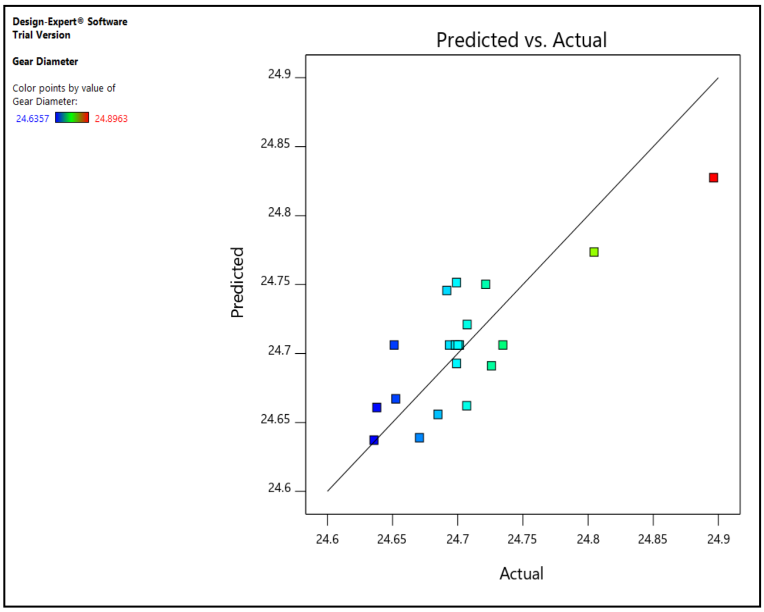

Fig. 4. Comparison of experimental and predicted values (Gear Bore).

The response surface plot is a good tool to estimate the region of optimum response, which is basically similar to the 3-D wire frame plot. *Fig. 5* represents the gear bore diameter as a function of nozzle temperature (A) and extrusion speed (B). In this case, feed (C) was kept at '20' level value. The plot for Figure 5 shows that the gear bore diameter decreases as extrusion speed increases and gear bore diameter decreases with the decrease of nozzle temperature. The response surface plot is a good tool to estimate the region of optimum response, which is basically similar to the 3-D wire frame plot. *Fig. 6* represents the gear bore diameter as a function of extrusion speed (B) and fills density (C). In this case, nozzle temperature (A) was kept at '230' level value. The plot for Fig. 6 shows that the gear bore diameter decreases as fill density increases and gear bore diameter decreases with the increase of extrusion speed. The interaction between extrusion speeds and fill density also appear to have a dominating effect on gear bore diameter.

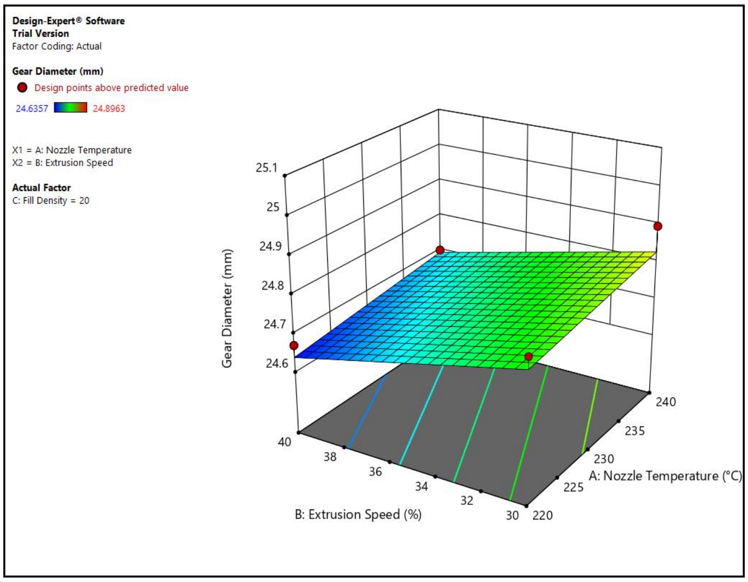

Fig. 5. Interaction effect analysis of factor A and B for the gear bore diameter.

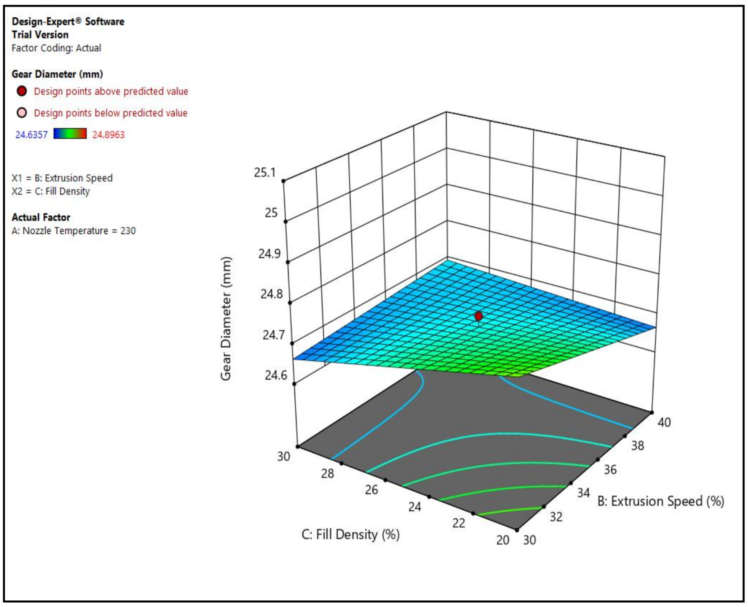

Fig. 6. Interaction effect analysis of factor B and C for the gear bore diameter.

From *Fig. 7*, the first optimum setting that was predicted by the desirability analysis is the nozzle temperature with the maximum value of 240 °C. In addition, the optimum setting for extrusion speed hit the minimum value from the parameter range which is 30%. Lastly, the predicted optimum setting for fill density is also the minimum value from the range that has been set which is 20%. Furthermore, the optimum predicted gear bore diameter by RSM is 24.8275 mm.

Table 6. Values of process parameters for the optimization of gear bore.

Number	A: Nozzle Temperature	B: Extrusion Speed	C: Fill Density	Gear Bore	Desirability	
1	240.000	30.000	20.000	24.827	0.736	Selected
2	240.000	30.000	20.038	24.827	0.734	
3	240.000	30.040	20.000	24.827	0.734	
4	239.718	30.000	20.000	24.827	0.733	
5	240.000	30.000	20.061	24.827	0.733	
6	239.626	30.000	20.000	24.826	0.732	
7	240.000	30.000	20.098	24.826	0.731	
8	240.000	30.100	20.000	24.826	0.731	
9	239.397	30.000	20.000	24.826	0.730	
10	240.000	30.000	20.142	24.826	0.729	

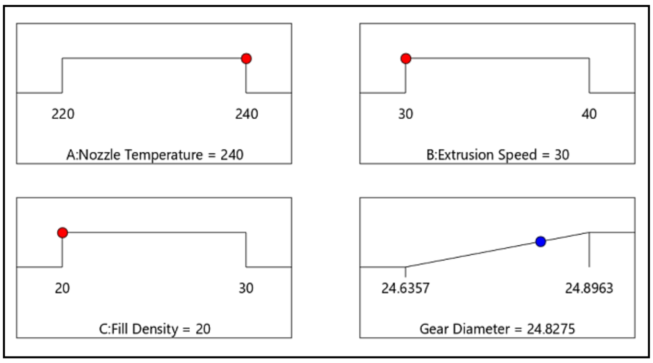

Fig. 7. Optimal parameters for gear bore diameter from RSM optimization.

4.2 | Extrusion Time

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ANOVA has been done as shown in *Table 7* to observe the influence of the process parameters which are nozzle temperature (A), extrusion speed (B) & fill density (C) on output response which is extrusion time. As per the ANOVA test the calculated "F value" of the second-order model is 664.64 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant. In this case B, C & B^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. The "Lack of Fit F-value" of 0.4217 implies the Lack of Fit is not significant relative to the pure error. There is an 86.69% chance that a "Lack of Fit F-value" this large could occur due to noise. The R2 value is very close to 1, which is desirable. The predicted R^2 of 0.9926 is in reasonable agreement with the adjusted R^2 of 0.9953; i.e. the difference is less than 0.2. The adjusted R2 value is particularly useful when comparing models with different number of terms. Adequate precision compares the range of the predicted values at the design points to the average prediction errors. Ratios greater than 4 indicate adequate model discrimination. In this particular case, the value is 95.973 indicates an adequate signal as it can be seen in *Table 7*.

Table 7. ANOVA for main and interaction effects on extrusion time.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	452.57	6	75.43	664.64	< 0.0001	significant
A-Nozzle Temperature	0.0025	1	0.0025	0.0219	0.8847	
B-Extrusion Speed	441.64	1	441.64	3891.47	< 0.0001	
C-Fill Density	0.6246	1	0.6246	5.50	0.0355	
AB	0.5050	1	0.5050	4.45	0.0549	
AC	0.3570	1	0.3570	3.15	0.0995	
B^2	9.54	1	9.54	84.04	< 0.0001	
Residual	1.48	13	0.1135			
Lack of Fit	0.5944	8	0.0743	0.4217	0.8669	not significant
Pure Error	0.8809	5	0.1762			
Cor Total	454.05	19				
Std. Dev.	0.3369	R^2		0.9968		
Mean	42.04	Adjusted R^2		0.9953		
C.V. %	0.8013	Predicted R^2		0.9926		
		Adeq Precision		95.9732		

Table 8. Final equation in terms of actual factors.

Extrusion Time	=
+184.16586	
-0.280152	Nozzle Temperature
-4.55087	Extrusion Speed
-0.928869	Fill Density
+0.005025	Nozzle Temperature * Extrusion Speed
+0.004225	Nozzle Temperature * Fill Density
+0.032254	Extrusion Speed^2

Fig. 8 shows the trace or perturbation plot. The perturbation plot compares the effects of the various factors in the design space. The intersection of the lines is at the reference point (where, X=0.00) and the actual conditions for the factors at the side point are as indicated in the figure. For an instance, in case of factor B, any shift to the right of the reference point (or towards the +1.00 of the deviation from the reference point axis) i.e. as the extrusion speed (B) increases, the extrusion time decreases. However, in case of nozzle temperature (A) and fill density (C), extrusion time tends to increase with a shift from the reference point to the right. Comparisons of the predicted results and the experimental results of the extrusion time were also performed. The experimental and predicted values were compared as shown in *Fig. 9*. For a good fit, the points are located in the vicinity of the fitted line, with narrow confidence bands. Points on the left or right of the plot, furthest from the mean, have the most leverage and effectively try

to pull the fitted line towards the point. Points that are vertically distant from the line represent possible outliers. *Fig. 9* shows that the points that have been plot are mostly very close to the fitted line so the model that had been generated can be considered as a good prediction in estimating the predicted gear bore diameter values.

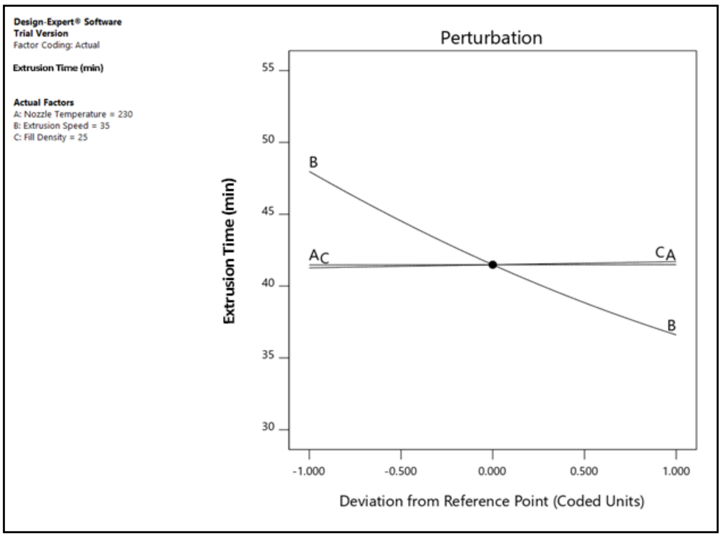

Fig. 8. Perturbation plot in measuring extrusion time.

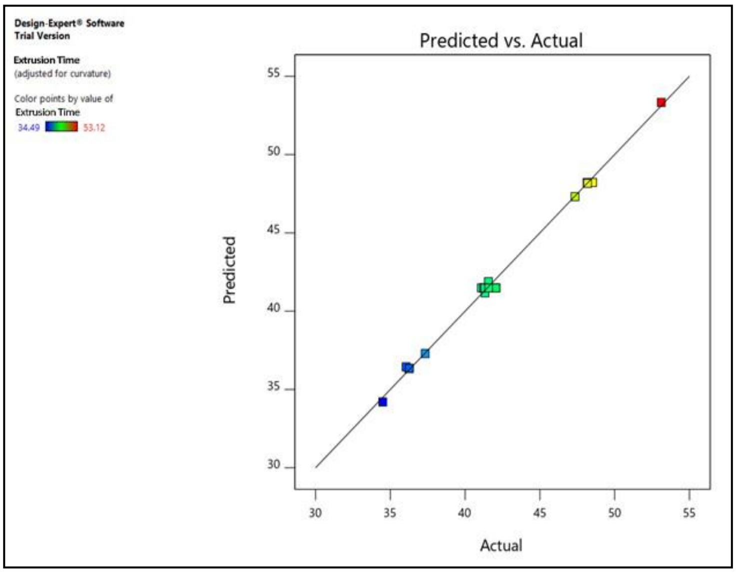

Fig. 9. Comparison of experimental and predicted values (extrusion time).

The response surface plot is a good tool to estimate the region of optimum response, which is basically similar to the 3-D wire frame plot. *Fig. 10* represents the extrusion time as a function of nozzle temperature (A) and extrusion speed (B). In this case, feed (C) was kept at '25' level value. The plot for *Fig. 10* shows that the extrusion time decreases as extrusion speed increases and extrusion time decreases with the decrease of nozzle temperature. The response surface plot is a good tool to estimate the region of optimum response, which is basically similar to the 3-D wire frame plot. *Fig. 11* represents the extrusion time as a function of extrusion speed (B) and fill density (C). In this case, nozzle temperature (A) was kept at '230' level value. The plot for *Fig. 11* shows that extrusion time decreases as fill density decreases and extrusion time decreases with the increase of extrusion speed.

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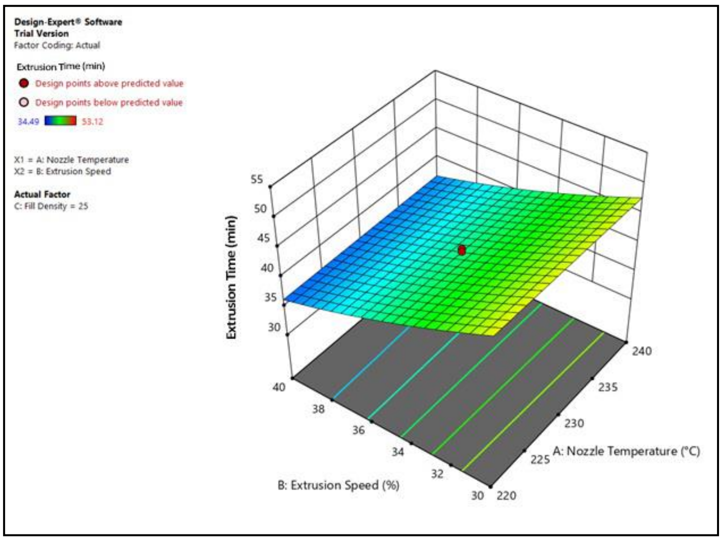

Fig. 10. Interaction effect analysis of factor A and B for the extrusion time.

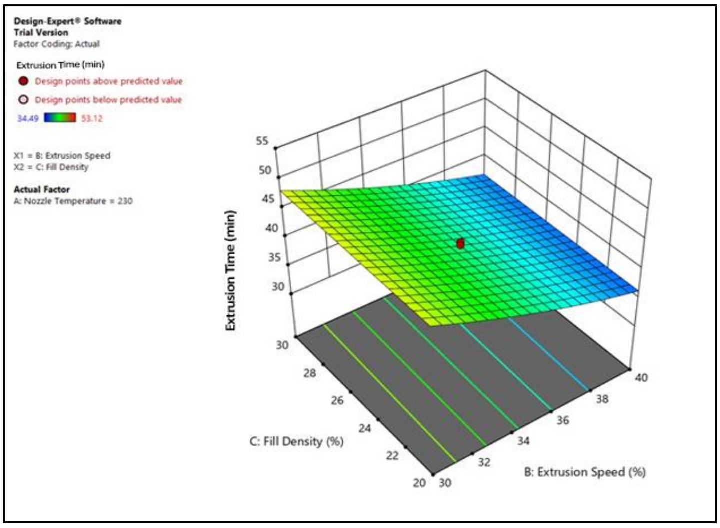

Fig. 11. Interaction effect analysis of factor B and C for the extrusion time.

From *Fig. 12*, the first optimum setting that was predicted by the desirability analysis is the nozzle temperature with the minimum value of 220 °C. In addition, the optimum setting for extrusion speed hit the maximum value from the parameter range which is 40%. Lastly, the predicted optimum setting for fill density is the minimum value from the range that has been set which is 20%. Furthermore, the optimum predicted extrusion time by RSM is 36.3232 min.

Table 9. Values of process parameters for the optimization of extrusion time.

Number	A: Nozzle Temperature	B: Extrusion Speed	C: Fill Density	Extrusion Time	Desirability	
1	220.000	40.000	20.000	36.323	0.901	Selected
2	220.002	40.000	20.072	36.337	0.901	
3	220.002	40.000	20.319	36.337	0.901	
4	220.008	40.000	20.366	36.337	0.901	
5	220.001	40.000	20.578	36.337	0.901	
6	220.048	40.000	20.153	36.337	0.901	
7	220.001	40.000	20.696	36.337	0.901	
8	220.000	40.000	20.997	36.338	0.901	
9	220.002	40.000	21.233	36.338	0.901	
10	220.000	40.000	21.404	36.338	0.901	

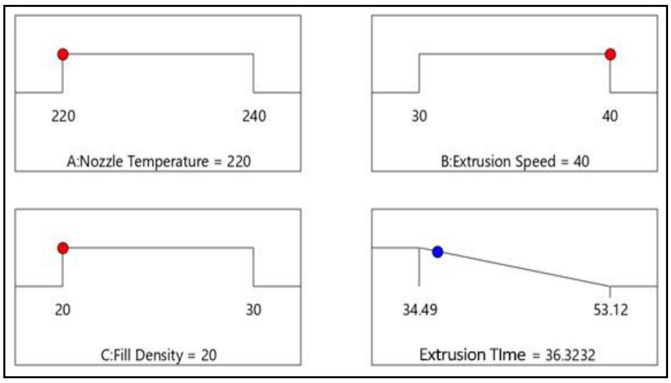

Fig. 12. Optimal parameters for extrusion time from RSM optimization.

5 | Conclusion and Recommendation

The major goal of this research was to build a 3D printer and look into the effects of various factors on the dimensional accuracy and extrusion time of PLA items that were manufactured. The construction of a portable 3D printer has been finished successfully. Aluminum channels are used to make the frame sturdy and compact. The use of a dual motor for vertical movement simplifies bed leveling. Because of the precise orientation of the motors, controlling the mechanism becomes simple, and good synchronization can be obtained with this 3D printing technology. After that, the impact of three process factors, namely nozzle temperature, extrusion speed, and fill density, on the dimensional accuracy of FDM produced components and their extrusion time, is investigated at three distinct levels. The experimental plan is created using RSM. The reduction in diameter of the specimen is observed to be greater than the desired value. RSM is used to identify relevant elements and their interactions. To increase the built part's dimensional accuracy, the parts must be manufactured in such a way that the dimensions are as close to the actual value as possible. As a result, optimum process variables should be determined using a systematic approach. The ANOVA analysis and surface interaction plot demonstrated that nozzle temperature, extrusion speed, and fill density, as well as the interaction between extrusion speeds and fill density, have a significant impact on dimensional accuracy. RSM predicts a gear bore diameter of 24.8275 mm as the best. Extrusion time is also influenced by extrusion speed and fill density. RSM predicts a maximum extrusion time of 36.3232 minutes. As a result, we conclude that a right combination of nozzle temperature, extrusion speed, and fill density can result in higher dimensional accuracy and reduced extrusion time.

The following suggestions for improving our manufactured 3D printer should be considered. For the rapid extrusion of a 3D printed component, multiple extruders could be assembled. To print an exact colored object, a multi-colored filament arrangement could be used. The use of a proximity sensor that can be easily monitored could make bed leveling much easier. The impact of other characteristics such as surface roughness and hardness can be investigated using RSM..

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