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Analysis of the Effect of Scaling on Dimensional Accuracy of 3D Printed Parts using DOE

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Abstract

3D printing is one of the most popular methods used in different fields and industries. The most popular advantage of this method is its flexibility in printing complex shapes and sizes. Quality is one of the important aspects when using this kind of technology which has a high advantage of printing complex shapes as this includes many factors like temperature, speed, material, infill types, etc. In this paper one such analysis has been done by 3D printing parts under different factors. The analysis is done on how scaling factors affect the dimensions like height and diameter of a 3D printed part and check factors affecting these variations using design of experiments (DOE) analysis.

Keywords

3d printing, Dimensional accuracy, DOE, Tolerances, and Quality control.

1. Introduction

A computer design can be made into a real object using the additive manufacturing technique of three-dimensional (3D) printing. To begin the process, thin layers of material, such as liquid or powdered plastic, metal, or cement, must be applied. After that, the layers need to be fused. The improvement of smaller 'work area' 3D printers and their reasonable expense have additionally made the innovation progressively available over the long haul. 3D printing function, as we saw before, includes developing an endless supply of liquid plastic to make an item. As each layer sets, the following layer is imprinted on top, and the item is developed. To make a 3D print, a computerized record is required that lets the 3D printer know where to print the material. The most well-known record design for this is the G-code documents. This record contains 'arrangements' to direct the printer's developments, both evenly and in an upward direction - otherwise called the X, Y, and Z directions. 3D printers can print these layers at various thicknesses, known as layer level. A piece like pixels on a screen, more layers in a print will give a higher 'goal'. This will give a superior-looking outcome yet take more time to print.

Standard 3D printer types, for example, FDM and SLS can print mixes of polymers and different materials (like metal, glass, or wood). These are known as composites and deal with a portion of the properties of the mixed material. With regards to FDM 3D printing, you might see the terms '3D printing material' and '3D printing fiber' utilized reciprocally. This is on the grounds that the natural substance comes on spools of slender fiber. Combined testimony demonstrating, or FDM for short is a material expulsion strategy for added substance fabricating where materials are expelled through a spout and consolidated to make 3D items. Specifically, the "standard" FDM process separates itself from other material expulsion methods, like cement and food 3D printing, by involving thermoplastics as feedstock materials, normally in types of fibers or pellets. A normal FDM 3D printer, in this way, takes a polymer-based fiber and powers it through a warmed spout, which liquefies the material and stores it in 2D layers in the form stage. While warm, these layers meld with one another to make a three-layered part at last. In this process, the need for quality control is high in order to get a perfect product with fewer deviations, and quality depends on several factors such as temperature, infill rate, scaling, feed speed, surface roughness, types of materials, types of infills, etc. Analysis has to be done in one such process to identify the cause of issues and reduce the deviations.

2. Literature Review

3D printing is a widespread technology used in various fields. Products of different sizes and types can be printed using this technology. It is a process where material is melted and placed in the form of layers one up on each other to form a final product. There are various factors affecting the quality of the product. This technology works based on different parameters like layer thickness, nozzle temperature, printing speed, infill rate, etc. As this process is based on multiple parameters the chances of deviation will be high and these deviations ultimately result in final product quality. There is a need to analyze and control these deviations to get a final product of good quality. Several research studies have been done in this area and some papers are referred to in this section.

2.1 3D printing

The process of printing a physical object from a three-dimensional model by using layers of melted material is known as 3D printing. The other name for this is Additive manufacturing. In present situations, the usage of this technology is high because of its flexibility and design benefits (Heidari-Rarani et al. 2022). STL files are the most popular 3D printing file format used in this process. Initially, the 3D model should be converted into a series of thin layers and produce a G-code file, for this conversion, there are different types of software, but “slicer” is the most used among them (Vinod and Raut, 2017). After conversion, this STL file is used to design 3D products. This process requires less postproduction machining process when compared to the traditional production process where there is a requirement for custom molds which is not the case of 3D printing (Pedram et al. 2019).

3D printing can be done in 3 important stages: Modeling, Printing and Finishing. In the initial stage modeling of the desired part is done using CAD software with all the geometric data which we have regarding the product. Later in the second stage slicer is used to convert the model into thin layers and the product is printed using the STL file. In the final stage some products are printed oversized and then the excess material is removed to get high-resolution output of the product (Vinod and Raut 2017).

There are many techniques in 3D printing, but Fused Deposition modeling (FDM) is the most used one because of its simplicity and low-cost process and the flexibility it gives in producing complex parts. In FDM the melted material is sent through a heated nozzle onto the beds. The schematic and process parameters of a FDM 3D printer is shown Figure 1 (Kumar et al. 2019). FDM fabricated parts have lower dimensional accuracy when compared to parts fabricated by other AM processes (SLA, SLS, Poly-jet) because there are various process parameters affecting dimensional accuracy either individually or in combination with different parameters (Zaneldin et al. 2021).

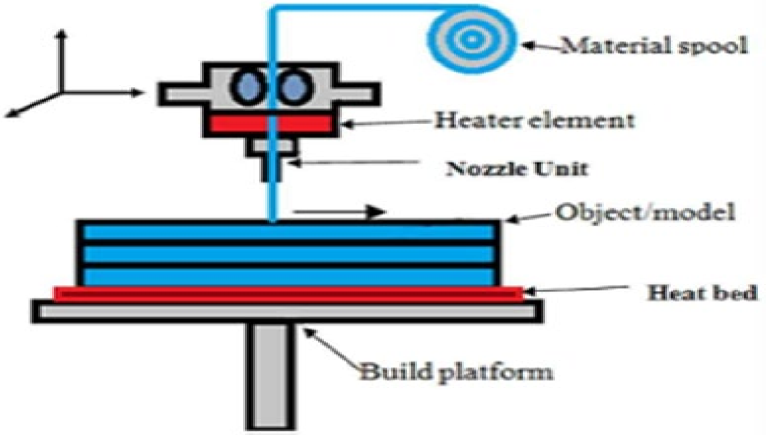


Figure 1. FDM 3D printer schematic (Kumar et al. 2019)

There are many materials which can be used for 3D printing Nylon, polyethylene terephthalate, laywoo-D3, lay brick, polylactic acid etc. But among these PLA (Polylactic acid) is the most used filament material in 3D printers. PLA is used when producing small amounts of products with reduced production costs and cycles (Teng et al. 2022). This material is widely used because of its good printability as it is compostable, biodegradable plastic with high mechanical strength and reduced toxicity (Leonardo et al. 2016). PLA is used when producing small amounts of products with reduced production cost and cycle. Though the material has good properties there are many chances for deviations to occur as it depends on different parameters under which the printing procedure is performed.

2.2 Analysis of Printing Layers

The main insufficiency of prototypes made by 3D printing with FDM method is structure inhomogeneity resulting from the basic principle of this technique. The material distribution is not uniform in the whole volume of scanned specimens, and higher density can be observed in the area of the layer-building start point. The unfilled areas are likewise found in almost every layer as well as among particular layers. (Gajdoš et al. 2013). When the infill percentage is given 100 percent, it can be seen that the filaments present voids, geometric distortions, and winding trajectories, representing a disturbance in the deposition process. Voids and some unusual filament paths and geometries were observed to suggest poor quality associated with the filament deposition during the fabrication of the PLA parts. The low repeatability in the manufacturing of 3D printed parts, as significant variations were found for specimens built under the same process parameters. The main cause for this effect was deposition failure, owing to filament slippage in the extruder head hobbed pulley (Leonardo et al. 2016).

2.3 Quality of the part

Product quality can be seen in the mechanical properties and surface smoothness. The printing temperature is the dominant parameter that affects surface roughness when it comes to 3D printing of polylactic acid material followed by printing pattern, infill rate, and the number of shells (Fountas et al. 2022). The choice of an appropriate orientation can also help to improve the surface finish of a 3D object. The type of printhead, such as the drop-on-demand type or the continuous jet type, and the logic behind the slicing program also influence the surface finish of a 3D printed object. Otherwise, post-processing treatments are required to polish the surface (Wu et al 2018).

Some techniques such as the design of experiments have not been used accurately and completely and therefore cannot optimize quality. Taguchi’s method and control charts can enhance the quality of 3D printed objects; however, these techniques require repetitive experimentation, which may not fit the workflow of 3D printing (Wu et al 2018). Taguchi's design of the experiment method is applied to reduce the number of experiments and find the optimal parameters for maximum mechanical properties, minimum weight, and minimum printing time (Heidari-Rarani et al. 2022). The proposed methodology is based on a design of experiment (DOE) approach, which serves as a guide for engineers when it comes to executing any experimental study.

2.4 Design of experiment

The study has improved understanding in two areas of action: the behavior of 3D technologies and the application of improvement methods based on the Design of experiments (DOE) methodology. We identified key factors for optimizing the new technology, including an impression in 3D. DOE techniques zeroed in on producing the greatest information with the least exertion isn't completely used (Eguren et al. 2020). The plan of examination strategy can be defined as a genuinely thorough methodology created to survey the influence of certain boundaries (called factors) that have some values inside a reach (called level) affecting the result of a certain interaction. DOE helps the comprehension of an interaction and, what is more, proposes the way that the variables may affect it. The DOE measurable examination depends on the correlation of some planning input of an examination, expecting to further develop the cycle information by as few as potential runs, in this way decreasing the requirement for various tests which might be costly both regarding time and cost (Auffray et al. 2022).

2.5 Tolerances

A tolerance is an acceptable amount of dimensional variation that will still allow an object to function correctly. Tolerance defines how accurate it needs to be in a given 3D print. The tolerance is defined by the user and will depend on each specific application. In most additive technologies, the dimensional tolerance is at least 0.1 mm. This means that the deviations in 3D printing are greater than in other technologies, such as injection molding. Many papers were reviewed to study the basic understanding, printing process, etc. of 3D printing. Several studies have shown that there is a need for quality improvement in printed parts and different factors that are affecting the part. It is seen that analysis has been done on factors like surface roughness, infill types, infill rates, and temperatures. There is also one such factor which is needed to be taken care of which is "Dimensions". In this project, we analyze how scaling factors affect the dimensional accuracy of a 3D-printed part.

3. Methodology

3.1 Design and Printing Process

The methodology involved in this study consists of three major parts. They are design, printing, and measurement. A 3D model is built in DS SolidWorks which is a cylindrical body with a radius of 25mm and height of 50mm where the isometric view of the model is shown in Figure 2.

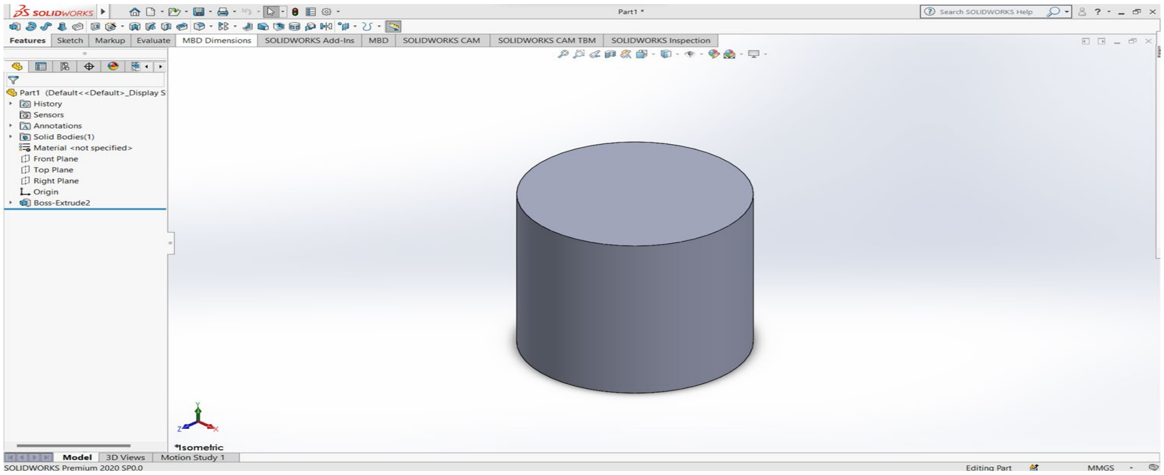


Figure 2. Isometric view of the model.

The file is saved in STL format and further used as input to Slicer software. Slicing software, also called slicer, takes in 3D model files, like STL and OBJ as input and creates G-code files as output based on the user's preferences and settings. Slicers are a crucial piece of the 3D printing workflow as they have a major impact on the quality and resolution of the finished product. G-code file has several lines of code, where each line performs specific functions like the movement of the nozzle and bed along X, Y, and Z directions for building the entire model. They also contain instructions for heaters and other connected devices, such as servos or leveling sensors. To generate a G-code file, the

Table 1. 3D Printer Specifications

Build Volume	5.5 x 5.5 x 5.5" / 14.0 x 13.97 x 14.0 cm
Number of Extruders	1
Supported Extruder Nozzle Diameter	400 micron / 0.4 mm
AC Input Power	115 to 230 VAC, 50 / 60 Hz
Supported 3D File Types	.obj, .stl
Wired Connections	1 x USB-A 2.0
Layer Resolution	XY Axis: 100 to 500 micron / 0.1 to 0.5 mm (5 Settings)
Filament Compatibility	1.75 mm Diameter: PLA

most common open-source slicer Ulti maker CURA 5.2.1 is used. CURA is beginner-friendly software and provides all basic information for the user. Before beginning the slicing, the printer should be added to the slicer. Go to Add printer search by the name of the printer and click Add. The printer used for the study is Flash Forge Finder in one of our laboratories is shown in Figure 3. The printer specifications are mentioned in Table 1.

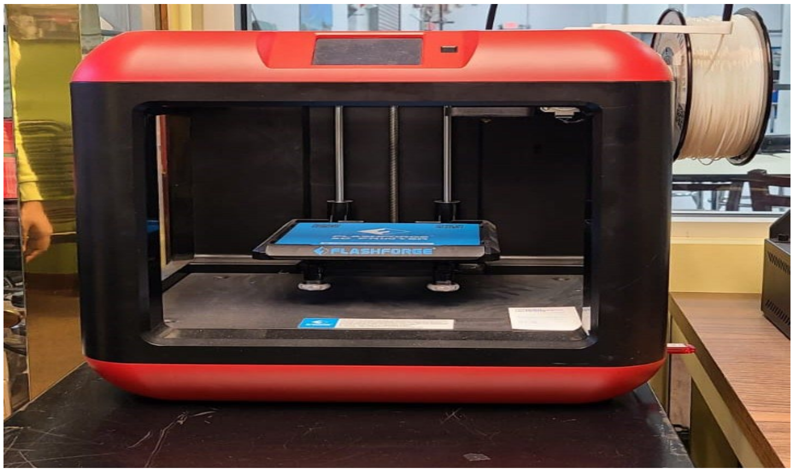
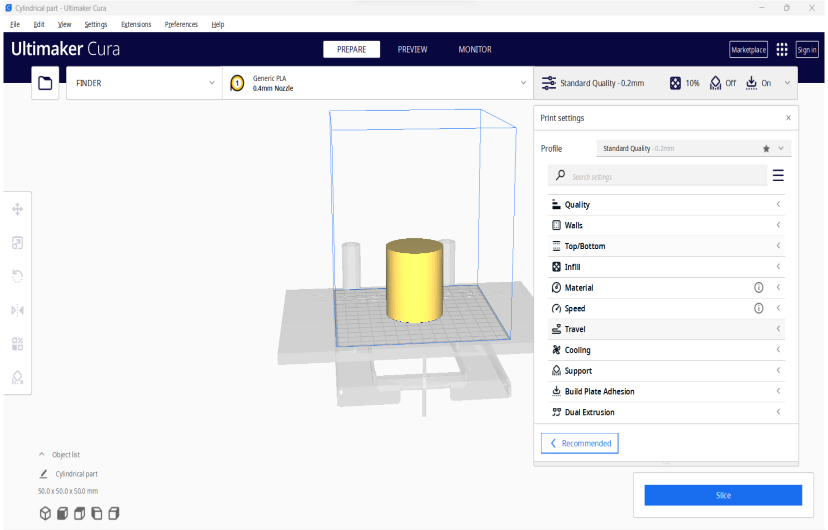


Figure 3. Flash Forge Finder 3D Printer



Profile Standard Quality - 0.2mm

Figure 4. Print settings and the model

The next step is to provide the material information for the slicer. The material used is Generic PLA with a filament diameter of 1.75 mm. Open the STL file and the model appears on the platform. Figure 4 shows the print settings and model. The generated G-codes are used to print the samples in a 3D printer. A total of 16 samples were printed depending on four factors which are temperature, infill rate, infill speed, and scaling. Each sample is printed by changing one factor, Table 2 shows the factors and respective values using which the samples have been printed. PLA material is used along with a layer thickness of 0.2 mm, infill pattern – Honeycomb /(Tri-hexagonal), and travel speed of 150mm/s. Table 3 shows the specifications of each sample under which they are printed and labeled with numbers from 1 to 16. One after the other each sample is printed. Figure 5 shows 16 printed parts in which 8 samples were printed at scaling level 2 and 8 were printed under scaling level 1. The next step in this process is to measure the samples.

Table 2. Varying Factors were used to print the samples.

Temperature	210 - 220 0C
Infill Percentage	10 - 20
Speed	60 - 80
Scaling size	1 - 2

In this measurement phase by using vernier calipers the diameter of each sample is measured at 3 different locations of the sample which includes one at the top, bottom, and at center of the sample average values are taken for all the samples and measured the height of the samples at 3 different locations

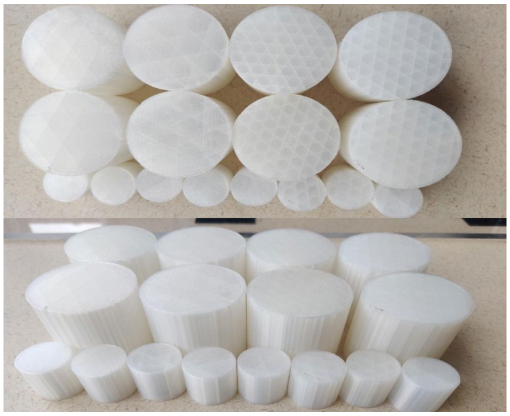


Figure 5. 3D printed samples

. Along with these measurements, the weights of the samples are taken 3 times for each sample and the average is calculated. Printed parts with sample numbers along with their respective average height, diameter, and weight are shown in Table 3.

Table 3. Sample specifications and Average values

Sample	Temperature	Infill	speed	scaling	Height(mm)	Diameter(mm)	Weight(gms)
1	220	20	60	2	50.14	49.92	34.00
2	220	20	60	1	25.15	24.93	5.00
3	210	20	60	2	50.17	49.80	32.00
4	210	20	60	1	25.15	24.86	5.00
5	220	20	80	2	50.18	49.94	32.00
6	220	20	80	1	25.14	24.85	5.00
7	210	20	80	2	50.12	49.85	32.00
8	210	20	80	1	25.15	24.89	5.00
9	220	10	60	2	50.08	49.86	22.00
10	220	10	60	1	25.07	24.87	4.00
11	210	10	60	2	50.14	49.92	22.00
12	210	10	60	1	25.13	24.87	3.67
13	220	10	80	2	50.12	49.97	22.00
14	220	10	80	1	25.13	24.82	3.67
15	210	10	80	2	50.09	49.89	21.00
16	210	10	80	1	25.13	24.88	4.00

4. Analysis

The 2^4 full factorial design is performed using Minitab. The three responses considered are tolerance in height, diameter and weight difference. Table 4 shows the tolerances observed in height, diameter, and weight for 16 samples in Minitab.

Table 4. Minitab data with tolerances

Temperature	Print speed	Infill	Scale	Height Tolerance	Diameter Tolerance	Weight Difference
210	60	10	1	0.13	-0.13	0.33
220	60	10	1	0.07	-0.13	0
210	80	10	1	0.13	-0.12	0
220	80	10	1	0.13	-0.18	0.33
210	60	20	1	0.15	-0.14	0
220	60	20	1	0.15	-0.07	0
210	80	20	1	0.15	-0.11	0
220	80	20	1	0.14	-0.15	0
210	60	10	2	0.14	-0.08	0
220	60	10	2	0.08	-0.14	0
210	80	10	2	0.09	-0.11	1
220	80	10	2	0.12	-0.03	0
210	60	20	2	0.17	-0.20	2
220	60	20	2	0.14	-0.08	0
210	80	20	2	0.12	-0.15	2
220	80	20	2	0.18	-0.06	2

4.1 DOE analysis - Height Tolerance:

With the response as tolerance in height, a regression equation is found in 4.1.1, and the normal plot of the effects is shown in Figure 6. The normal plot shows the factor C, which is infill density, and has a significant effect on the response. As the points that are not close to the line imply that it is an important effect. The infill density has a major influence on response. The pareto chart of the effect shown in Figure 7 gives the magnitude of the effect by showing the absolute value.

4.1.1 Regression Equation:

Height Tolerance = 13.82 - 0.06600 Temperature - 0.1760 Print speed - 1.070 Infil- 3.000 Scale + 0.000850 Temperature*Print speed+ 0.005100 Temperature*Infil + 0.01500 Temperature*Scale+ 0.01470 Print speed*Infil + 0.03950 Print speed*Scale+ 0.5050 Infil*Scale - 0.000070 Temperature*Print speed*Infil- 0.000200 Temperature*Print speed*Scale - 0.002400 Temperature*Infil*Scale - 0.007350 Print speed*Infil*Scale + 0.000035 Temperature*Print speed*Infil*Scale

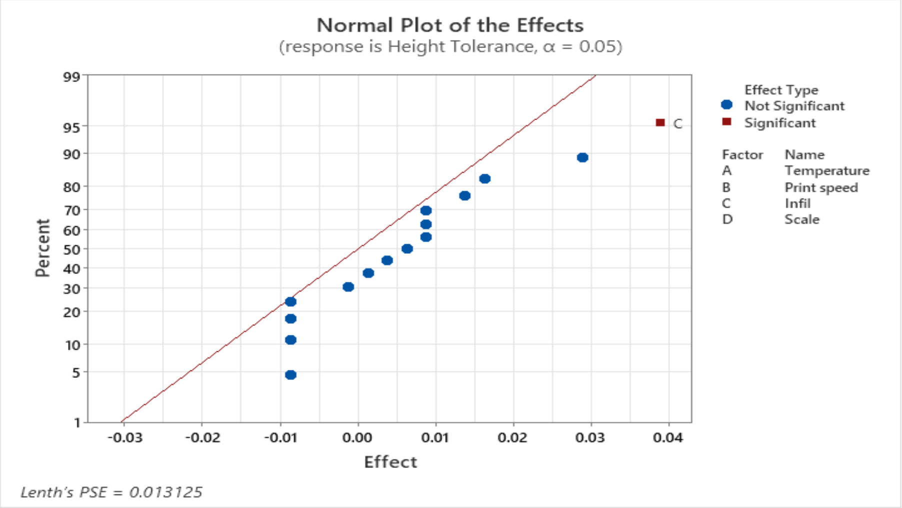


Figure 6. Normal Plot of the Effects

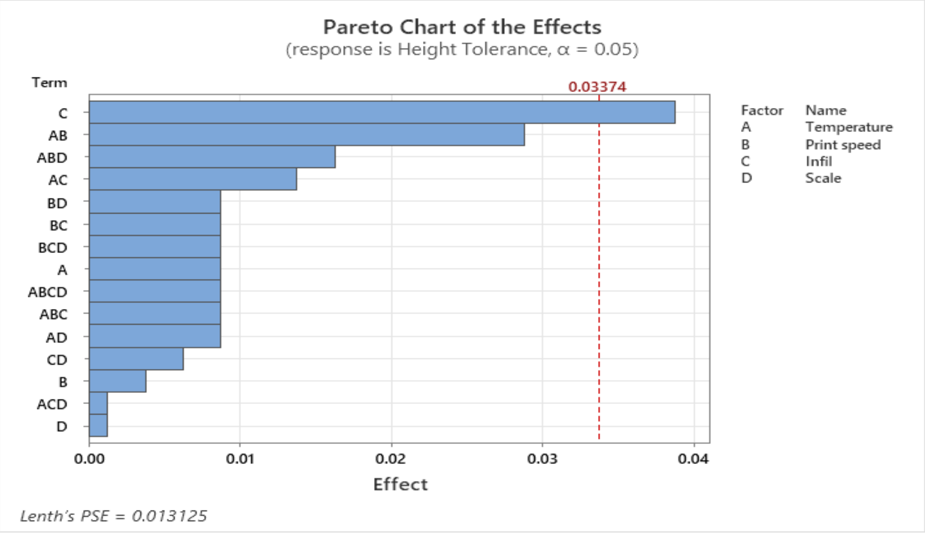


Figure 7. Pareto chart of effects

4.1.2 Main and interaction effects plots:

The following are the main effects in Figure 8 and interaction effects in Figure 9, these plots are taken from MINITAB. From the main effects plot, we can see that the infill rate has the highest deviations in tolerances when it changes from 10 to 20. The other factor that affects tolerance is temperature. We can observe the variations from the interaction plot when the infill changes.

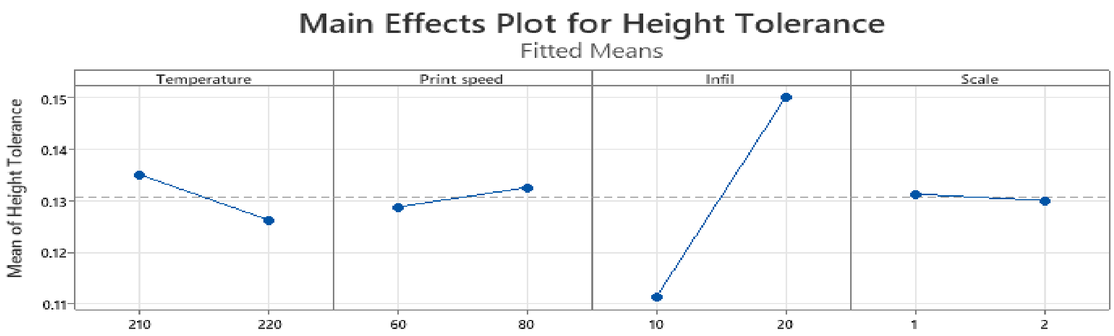


Figure 8. Main effects plot for height tolerance

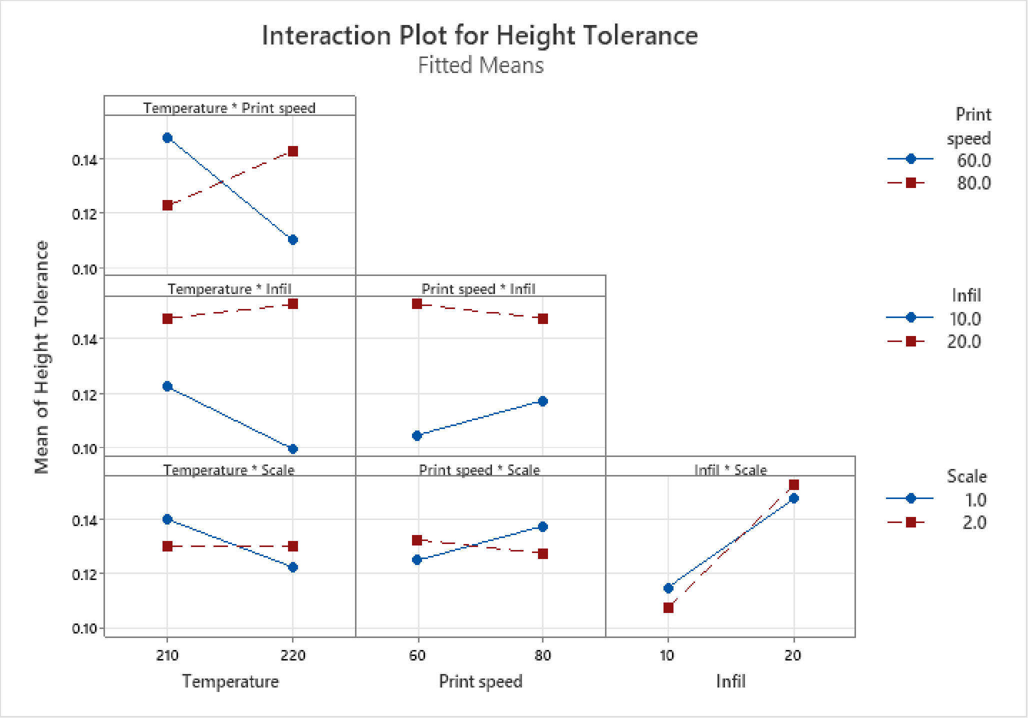
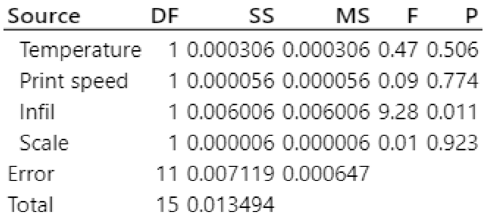


Figure 9. Interaction plot for height tolerance

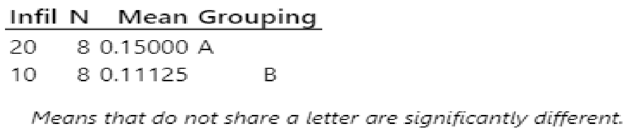
4.1.3 ANOVA for Height Tolerance:



Source	DF	SS	MS	F	P
Temperature	1	0.000306	0.000306	0.47	0.506
Print speed	1	0.000056	0.000056	0.09	0.774
Infil	1	0.006006	0.006006	9.28	0.011
Scale	1	0.000006	0.000006	0.01	0.923
Error	11	0.007119	0.000647		
Total	15	0.013494			

Figure 10. Interaction plot for height tolerance

4.1.4 Fisher's pairwise comparisons:

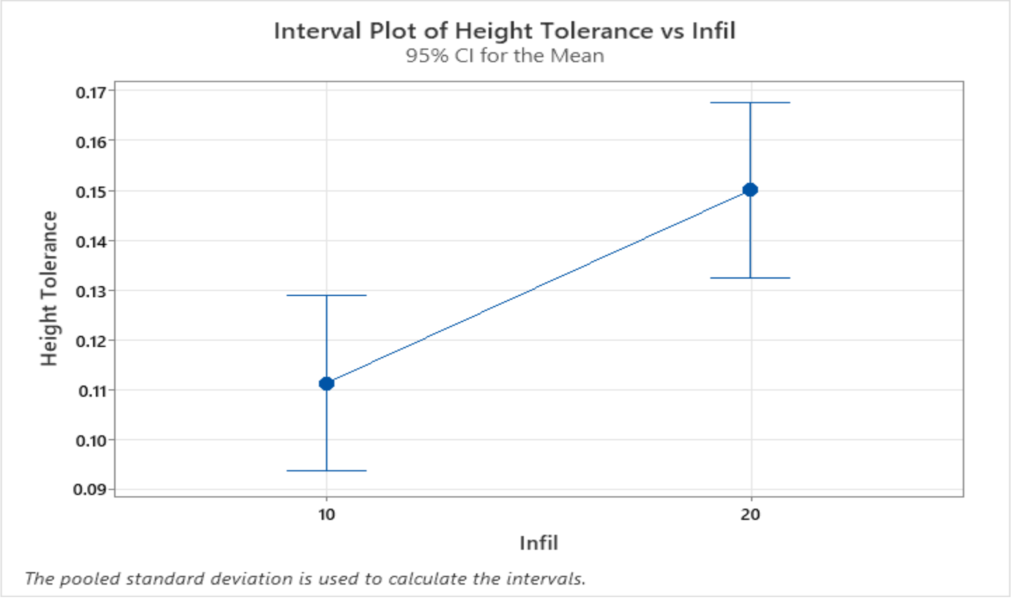


Infil	N	Mean	Grouping	
20	8	0.15000	A	
10	8	0.11125		B

Means that do not share a letter are significantly different.

Figure 11. Grouping Information using the Fisher LSD method and 95% confidence

4.1.5 ANOM:



The pooled standard deviation is used to calculate the intervals.

Figure 12. Interval Plot of Height Tolerance vs Infill

4.2 DOE analysis - Diameter Tolerance:

With the response as tolerance in diameter, a regression equation is found in 4.2.1, and the normal plot of the effects is shown in Figure 13. The pareto chart of the effect shown in Figure 14 shows that these factors have minor effect on variation of diameter.

4.2.1. Regression equation

Diameter Tolerance = -23.44 + 0.1090 Temperature + 0.3510 Print speed + 0.5470 Infil+ 24.19 Scale - 0.001650 Temperature*Print speed- 0.002500 Temperature*Infil - 0.1130 Temperature*Scale- 0.007550 Print speed*Infil - 0.3410 Print speed*Scale- 1.016 Infil*Scale + 0.000035 Temperature*Print speed*Infil+ 0.001600 Temperature*Print speed*Scale+ 0.004700 Temperature*Infil*Scale + 0.01290 Print speed*Infil*Scale - 0.000060 Temperature*Print speed*Infil*Scale

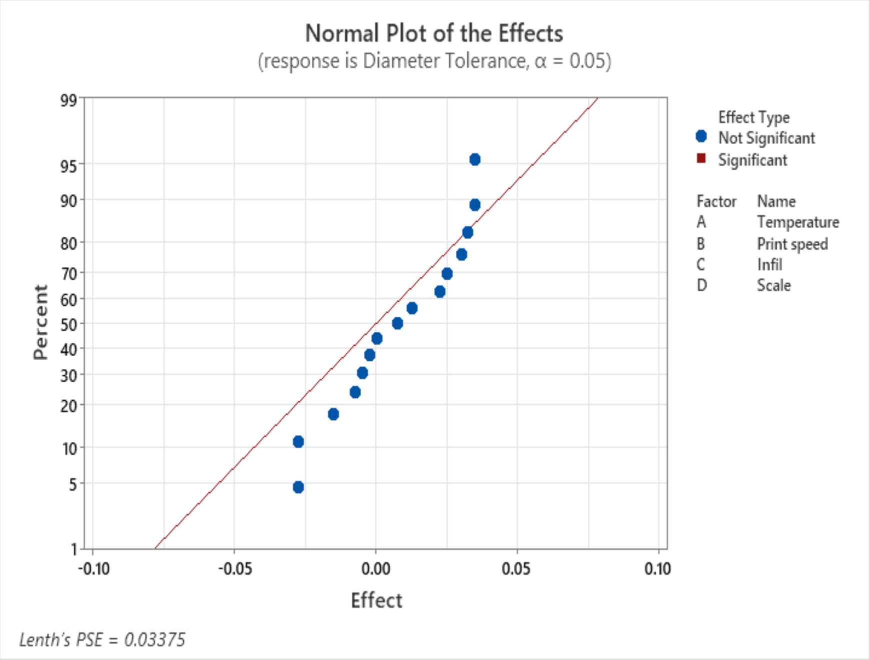


Figure 13. Effects plot for diameter tolerances

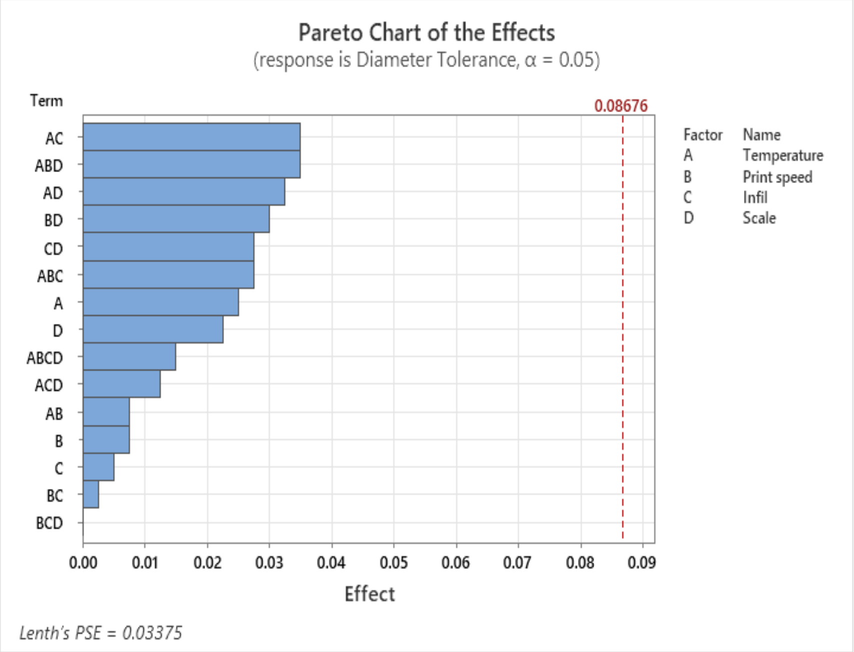


Figure 14. Pareto chart of the effects

4.2.2 Main effects and interactions effects plots:

The graphs show the main effects in Figure 15 and interaction affects plots in Figure 16, with diameter tolerances from which it is observed that scaling and temperature are the factors that show the deviations in dimensions when there is a change in factors from 2 to 1 and 210 to 220 in scaling and temperature respectively.

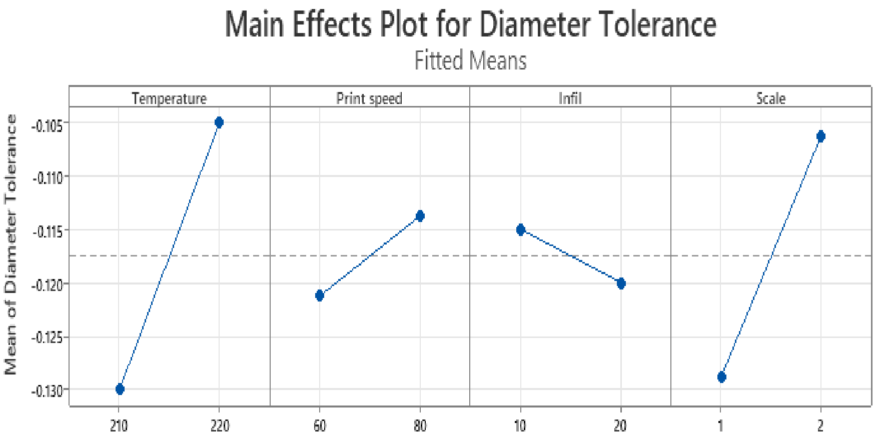


Figure 15. Main effect plot for diameter tolerances

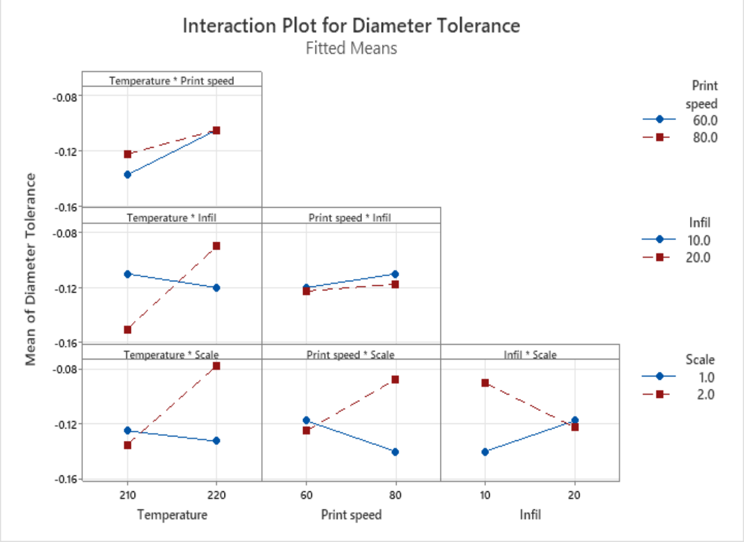
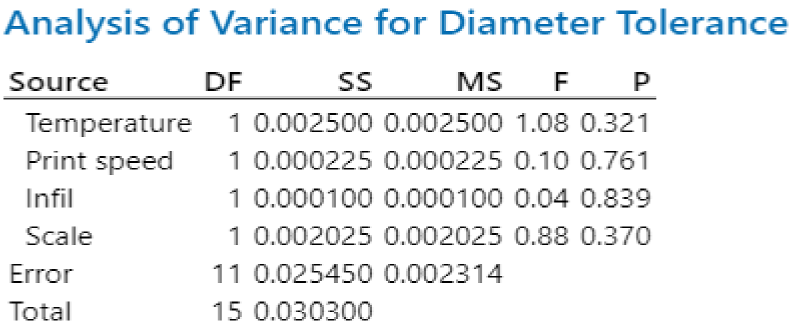


Figure 16. Interaction plot for diameter tolerances

4.2.3 ANOVA for Diameter Tolerance:



Analysis of Variance for Diameter Tolerance

```
Source        DF        SS        MS     F      P
  Temperature  1  0.002500  0.002500  1.08  0.321
  Print speed  1  0.000225  0.000225  0.10  0.761
  Infil        1  0.000100  0.000100  0.04  0.839
  Scale        1  0.002025  0.002025  0.88  0.370
Error         11  0.025450  0.002314
Total         15  0.030300
```

Figure 17. Interaction plot for diameter tolerances

4.2.4 ANOM:

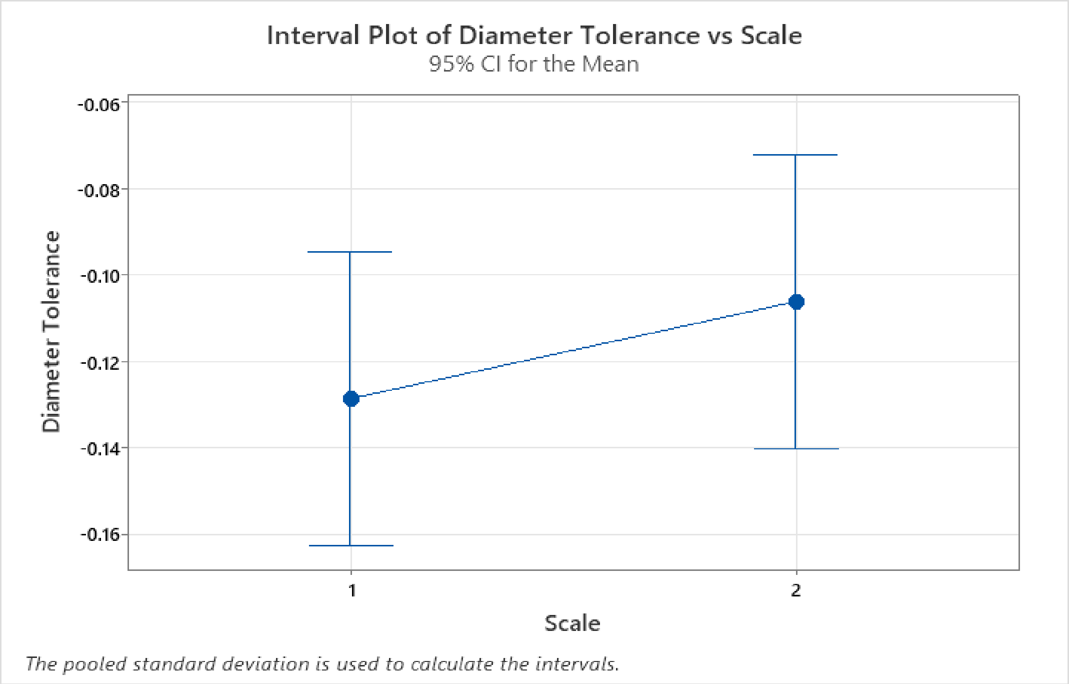
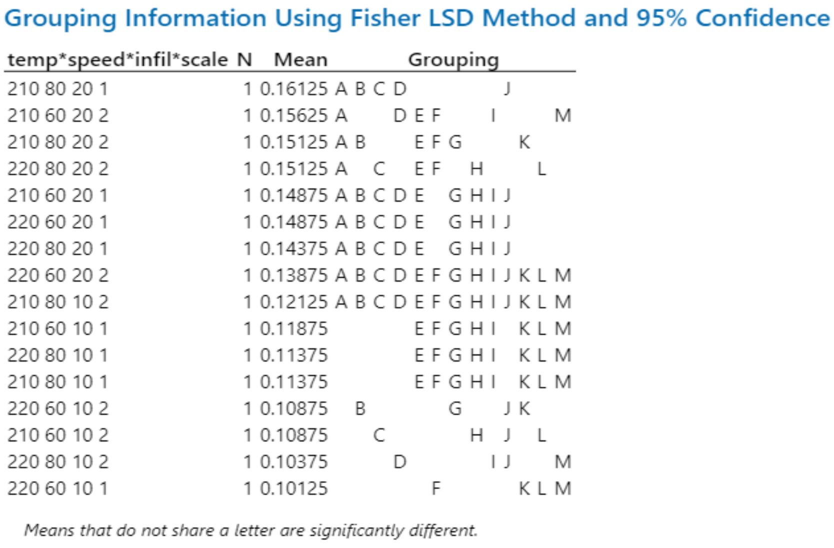


Figure 18. Interaction plot for diameter tolerances



Grouping Information Using Fisher LSD Method and 95% Confidence

```
temp*speed*infil*scale  N  Mean     Grouping
210 80 20 1             1  0.16125  A B C D           J
210 60 20 2             1  0.15625  A     D E F     I       M
210 80 20 2             1  0.15125  A B     E F G       K
220 80 20 2             1  0.15125  A   C   E F   H       L
210 60 20 1             1  0.14875  A B C D E   G H I J
220 60 20 1             1  0.14875  A B C D E   G H I J
220 80 20 1             1  0.14375  A B C D E   G H I J
220 60 20 2             1  0.13875  A B C D E F G H I J K L M
210 80 10 2             1  0.12125  A B C D E F G H I J K L M
210 60 10 1             1  0.11875          E F G H I   K L M
220 80 10 1             1  0.11375          E F G H I   K L M
210 80 10 1             1  0.11375          E F G H I   K L M
220 60 10 2             1  0.10875    B         G     J K
210 60 10 2             1  0.10875      C         H   J   L
220 80 10 2             1  0.10375        D         I J     M
220 60 10 1             1  0.10125            F         K L M
```

Means that do not share a letter are significantly different.

Figure 19. Grouping information using fisher LSD method and 95% CI

5. Results and Conclusion

For the two-level factorial design, the data is collected by 3D printing the samples. The values of dimensional tolerances are entered into the Minitab as a response and analyzed in the factorial design. The tolerance range in height and diameter is 0.07mm to 0.18mm and -0.07mm to -0.20mm respectively. The dimension of the printed samples in the radial direction is less than the design dimension. This is due to the shrinkage of the part in the radial direction.

The analysis shows that temperature and scale played a major role in these deviations. The height of the printed samples is greater than the design dimension implying layer height inaccuracy.

ANOVA for height tolerance shows that infill density affects the height dimension. To obtain the desired infill density the variation in layer thickness probably resulted in height variation. The shrinking in radial direction can also result in internal material pressure in vertical direction. From the general linear model performed in Minitab it is able to provide a set of factors which can give dimension closer to the design value. Figure 19 shows that temperature 220, print speed 60, infill density 10 and scale 1 has least dimensional tolerance. These input conditions are optimal for printing a 3D part with lower dimensional inaccuracy.

References

Heidari – Rarani, M., Optimization of FDM process parameters for tensile properties of polylactic acid specimens using Taguchi design of experiments, *Journal of Thermoplastic Composite Materials*, Vol. 35(12), Pp no 2435 – 2452, 2022.

Vinod, G and Dr. Raut, D, N., A review paper on 3D-printing aspects and various processes used in 3D-printing, *International Journal of Engineering Research and Technology (IJERT)*, Vol. 6, June 2017.

Pedram, P., Zhou, C and Dong, lin., 3D printing of ultrahigh strength continuous carbon fiber composites, *Advanced Engineering Materials Journal*, 2019.

Kumar, M., Ramakrishnan, R and Alnura, O., 3D printed polycarbonate reinforced acrylonitrile-butadiene-styrene composites: composition effects on mechanical properties, microstructure and void formation study, *Journal of mechanical science and technology*, Vol. 33(11), Pp no. 5219-5226, 2019.

Gajdoš, I., Slota, J., Influence of printing conditions on structure in fdm prototypes, *Technical Gazette 20.*, 231-23, 2013.

Fountas, N. A., Kitsakis, K., Aslani, K.E., Kechagias, J.D., Vaxevanidis, N. M., An experimental investigation of surface roughness in 3D-printed PLA items using design of experiments, *Journal of Engineering Tribology*, Vol. 236(10) 1979–1984, 2022.

Zaneldin, E., Ahmed, W., Mansour, A., Hassan, A.E., Dimensional Stability of 3D Printed Objects Made fromPlastic Waste Using FDM: Potential Construction Applications. *Buildings* ,11, 516, 2021.

Eckert, T., Klein, F.C., Frieler, P., Thunich, O., Abetz, V., Experimental Design in Polymer Chemistry-A Guide towards True Optimization of a RAFT Polymerization Using Design of Experiments (DoE), *Polymers*, 13, 2021.

Wu, H., Toly Chen, T.T., Quality control issues in 3D-printing manufacturing: a review, *Rapid Prototyping Journal* 24/3, 607–614, 2018.

Zhang, J., Thakkar, R., Zhang, Y., Maniruzzaman, M., Structure-function correlation and personalized 3D printed tablets using a quality by design (QbD) approach, *International Journal of Pharmaceutics*, 590, 119945, 2020.

Teng, H.M., Fan, S.K., Jiang,C.H., Yang, Q.W., Liu, F.H., Tsao, C.C., Study on the printing quality of fused deposition modeling using Taguchi method, *Journal of Physics: Conference Series*, 2345,012014, 2022.

Leonardo, S., Carlos, H, A., Netto, A and Cassiano, B., Evaluating the deposition quality of parts produced by an open-source 3D printer, *Rapid prototyping journal*, 15 Aug 2016.

Auffray, L., Gouge, P and Hattali, L, Design of experiment analysis on tensile properties of PLA samples produced by fused filament fabrication, *The international journal of advanced manufacturing technology*, Vol. 118, Pg no. 4123-4137, 2022.

Eguren, J, A., Esnaola, A and Unzueta, G, Modeling of an additive 3D printing process based on design of experiments methodology, *Quality innovative prosperity*, Vol. 2411.1435, 2020.

Griffiths, C.A., Howarth, J., De Almeida-Rowbotham, G., Rees, A., Kerton, R., A design of experiments approach for the optimisation of energy and waste during the production of parts manufactured by 3D printing, *Journal of Cleaner Production,* Vol. 139, pg 74-85, 2016.

Chowdhry, S., Quality Improvement of the 3D Print Using Design of Experiments, *International Journal of Research and Technology (IJERT)*, Vol 09, Issue 04, 2022.

Espino, M.T., Tuazon, B.J., Espera Jr, A.H., Nocheseda, C.J.C., Manalang, R.S., Dizon, J.R.C., Advincula R.C., Statistical methods for design and testing of 3D-printed polymers, *National Center for Biotechnology Information,* 2023.

Schneidler, J., Berry, C., Barari, A., Improving 3D Printing Geometric Accuracy Using Design of Experiments on Process Parameters in Fused Filament Fabrication (FFF), *14th IEEE International Conference on Industry Applications (INDUSCON),* pp. 1360-1365, 2021.

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