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Review Article

A Comprehensive Review on the Optimization of the Fused Deposition Modeling Process Parameter for Better Tensile Strength of PLA-Printed Parts

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Fused Deposition Modeling (FDM) is a kind of Additive Manufacturing technology, which can produce complex parts by adding layer-by-layer mold automatically from 3D computer-aided design (CAD) data. Although the FDM process has its obvious merits, a fundamental backward factor of its professional enterprise acceptance is the inadequacy of higher mechanical properties and heavy structure of the manufactured product. For that reason, the properties of the manufactured product by FDM are highly dependent upon the choice of FDM parameters. Several studies are investigated to look at the effect of various FDM process parameters to improve print quality characteristics such as mechanical properties, build time, dimensional accuracy, and surface finish of the manufactured parts with having convenient process parameter settings. However, the progress has been gradual and not well organized because of the complex attributes of the FDM process and conflicting process parameters. This paper aims to comprehensively summarize recent studies of advanced statistical and experimental design techniques for better tensile strength of polylactic acid (PLA)-printed parts, the effect of process parameters on tensile strength, and the existing work on the optimization of process parameters.

1. Introduction

Additive manufacturing (AM) also called layer manufacturing (LM), is a recent computer-dependent technology that has proven its success as an option for making parts in a very wide application range, but is still subject to some important limitations. AM can generate high complexity items, which may be very difficult or perhaps impossible to be manufactured by other conventional processes. Because of its computer-based production technology, AM presents accessible applications on reverse engineering to develop new parts that are almost identical to those created using three-dimensional (3D) scanning of actual parts, in place of a completely new design [1–3]. Therefore, this technology is applicable in vast areas such as in the aerospace and defense industries [4], in biomedical applications like dental [5] and organ surgeries [6], in automobiles [7], for energy storage devices [8], etc. There are several well-known AM techniques available in the engineering industry. Fused deposition modeling (FDM), stereolithography (SL), selective laser sintering (SLS), laminated object manufacturing (LOM), three-dimensional printing (3DP), and ink-jet printing are a few of them. Nowadays, FDM is one of the popular additive manufacturing technologies used for producing various products because of its ease of use, simple fabrication process, cost-effectiveness, wide material customization, its ability to manufacture complicated part processes based on extrusion mechanism, and its ability to process various thermoplastic polymers like PLA (polylactic acid), ABS (acrylonitrile butadiene styrene), PS (polystyrene), PC (polycarbonate), nylon, and PET (polyethylene terephthalate) [9]. However, FDM-printed materials are deposited layer by layer, and hence interlayer bonding is weak, resulting in poor mechanical properties compared with injection-molded [10, 11] materials.

The FDM process has a fair number of advantages and limitations. For most useful applications of FDM-printed parts, mechanical properties, dimensional accuracy, and surface roughness of the final parts are considered as essential characteristics [12]. The simplicity of the processes, less incurred costs, and insignificant building time are taken into account as the most constructive facts [13]. On the contrary, complex process parameters that significantly influence the component build are considered as a major limitation, and hence adequate works of studies are not undertaken to have an all-inclusive analysis of overall parameters. Now investigators are working on this big area of interest to get an optimal process parameter for the standardization of the process which could be performed to achieve customized needs [14]. Thus, the optimization of process parameters becomes the most important action area. An optimal combination of process parameters can give a better 3D-printed product of a desired mechanical strength than the individual optimization of process parameters because of their dependency on each other [15, 16].

The FDM process includes applications starting from prototype to functional parts. Creation of the CAD model, conversion of the CAD model into the STL (stereolithography) format, slicing of the STL format into thin layers, construction of the part in a layer-by-layer fashion, and cleaning and finishing are the five simple steps utilized in the FDM process to manufacture a component as shown in Figure 1.

1.1. FDM Process Parameters. Several attempts were made to enhance FDM process parameters that have a big impact on the strength of the built parts. Many researchers analyzed various controllable parameters to attain desirable properties of parts and more of them agree on an identical number of critical parameters [16–20]. They observed that the strength and part characteristics of the parts were affected by three general categories listed below and their diagrammatic representation is shown in Figure 2:

(a) Slicing parameters are as follows:

(i) Air gap: it is the gap between two adjacent rasters and it can be negative, which cause adjacent rasters to overlap partially; an equivalent space and dense structure is achieved but the build time increases [21]; it can often be zero, in which case the raster is in touch with every other and/or it can be positive in which case adjacent rasters do not touch one another and form a loosely packed structure, thus reducing build time. The air gap affects the tensile properties of the material based on the degree of dense structure of overlapping adjacent filaments [22].

(ii) Infill density: it denotes the material volume printed on the given component. Infill density directly influences the printed component's properties. A solid cross section has a small effect on the failure of the material considerably with a lower infill used, though an optimum infill density gives a better mechanical strength for fair material customization and build time [23], and a fully infilled density gives the best mechanical strength where build time is not considered a constraint [24].

(iii) Infill pattern: it is the methodology used to print the interior structure of the component being printed. A lot of filling patterns are available like linear, hexagonal, cubic, honeycomb, and diamond, among which honeycomb is better for good mechanical properties of the internal structures [25] but can increase the build time [26]. Therefore, without affecting the build time and other print quality settings, the optimal infill pattern is highly recommended.

(iv) Layer thickness: it is referred to as the amount of material deposited along the vertical axis of the FDM machine in a single pass. In AM, slicing the 3D CAD model is one of the important steps because slicing the 3D CAD model with a really small slice thickness results in a large build time. At equivalent time, if a large slice thickness is chosen, the surface quality is extremely poor because of the staircase effect. As layer thickness decreases better mechanical strength is achieved because of a decrease in void density [27, 28].

(v) Number of shells: it is the number of contours that the FDM nozzle deposits to make the perimeter and limits of a given part. The number of shells significantly affects the mechanical properties of the FDM PLA-printed part and as it increases flexural strength [29], it decreases other mechanical properties [27].

(vi) Print speed: it can be described that the speed of the build nozzle traverses when depositing material along the X and Y axes on the build platform. The print speed significantly affects the build time and the print quality but also depends on the material properties used for deposition [30]. A higher print speed enhances tensile strength due to the quick bonding between the successive layer interfaces [31].

(vii) Raster orientation: it is the angle created between the raster/deposited layer and the X-direction of the build platform. The raster angle has a moderate influence on the overall mechanical properties of FDM PLA-printed parts. This is because it only determines the direction of the deposited filaments during the printing process [32].

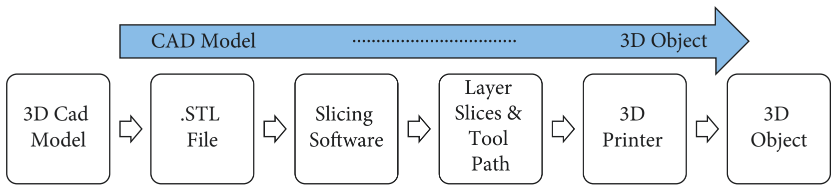

Figure 1: Basic steps of the FDM process.

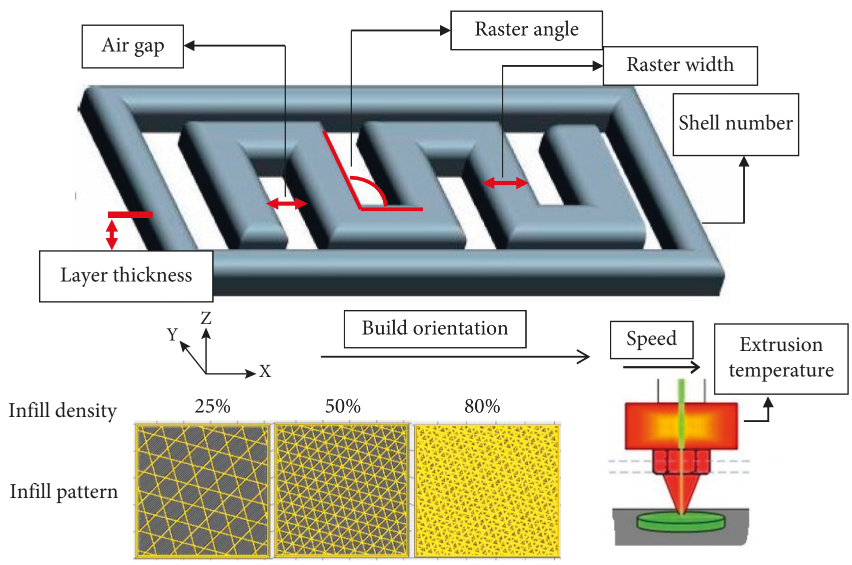

Figure 2: Diagrammatic representation of FDM process parameters [20].

(viii) Raster width: it is the thickness of the raster that the FDM nozzle deposits to fill the inside region of the part. The higher value of the raster width decreases tensile strength [22] and improves flexural strength [29].

(b) Building orientation: part builds orientation deals with the angular direction of the deposited parts in the build bed concerning the *X*, *Y*, and *Z* axes. The *X* and *Y* axes are parallel to the build platform and the *Z* axis is along the thickness or height direction of a part. Build direction strongly affect the surface and mechanical properties of a part [33].

(c) Temperature condition: it is the temperature at which the model material is heated by the system. This controls the extrusion of the molten material through the nozzle. Thus, the temperature kept inside the heating head nozzle of the FDM before the filament is extruded is named extrusion temperature. As the temperature increases, the mechanical properties increase because of the improved fusion within the extruded layer and between the layers [34].

2. Previous Work and Analysis on the Optimization of FDM Process Parameters

At present, related research focuses on the effects of FDM processes and the optimization of the process parameter of FDM-printed parts to enhance mechanical properties. Researchers use different optimization techniques like response surface methodology (RSM) [35], Taguchi method [36], full factorial [36] and fractional factorial [37], Gray relation [38], artificial neural network (ANN) [39], fuzzy logic [40], genetic algorithm [41], and more others to optimize a number of the process parameters for improving tensile properties.

It is also essential to be able to forecast how the parts will perform when applied to mechanical loads to assess their appropriateness for a given application. Thus, studying the mechanical properties of FDM-printed parts serves as an effective subject of concern and research. Accordingly, the effect of FDM process parameters on different mechanical properties like tensile, compressive, flexural, impact, and fatigue strength of test samples has been widely studied for various types of materials and sets of process parameters/manufacturing conditions. Table 1 gives the summary of the latest literature reviewed in terms of the parameters considered, a method used/optimization techniques, output response, the significant parameters obtained in the studies, and the results recommended.

Figure 3 shows an overview of the methods used in the optimization of FDM process parameters of PLA-printed parts. Over 70 earlier research have been considered to do the overview and the RSM method has the highest number of occurrences with almost 38.5%.

Table 1: Summary of review of earlier (2020 and above) works of literature.

Material/s	Process parameter considered	Method/technique considered	Mechanical properties considered	Analysis/results	References
PLA, ABS, CFR-PLA, CFR-ABS, CNT-ABS	Infill density, infill pattern, print speed, and print temperature	DSC[a], SEM[b], TGA[c]	Tensile, compressive flexural,	Optimum infill density of 100%, infill pattern of linear, print speed of 90 mm/s, and print temperature of 215°C. CFR-PLA[d] is the strongest material.	[42]
PLA	Infill density and angle of orientation	Full factorial	Tensile	100% infill density and ±45° build direction are the ones with the optimum performance.	[43]
PLA	Raster angle	DIC[e]	Tensile, fracture	Anisotropic behavior in both, largest at 45°/−45° and least at 0°/90°.	[44]
PLA, ABS	Layer thickness, raster width, airgap, and part orientation	Mathematical approach (MATLAB), DOE, RSM	Geometrical deformation, surface roughness	According to mathematical analysis, among all process parameters, layer thickness and raster width have a significant effect.	[45]
PLA	Raster angle, raster width, and layer height	ANFIS[f]	Tensile	Tensile strength is decreased with increment in layer height and is the highest for a raster angle of 0° and raster width of 0.6 mm.	[46]
PLA	Infill density, speed, and print temperature	RSM, CCD[g], GA-RSM, GA-ANN[h], GA-ANFIS	Tensile	Highest tensile strength achieved at the result of 100%, 124.778 mm/s, 210°C using GA-ANN with the maximum accuracy of 99.89%.	[47]
PLA	Infill density, print speed, and layer thickness	Taguchi method, S/N ratio	Tensile	Optimum parameters are infill density of 80%, print speed of 40 mm/s, and layer thickness of 0.2 mm.	[48]
PLA	Infill density, layer thickness, and extrusion temperature	Taguchi	Tensile, impact, and hardness	50%, 0.4 mm, 220°C for tensile 30%, 0.2 mm, 210°C for impact 50%, 0.3 mm, 215°C for hardness 50%, and 0.3 mm, 210°C for combinations.	[49]
PLA	Layer height, shell thickness, infill density, orientation angle, and print speed	RSM, L16 factorial	Tensile	Infill density is a principal parameter, printing speed strongly influences thermal energy, the higher the thickness, the stronger the manufacturing parts.	[50]
PLA	Layer thickness, airgap, orientation, temperature	Heat and chemical treatment	Tensile	Improvement with heat treatment is less (6%) but with chemical treatment it is high up to a 12% change.	[51]
PLA	Infill density	Full factorial	Tensile, hardness, impact, flexural	100% infill density gives the best mechanical properties.	[52]
PLA	Printing speed, infill rate, and raster angle	Taguchi	Tensile	30 mm/s of printing speed, 100% of infill rate, and 0/90° scanning angle are optimum operations determined as parameters.	[15]
CFR-PLA	Build direction, infill percentage, and layer thickness	TOPSIS[i]	Tensile, izod impact	Infill percentage and layer thickness effects are significantly higher. Optimum results according to TOPSIS are: 80% infill, 0.2 mm layer thickness, and *X* building direction for tensile strength.	[53]

Table 1: Continued.

Material/s	Process parameter considered	Method/technique considered	Mechanical properties considered	Analysis/results	References
PLA	Raster angle	RSM, DIC	Tensile	Tensile strength is highest if the fibers are aligned with the loading direction and for orientation with a raster angle of 90°, the material is quite isotropic. Investigate a new layer staggering scheme with alternating layers aligned symmetrically to the loading direction, indicated by $[\beta/-\beta]$.	[30]
PLA	Layer thickness, nozzle temperature, bed temperature, infill density	Thermal and chemical treatment	Tensile	Tensile strength when using thermal treatment did not change significantly; but in the case of chemical treatment with acetone, there was a noticeable decrease in strength.	[54]
CFR-PLA	Infill density, print speed, and layer height	Taguchi, L9 orthogonal array	Tensile	The optimum set is 80% infill density, 80 mm/s print speed, and 0.1 mm layer height.	[55]
CFR-PLA	Print orientation, bed temperature, nozzle temperature, print speed, infill density	Taguchi, L18 orthogonal array	Tensile, impact	CFR-PLA showed a rougher surface morphology than pure PLA. 45°, 60%, 70°C, 220°C, and 55 mm/s give an optimum combination of mechanical properties.	[56]
PLA	Layer thickness, infill density, print speed, temperature, and build orientation	RSM, CCD, ANN	Tensile	0.27 mm, 70%, 60 mm/s, 200°C, 45° give best tensile strength.	[16]
PLA	Infill density and print pattern	Taguchi method, L9 orthogonal array	Tensile	Hexagonal printing pattern and filling rate of 100%. The printing pattern parameter is the most influential parameter that affects the tensile strength of FDM specimens.	[57]
PLA, ABS, PETG	Infill density and infill pattern	Full factorial	Tensile	Only the infill pattern significantly influences the tensile properties. For base PLA, ABS increased by 7.5%, and PETG increased by 10% strength.	[58]
PLA	Print speed and print temperature	DIC, SEM	Tensile	The print temperature increases, the tensile strength tends to rise first and then decreases, and as the print speed increases, the tensile strength tends upward. The optimum print temperature is 230°C and the print speed is 60 mm/min.	[59]
PLA	Print orientation and layer thickness	Full factorial	Tensile	Tensile strength is highly dependent on print orientation and is the highest at 0°/90° and it increases when layer thickness decreases.	[60]
PLA	Infill density number of aluminum layer and bed temperature	Taguchi	Tensile	Tensile strength is directly proportional to infill density but inversely proportional to the number of aluminum layers. Bed temperature is insignificant.	[61]

Table 1: Continued.

Material/s	Process parameter considered	Method/technique considered	Mechanical properties considered	Analysis/results	References
PLA	Printing angle, layer thickness, fill rate, and nozzle temperature	RSM	Tensile	When the printing angle is less than 45°, the failure mode of the specimens is an interlayer fracture, and when its greater than 45°, the failure mode is an intra-layer fracture. Tensile strength at break decreases with decreasing fill rate and increases with the layer thickness. But tensile strength increases as nozzle temperature raises from 195°C to 210°C and rapidly decreases as nozzle temperature raises from 210°C to 230°C.	[9]
PLA	Layer height, infill percentage, and infill pattern	RSM, CCCD	Tensile	Tensile strength greatly depends on layer thickness. The optimum setting is 0.1 mm layer thickness, 100% infill density, and hexagonal infill pattern.	[62]
PLA	Layer thickness, print orientation	GRRMSE[j]	Tensile failure	As layer thickness declines from 0.3 mm to 0.1 mm, the tensile failure strength increases for 45° and 60°.	[63]
PLA	Layer height, fill density, printing velocity, and orientation	Taguchi	Tensile	75% of infill density, 0° of orientation, 0.4 mm of layer height, and 40 mm/s velocities are the best combination to give better tensile strength.	[64]
PLA	Raster angle and moisture content	DOE	Tensile, strain, modulus of elasticity	The specimen with a 90° raster angle and 10% moisture content has the optimum mechanical strength and strain.	[65]
FR-PLA	Layer height, extrusion width, printing temperature, printing speed	FESEM[k]	Tensile	Tensile strength gradually decreases with an increase in layer height and extrusion width.	[66]
PLA, CF-PLA	Bed temperature, extrusion temperature	SEM	Tensile, flexural, shear	On-edge and flat orientations displayed the best mechanical properties. CF-PLA has the greatest tensile and flexural strength with 47.1% and 89.75% of enhancement, respectively.	[67]
PLA	Layer thickness, infill density, and print bed temperature	RSM	Tensile, impact	It shows that an infill density of 44.7%, a layer thickness of 0.44 mm, and a bed temperature of 20°C give the optimum tensile and impact strength.	[68]

[a]Differential Scanning Calorimeter, [b]Scanning Electron Microscope, [c]Thermogravimetry Analysis, [d]Carbon Fiber-Reinforced Polylactic Acid, [e]Digital Image Correlation, [f]Adaptive Neuro-Fuzzy Interface System, [g]Centered Composite Design, [h]Genetic Algorithm Artificial Neural Network, [i]The Technique for Order of Preference by Similarity to Ideal Solution, [j]Generalized-Relative Root-Mean-Square Error, and [k]Field Emission Scanning Electron Microscopy.

2.1. Tensile Strength of FDM-Printed Parts. Several studies have been conducted to determine the effect of various FDM process parameters on the tensile strength of manufactured parts using suitable process parameter configurations. From previous work, it can be said that layer thickness is the most significant parameter for the characteristics of tensile strength of FDM-printed parts. Figure 4 shows the graphical representation analysis for earlier works of literature summarized in Table 1. According to the analysis of the results in Figure 4(a), tensile strength is significantly affected by the extrusion temperature of FDM PLA-printed parts. For lower extrusion temperatures (mostly below 210°C), filament viscosity decreases which results in the waning of the adhesive bonding in between layers and at a higher temperatures, the material kept over melts which results in taking a long time to cool to have optimum viscosity, thus

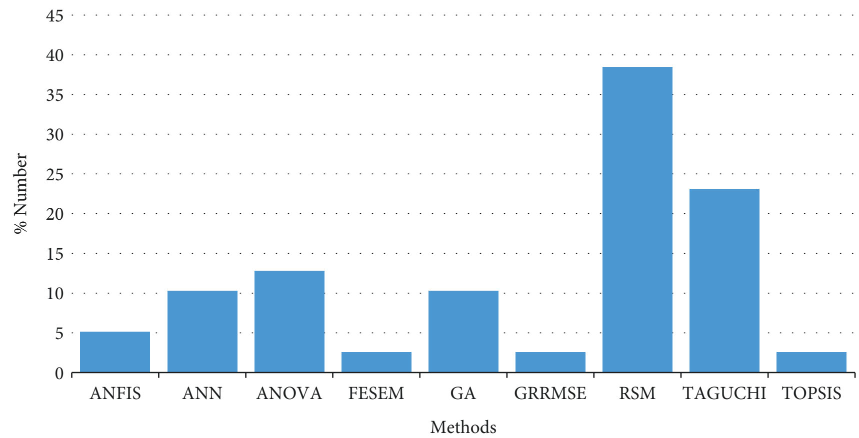

Figure 3: Overview of the methods used in the optimization of FDM process parameters.

Figure 4: Graphical representation analysis of FDM process parameter value: (a) tensile strength vs. extrusion temperature, (b) tensile strength vs. bed temperature, (c) tensile strength vs. layer thickness, (d) tensile strength vs. infill density, (e) percentage of raster angle works for 45/−45°, and 0/90°, and (f) percentage of infill pattern works for linear, grid, cubic, rectilinear, zigzag, and hexagonal structures.

influencing the degree of crystallinity [49]. Therefore, the optimum extrusion temperature can be maintained between 215°C and 225°C for better tensile properties. A better agreement is met for bed temperature (Figure 4(b)) between 60°C and 70°C to have better mechanical strength. Layer thickness is a highly significant parameter that affects the adhesive bonding strength of layers and it gives better tensile strength with decremental values but correspondingly increases the build time of the parts [69]. Thus, as shown in Figure 4(c), a 0.1 mm layer thickness takes a majority considerably with 0.2 mm for better tensile strength of printed parts where build time is not a concern. In another way, the infill density (Figure 4(d)) increases the tensile strength as the part printed with 100% but for the minimization of production time and material customization, one can use the optimum infill density of 80% [70]. Oriented parts in line with the X axis or Y axis of the build plate have better mechanical strength. On the contrary, because of more fluctuations of the result for print speed (30–125 mm/s), it is difficult to standardize based upon the works, which implies it needs more investigation.

According to the survey of the reviewed literature, the airgap parameter mostly goes flat at 0 mm, which implies most of the researchers agreed that a 0 mm air gap is optimal for any required good mechanical strength. The survey of those studies presents that the optimal result of raster width is not isolated, which needs more investigation for standardization. The results in Figures 4(e) and 4(f) represent that a 45/−45° of raster angle and rectilinear or conveniently cubic infill pattern give better mechanical strength. The dash red lines across the figures show the mean of the results.

3. Conclusion and Research GAP

In this review article, the build quality of the FDM-printed part majorly focuses on the selected parameters. The main concerns of any FDM user corresponding to the quality are the tensile strength, compressive strength, impact strength, yield strength, build time, and build cost. It can be summarized that layer thickness is the most significant parameter that influences the tensile strength of FDM-printed parts. Tensile strength is significantly affected by the extrusion temperature, raster angle, infill density, infill pattern, and print speed of FDM PLA-printed parts. However, the survey of the studies presents that the optimal result of raster width is not isolated which needs more investigation for standardization and to apply to future industrial applications. Different attempts have been made to enhance the properties of printing filaments by adding particles such as short fibers, nanoparticles, and other suitable additives. Hence, good agreement is met on those added particles in which the strongest material is formed in terms of tension, bending, and compression (with the highest modulus). Similarly, different investigations have been undertaken concerning the effect of heat/thermal and chemical treatments on the tensile strength of PLA-printed parts, such that a good agreement is met. Thus, improvement with heat treatment has the least effect, but chemical treatment has the highest effect. On the other hand, the RSM method followed by the Taguchi method implies the highest occurrence of optimization tools with better accuracy of the results and minimum error. Thus, most of the studies are based on experimental data [71, 72].

The critical findings during this review and therefore the need for further research are presented as follows:

(i) FDM applies only to thermoplastic materials and because of this most of the research on FDM is study PLA and ABS thermoplastic materials.

(ii) Certain FDM process parameters such as raster orientation/raster angle, layer thickness, infill density, extrusion temperature, and raster width are analyzed broadly over other process variables like interior infill pattern, build orientation, number of contours, etc. This leads to insufficient details to analyze and standardize the set parameters to apply to future industrial applications.

(iii) Most of the investigations concentrated on a few (even one) parameters at a time. However, in real-time production of parts using FDM 3D print, a lot of process parameters come into play to make the final products. Also, the process parameters considered in most of the investigations seem to lack. Hence, it is paramount to study the simultaneous effect of essential parameters to get better mechanical properties of FDM-printed parts.

(iv) Developing an uncertainty model to gauge and assess the uncertainty at different stages of the FDM process to rule out an error in optimizing is essential. This can include the factor of uncertainty within the optimization algorithm and uncertainty in the mathematical modeling of the FDM process.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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