Optimization of FDM 3D printing process parameters using Taguchi technique

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Abstract. Fused deposition modelling (FDM) is a fast growing and low-cost 3D printing technology in order to comply most prominent demands of today’s industries in terms of capability to fabricate complex parts along with high flexibility in design. The dimensional accuracy, is an urgent need of final parts printed by FDM process, that is primarily influenced by the process parameters. Optimizing the process parameters which significantly influence the dimensional accuracy is the primary goal of this study in order to achieve the ultimate final part quality. This experimental study investigates the effect of different process parameters viz. layer height, raster angle, nozzle temperature and surrounding pressure on thickness of the final part for Poly Lactic Acid (PLA) filament. Experiments, based on Taguchi’s L9 orthogonal array, were performed and subsequently experimental data have been analysed by ANOVA. It has been observed that the layer height is the most significant factor in order to achieve the dimensional accuracy.

Key words- FDM, Taguchi Method, ANOVA

1. Introduction

3D (3 Dimensional) printing or Additive manufacturing (AM) has gained great popularity over the past few years due to its ability to produce complex objects with ease, available sizes, flexibility of usable materials, easy handling and wide range of applications such as engineering industry, medical sciences, food industry, construction, aeronautics, textile industry, automotive industry and so on [1]. There are various methods of Additive Manufacturing such as stereolithography, syringe extrusion, selective layer sintering, fused deposition modelling(FDM)/fused filament fabrication(FFF) being used over the field of its applications as per the requirements of industry but Fused Deposition Modelling (FDM) has become the most widely employed rapid prototyping technique among other methods [2]. FDM uses a temperature controlled head to extrude semi liquid thermoplastic through a nozzle of fixed orifice in layer by layer formation, shown in figure 1[3], the movement of printing head is controlled by a computer aided manufacturing (CAM) software[4].

![Figure 1 FDM Process Schematic](image)

Researchers are continuously working towards improving different characteristics of FDM produced parts by tweaking with different process parameters and stating a range of optimum settings for a FDM machine and material at which the strength or production time or production cost or any other aspect is
Commonly optimized process parameters are layer height, line width, nozzle temperature, bed temperature, print speed, raster angle etc. Most researchers follow conventional technique for experimentation i.e., varying only one parameter while keeping others constant at one time. This conventional approach of experimentation is very time consuming and demands enormous number of resources as number of experiments grows exponentially as more optimizable parameters are to be taken into consideration. Moreover, interaction terms of various process parameters are not entertained in this study. Taguchi method is a powerful tool to screen significant process parameters from many while performing a significantly lesser number of experiments[5]. Taguchi’s L9 OA is adopted here to study the effect of each processing parameter on dimensional accuracy of parts produced by FDM, and then to determine optimum process parameters.

2. Literature Review
Parametric optimization of any manufacturing process is a prime necessity of the researchers for producing quality final product in terms of dimensional accuracy and mechanical properties. This section provides an extensive review of many researchers regarding optimization of process parameters of FDM process. Srivastava et al.[6] proposed a hybrid approach to optimize model material volume and build time in fused deposition modelling. RSM based experimentation was conducted on FDM Maxum modeler for ABS workpiece and a conical primitive of STL size X=20mm, Y=20mm and Z=69.99mm was taken. Established optimal condition by grey analysis approach are as follows: an air gap of 0.0254mm, contour width of 0.654mm, orientation of 0.0˚ and raster angle of 0˚. Prashantha and Roger [2] used fused deposition modelling based three dimensional (3D) printing system for the fabrication of conductive polymer nanocomposites. Printing was done at 210°C with a nozzle of diameter 0.4 mm. Bed temperature at the time of printing was 60°C and distance between bed surface and nozzle was fixed at 0.2mm. Specimens printed with two surface layer shells, layer height is fixed at 0.2mm and infill is set to 100% linear infill pattern with a stacking alternating between 45˚ and -45˚. Panda et al.[7] used a recently developed technique such as bacteria foraging was adopted as its superior performance over other random search techniques as there are only few parameters needed to be adjusted. The control factors considered in this study are thickness, build orientation, raster angle, raster width and air gap. Functional relationship between strength and process parameters is developed in this work using surface methodology for prediction process. Hmeidat et al.[8] used an epoxy resin, Epon 826 in their study, a Bisphenol A diglycidyl ether (DGEBA) resin with 178-186 weight per epoxide with a density of 1.162 g/cc. These 3D printed nanocomposites had a strength in range of 80 to 143 MPa, which is significantly higher than any previously reported values for 3D printed thermostos composites, including short fiber-reinforced materials. These materials have excellent layer-to-layer bonding because of the crosslinking process which occurs after the component has been printed. Papon and Haque[9] produced CNF/PLA nanocomposite filaments using a laboratory mixing extruder. The matrix material used was polylactic acid-biopolymer (PLA) granulates of 3mm size with a glass transition temperature of 55°C and melting temperature of 175°C. The reinforcing material they used was CNF with a maximum length of 400nm and average diameter of 50nm. It was observed that geometry of nozzle affects the bead spreading architecture. Improved ultimate strength and modulus of elasticity was seen in CNF/PLA nanocomposites with 0.5% CNF as compared to neat PLA. Bead orientation direction and orientation of CNF was seen to be affected by extruder orifice and printer nozzle. Cataldi et al.[10] used a single screw extruder for producing nanocomposites consisting of polyvinyl alcohol and cellulose nanocrystals. Thermoplastic polyvinyl alcohol was used as Matrix for the composite in this work. Stiffness of filament and 3D printed specimens was increased after the introduction of CNC. The toughness of 3D printed material was increased due to good edition between CNC and PVOH. Lower densification was achieved upon introduction of CNC. Alafaghani et al.[7] examined the effect of infill percentage, building direction, infill pattern, printer speed, extrusion temperature and layer height independently on mechanical properties and dimensional accuracy. Extrusion temperature, layer height and building direction affected dimensional accuracy more than infill pattern, infill percentage and printing speed. B. Coppola et al.[8] studied the effects of printing
temperature on PLA/clay nanocomposites in 3D printing. Semi-crystalline polylactic acid (PLA) was used as matrix in this study. They used FDM technique to print bone specimens at three different temperatures: 185, 200 and 215°C to mechanically test in tensile mode. A higher elastic modulus was exhibited by nanocomposite 3D printed samples as compared with PLA specimens and it increases with increase in printing temperature. They concluded that printing temperature strongly affects properties of final object. Ceretti et al.[9] produced multi-layered PCL scaffolds and analysed the influence of process parameters and extrusion technology on the deposited material. The three configurations used were: 0.6mm x 0.6mm, 0.8mm x 0.8mm and 1mm x 1mm and path heights were 0.3mm, 0.4mm and 0.5mm for each configuration respectively, while the area of the whole grid was 10mm x 10mm. Human foreskin fibroblasts cells were seeded at a cellular density of 40000 cells/cm to verify the effectiveness of produced scaffolds. They concluded that extrusion head don't have significant effects on resulting geometry of the samples and for the extrusion of poly-caprolactone, grain extrusion head is preferable. Bartolomeo Coppola et al.[10] used a layered silicate-reinforced polylactic acid (PLA) for manufacturing samples with additive manufacturing. During the melt-compounding process, the temperature profile used was: 160°C-180°C-180°C-180°C-180°C-180°C-180°C-180°C-170°C (from hopper to die). The single screw extruder had a die of 3mm, operating temperature profile: 180°C-180°C-160°C (from hopper to die) and had a screw speed of 10rpm. At the time of printing of specimens, bed temperature was fixed at 50°C, layer height was fixed at 0.2mm, faster angle was fixed at +/- 45° and nozzle diameter were fixed at 0.35mm. Printing temperature had a direct effect on specimen transparency, the transparency increases with increase in printing temperature. They concluded that, printing temperature should be chosen considering polymer architecture and nanocomposite morphology. Balchan and Drickamer [11] studied the effects of pressure from 60 to over 400 kbar on resistance of iodine and selenium. A rapid drop in resistance of selenium was seen between 60 and 128 kbar then a discontinuous drop. When pressure if further increased, its behaviour is apparently metallic. Iodine shows rapid drop in resistance between 60 and 255 kbar, further increasing pressure shows slower drop in resistance. Sobczak and Asthana[12] reviewed the effect of pressure on solidification structure formation in metal castings. They analysed effects of pressure on nucleation growth, phase diagrams, interfacial energy and diffusion coefficient. Refinement of structure was seen to be promoted due to high pressure which may be caused by reduced critical radius and reduced rate of new phase nucleation and decreased interfacial free energy. Russell J. Hemley[13] studied the effect of high pressure on molecules such as halogens, nitrogen and group V, oxygen and chalcogens, CO and CO₂. Simple hydrocarbons, H₂O, related hydrogen bonded systems, simple molecular mixtures, clusters and complex molecules. Resit Unal and Dean[14] used Taguchi approach in their study to design and optimize quality and cost. They presented and overview of Taguchi method with steps involved. They found out Taguchi method is a powerful tool which can simultaneously improve quality and cost. They concluded, Taguchi method emphasizes on pushing quality back to design stage, resulting in designing a product or process which is robust to cause quality problems. Mohan Pandey et al. [15] presented and classified different slicing algorithms used in rapid prototyping or layered manufacturing process into two categories, one which consider build edge as rectangular and other which consider build edge as a slope. Ahn et al.[16] studied the surface roughness in parts produced by fused deposition modelling. They presented a new approach to formulate surface roughness. Effects of surface angle, layer thickness, cross-sectional shape of filament and overlap interval on surface roughness were showed. They concluded surface roughness expression can predict roughness of FDM parts. Boschetto and Bottini [17] formulated a method to predict dimensional accuracy and surface roughness of FDM parts as a function of process parameters such as layer thickness and deposition angle. They investigated 60 different deposition angles between 0-180°. The used ABS for their research. They performed a case study which evidenced that it is possible to predict dimensional deviations and geometrical tolerances. They concluded that dimensional deviations are greatly influenced by deposition angle. Bellini et al.[18] studied new developments in field of fused deposition modelling of ceramics. They developed a new extrusion system which uses granules instead of filament. Core finding of this study is overcoming the limitations presented by material being in filament form by using granular form. Pandey et al.[19] presented a semi empirical
model for evaluation of surface roughness of a FDM part. One of the major problems in FDM part is surface roughness caused by staircase effect. Hot cutter machining (HCM) is used to address this problem. To find significance index of process variables ANOVA is used. They concluded that HCM can achieve a surface finish of the order 0.3 µm with 87% confidence level.

The process parameters taken into consideration for optimization for a FDM process are generally the parameters which could be controlled by the FDM machine itself. In other words, only the parameters bound to the FDM machine are to be optimized while external factors like surrounding temperature, pressure, humidity remains unchanged. These external factors can greatly affect the quality and characteristics of parts produces by FDM. In this study, surrounding pressure is treated as a process parameter and its value is varied to analyse the effect of surrounding pressure as well as other process parameters on strength of FDM manufactured parts. Effect of pressure on properties and structure of material is extensively studied by Nobel laureate physicist P.W. Bridgman[23]. His work showed importance of pressure for studying changes in structure and properties of matter. It was suggested by J.D. Bernal in 1928 that all matter should become metallic at sufficiently high pressure due to electron dislocation caused by forced overlap of electrons[15,24].

3. Experimental Methodology
3.1 Selection of process parameters
Based on literature, it was analysed that the process parameters such as layer height, raster angle and nozzle temperature greatly affect the dimensional accuracy and mechanical properties of printed parts. In this study, a new process parameter, surrounding pressure is used with all other process parameters for evaluating its effect on dimensional accuracy in terms of thickness. Pressure is not taken as a process parameter in any study before as per the literature review, so surrounding pressure is a novel parameter in this study. Three levels of parameters are considered for sample preparation because Taguchi l9 method is being used for process parameter selection in this study. The levels of these parameters were selected with the help of machine manual and performing the preliminary test on a 3D printer. On the basis of preliminary experimentation, the ranges and subsequently the levels of the printing parameters were chosen as shown in Table 1. The parameters which are kept fixed throughout experimentation are shown in Table 2.

| Control Factors       | symbols | units | Levels     |
|-----------------------|---------|-------|------------|
|                       |         |       | I   | II   | III  |
| Layer Height          | A       | mm    | 0.1 | 0.15 | 0.2  |
| Raster Angle          | B       | degree| 0   | 45   | 90   |
| Nozzle Temperature    | C       | ° C   | 200 | 210  | 220  |
| Surrounding Pressure  | D       | psi   | 0   | 50   | 100  |

Table-2: List of fixed parameters

| S.No. | Parameter         | Fixed Value  |
|-------|-------------------|--------------|
| 1     | Bed Temperature   | 60°C         |
| 2     | Nozzle Diameter   | 0.4mm        |
| 3     | Infill Percentage | 100%         |
| 4     | Printing Speed    | 3600 mm/min  |
| 5     | Solid Layers      | 3            |
| 6     | Extrusion Width   | 0.4mm        |
3.2 Materials
The specimens used in this study are printed using white 1.75±0.03 mm diameter Polylactic Acid (PLA) filament. The filament was purchased from amazon.in and sold by 3D bazaar. PLA is a thermoplastic polyester with chemical formula \((C_3H_4O_2)_n\). It is the most widely used filament material in FDM printers.

3.3 Experimental Setup
Inferno i3 FDM 3D printer (Figure 2) is used in this research for producing specimens. This printer is capable of producing specimens up to a maximum size of 220*220*250mm by using polylactic acid (PLA), Acrylonitrile butadiene styrene (ABS), Polyvinyl Alcohol (PVA), High-density polyethylene (HDPE) and similar materials as this machine is equipped with heated print bed. This machine is running on marlin firmware and can print over USB while connected to a computer or via SD card which have G-code file for the part. To control and vary pressure around FDM printer, an air compressor and an air-tight enclosure is used, shown in Figure 2. The compressor employs a pressure switch which could be set to a desired value of pressure and a pressure difference, when the desired pressure is reached. This pressure switch automatically detects the pressure difference and turns off the compressor if there is any pressure drop and turns the compressor on, allowing the setup to maintain constant pressure. The printer is kept inside the enclosure then the lid of the container is sealed with the help of fasteners.

3.4 Sample Preparation
The samples used in this study are modelled based on ISO 527-2 (Model 5A) which is standard used for determination of tensile properties of reinforced and non-reinforced plastics [25]. Figure 3 indicates the dimensions and shape used to create CAD model. All test specimens are printed using Polylactic Acid (PLA) on Inferno i3 FDM printer. To evaluate the influence of processing parameters over the dimensional accuracy and repeatability of samples, the samples were measured and compared with CAD model. Thickness of printed parts of all 9 samples was measured using a vernier calliper (least count of 0.01 mm) at 3 different points along its axis and average of 3 was taken as a result (Figure 4).

Figure 2 Experimental Setup
Figure 3 Specimen CAD model, dimensions in mm
Figure 4: Measurement of dimensions
3.5 Experimental design based on Taguchi Method

In order to evaluate the effect of printing parameters of FDM process in terms of dimensional accuracy of width of parts, a Taguchi method is used here to optimize the process. The Taguchi method has become a powerful tool for the systematic application of design and analysis of experiments for the purpose of designing and improving the product quality[26].

According to Taguchi methodology, the characteristic that a target value represents best performance in terms of dimensional accuracy, is called Nominal is best type of problem. The S/N ratio can be calculated as shown below:

$$S/N = -10 \log_{10} \left( \frac{(y_1-m)^2+(y_2-m)^2+\cdots}{n} \right)$$  (1)

Where, 

- $m$ = Target value
- $n$ = Number of repetitions

Table 3 Response values using L9 orthogonal array

| Experiment Number | A | B | C | D | Thickness (mm) |
|-------------------|---|---|---|---|----------------|
|                   |   |   |   |   | Trial | Average value | S/N ratio (db) |
| 1                 | 1 | 1 | 1 | 1 | 1.99  | 2.02          | 37.78          |
| 2                 | 1 | 2 | 2 | 2 | 2.01  | 2.04          | 32.22          |
| 3                 | 1 | 3 | 3 | 3 | 1.97  | 2.01          | 34.36          |
| 4                 | 2 | 1 | 2 | 3 | 2.02  | 2.02          | 29.59          |
| 5                 | 2 | 2 | 3 | 1 | 2.01  | 2.07          | 27.45          |
| 6                 | 2 | 3 | 1 | 2 | 2.03  | 1.98          | 33.31          |
| 7                 | 3 | 1 | 3 | 2 | 2.1   | 2.14          | 19.01          |
| 8                 | 3 | 2 | 1 | 3 | 2.09  | 2.15          | 19.43          |
| 9                 | 3 | 3 | 2 | 1 | 2.07  | 2.13          | 18.31          |

Figure 5 Printed parts by FDM process

L9 orthogonal array chosen for the experimentation in which 9 rows corresponding to the number of experiments, with 4 columns at three levels as shown in Table 3. The experiments were performed for each combination of rows as per selected L9 orthogonal array and the results are indicated in Table 3. Figure 5 shows the all 9 printed parts under printing parameters shown in Table 3. Figures 7, 8, 9 show
the optical micrographs of the surface of the FDM printed parts under different printing conditions. Dimensional accuracy plays an important role in the assembly of the final product.

4. Result and Discussion

In the present study, the first step in the analysis is to review the test results for each experiment conducted by the Taguchi’s L9 OA. The S/N ratios are calculated for each experiment by applying Nominal the Best characteristics, as shown in Table 3. The plot of average values of S/N ratio for each factor at different levels are shown in Figure 6. In S/N analysis, the greatest value of S/N represents a more desirable condition for a particular control factor. Figure 6 suggests that the factors at levels A1, B1, C1, D2, are the best levels that give the target value of the thickness.

Effects of layer height on dimensional accuracy are clearly visible in this study. It is seen that as the layer height is increased, dimensional accuracy is decreased. When a layer is printed on top of previous layer, a step is formed and this is called stepping effect. At lower layer height, this stepping effect is minimized as it results in a smoother and even surface finish. Lower layer height is also known as higher resolution for 3D printed parts because better surface finish and so have greater dimensional accuracy. In this study, 0.1mm layer height is optimum layer height because it shows minimum deviation and highest accuracy. The same results have been observed by [18] in his study. It is observed that as the nozzle temperature is increased, the dimensional accuracy is decreased within the temperature range taken in this study, which might be a result of increasing fluidity of extruded PLA with increase in extrusion temperature. The extruded material, which is in semi liquid form, tends to flow in any direction it is free to flow, but it gets a very small fraction of time to do so because it begins to cool as soon as it is out of nozzle. When extrusion temperature is increased, the extruded material takes more time to cool down and thus have a little longer to flow, which causes dimensional inaccuracy. In this study, 200°C is optimum nozzle temperature. Higher dimensional accuracy is seen in parts which are printed at 0˚ raster angle in this study which might be because when printing at 0˚ raster angle, all the layers are printed parallel to x-axis and subsequent layers are also parallel which results in higher accuracy.

Figure 6 Effect of control factors on thickness

Analysis of Variance (ANOVA) is executed on S/N data and indicated in Table 4. Table 4 describes that the percent contribution of factor D (surrounding pressure) is very small (0.06 %) in comparison to factors A, B and C. Hence factor D can be treated as an error. Table 5 indicate pooled ANOVA at 95%
confidence interval for S/N data. Table 5, the percent contribution of parameters affecting the target value of thickness, i.e., layer height (92.15%), raster angle (0.53%) and nozzle temperature (1.14%), indicates the influence of layer height is more than the other process parameters. In Table 5, the error percentage contribution is less than 15%. Therefore, it is verified that no significant process parameters are omitted during the experiment, therefore, no opportunity for the further improvement.

Table 4 ANOVA for S/N ratio

| Factor | DOF | Sum of Square (SS) | Variance (V) | Percent Contribution (%P) |
|--------|-----|--------------------|--------------|--------------------------|
| A      | 2   | 399.11             | 199.55       | 92.15                    |
| B      | 2   | 11.16              | 5.58         | 2.58                     |
| C      | 2   | 22.57              | 11.28        | 5.21                     |
| D      | 2   | 0.26               | 0.13         | 0.06                     |
| Error  | 0   | 0                  | indeterminate|                          |
| Total  | 8   | 251.45             |              |                          |

Table 5 Pooled ANOVA for S/N ratio

| Factor | DOF | Sum of Square (SS) | Variance (V) | F-ratio | Pure Sum (S') | Percent Contribution (%P) |
|--------|-----|--------------------|--------------|---------|---------------|--------------------------|
| A      | 2   | 399.11             | 199.55       | 1511.36 | 398.35        | 92.09                    |
| B      | 2   | 11.16              | 5.58         | 42.26   | 2.32          | 0.53                     |
| C      | 2   | 22.57              | 11.28        | 85.48   | 4.95          | 1.14                     |
| Error  | 2   | 0.26               | 0.13         | 6.23    |               |                          |
| Total  | 8   | 251.45             |              |         | 100           |                          |

\[ F_{0.05}(2,2) = 19.0 \]

4.1 Estimation of Optimum Quality Characteristics

After analysis, the selected significant process parameters are A1, B1 and C1. The optimum value of width can be evaluated as:

\[ \mu = \bar{T} + (\bar{A}_1 - \bar{T}) + (\bar{B}_1 - \bar{T}) + (\bar{C}_1 - \bar{T}) \]  

\[ \bar{T} = 27.94 \]

\[ \bar{A}_1 = 34.79 \]

\[ \bar{B}_1 = 28.79 \]

\[ \bar{C}_1 = 30.17 \]

\[ \mu = 37.74 \text{ mm} \]

\[ F_{0.05}(2,2) = 19.0 \quad \text{(Tabulated)} \]

Confidence Interval = C.I. = \[ \pm \sqrt{F_{0.05}(2,2) \frac{V_e}{N_e}} \]

\[ V_e = \text{Error Variance} = 0.13 \]

\[ N_e = \text{Effective Number of Replications} = \frac{\text{Total Number of Results}}{\text{Dof of Mean} + \text{Dof of all Factors}} \]  

\[ N_e = \frac{9}{1+6} = 1.28 \]
Confidence Interval = \( C.I. = \pm 1.92 \)
\[ 37.74 - 1.92 < \mu < 37.74 + 1.92 \]

For 95% C.I., the predicted optimum thickness in decibel is
\[ 35.82 < \mu < 39.66 \]

For 95% C.I., the predicted optimum thickness in mm is
\[ 2.01 < \text{thickness} < 1.97 \]

5. Confirmation Experiments

The confirmation step is the final step to authenticate the results obtained from the analysis phase. The expected value of thickness at optimum condition is equal to 37.74 db (= 2.00 mm) which is already calculated in Section 4. Three confirmation experiments are conducted for significant parameters at their optimal levels obtained in the analysis phase. The average value of thickness at the optimal setting of process parameters of the FDM process was observed to be 36.68 db. The result of the confirmation experiment is shown in Table 6. The value of width lies within the range calculated in the analysis phase. An error of 1.58 % is observed. Therefore, the optimal setting of process parameters, predicted in the analysis phase, can be recommended. Optical micrograph of confirmation experiment is shown in Figure 9.

Table 6 Result of confirmation experiments

| Optimal printing parameters | Prediction | Experimental |
|----------------------------|------------|--------------|
| Levels \( A1B1C1D2 \)      | 37.74      | 37.14        |

6. Surface morphology

The samples were observed under an optical microscope (Nikon YTV55) to understand and study their microscopic structure, voids and irregularities. The samples were observed in such a manner that different layers could be seen. When samples were observed under microscope, the irregularities in extruded PLA were clearly visible. The parts printed at 0.1mm layer height have less irregularities and as the layer height is increased irregularities gradually increased, shown in Figures 7, 8 and 9.
The irregularities obtained in the parts at higher layer height might be caused due to large compressive force (due to weight of a layer) experienced by extruded material at thick layer height and it caused the extruded semi liquid material to squeeze. As the layer height is decreased, the value of compressive force is reduced and material got more space to settle which resulted in less squeezing of material and hence less irregularities.

7. Conclusions

1. The lower value of layer height (0.1mm), lower value of raster angle (0º) and lower value of nozzle temperature (200º C) are significant printing parameters to achieve the target value (2 mm) of thickness.

2. Statistically, influence of layer height is more than any other parameters to maintain dimensional accuracy.

3. The value of part’s thickness (37.14 db) obtained by confirmation experiment is very close to the predicted value (37.74 db) at optimal setting of process parameters.

4. The predicted optimal range of thickness at 95% confidence interval is

\[ 2.01 \text{ mm} < \text{thickness} < 1.97 \text{ mm} \]

5. Effects of surrounding pressure on dimensional accuracy are not clearly visible in the range taken in this study (0-100psi). Therefore, it can be said that the parameter surrounding pressure is ineffective within this range on dimensional accuracy of FDM parts. Further increasing pressure may have some effects and there is scope to study this parameter further.

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