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Multi Objective Optimization of Fused Deposition Modeling Process Parameters with Desirability Function

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Abstract

Today's production technologies strive hard to meet customers demand in terms of quality, quantity and cost of products. Many new technologies are coming forward with huge capabilities. Additive Manufacturing processes have an immense influence on existing production technologies. Because of their nature and freedom of manufacture, they are popular in many production plants. 3D printing is a process employed in many industrial sectors such as aircraft, cars , buildings and several medical fields to fabricate products. One of the common processes used for 3D printing of plastics and composite plastic parts is Fusing Deposition Modeling (FDM). The performance of FDM is governed by diverse process parameters that can have a great impact on cost and quality of the 3D printed parts. This article focuses on the optimization of FDM process parameters using an approach based on Desirability Function.

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Keywords: Fused Deposition Modeling; Optimization; Additive Manufacturing; Desirabilty Function

1. Introduction

The digital transformation of manufacturing involves the combination of manufacturing processes and advancing IT technologies working together to drive manufacturing forward and address inefficiencies in the current sector [1].

Additive manufacturing (AM) is a core component of the digital transformation of manufacturing as it can be viewed as a way to turn a digital model of the object to be fabricated into a physical one, starting from a (3D) software design [2].

In additive manufacturing (AM), the products are built by adding material layer by layer. It is employed in many industrial sectors, including aircraft, fuel, automotive, medical and consumer products [3]. Through AM processes, parts made of metals, plastics and composites can be produced. Many of the AM processes are utilised to manufacture various complex shapes used in a large variety of applications.

Fused Deposition Modeling (FDM) is an important AM process applied to fabricate plastic and plastic composite parts. In FDM, a plastic filament is extruded through a heated extruder and the material is deposited layer by layer through a nozzle. The nozzle moves according to codes generated by a 3D model of the object to be printed.

Figure 1 shows the steps of 3D printing by FDM. The 3D printing process starts with the creation of a 3D model of the object to be printed. After this, the model is converted into a STL file which is later sliced into a number of layers by a suitable slicing software. Finally, the parts are fabricated and cleaned according to the end part requirements [3].

As an AM process, FDM is governed by several process parameters with multiple responses. This makes it a rather complex process from point of view of analysis. Extensive research is going on to study the effect of various process parameters of FDM on the different responses involved in it.

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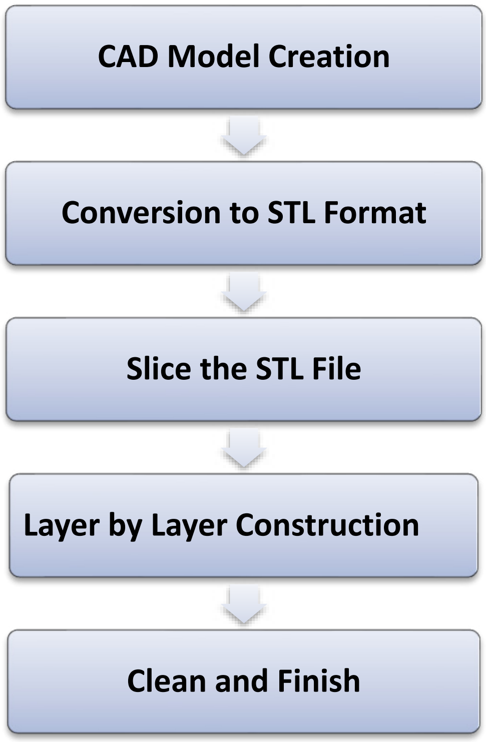

Fig. 1. Steps in 3D printing with FDM

Bahr and Westkamper [4] reported that the quality of FDM parts is greatly influenced by the material composition, the slicing and deposition procedure, and the cooling process.

According to Simon et al. [5], printing speed and material flow have an effect on particle emission rate but this effect is very small.

More work is required on FDM process parameters such as pattern and density of infill, temperature of extrusion, and number of contours [6].

Raster angle and direction of printing have a major impact on the polymer's mechanical properties. Edge position 0° layer orientation is very suitable in terms of mechanical properties for improved performance [7].

According to Mohamed et al. [8-10], a great deal of work has been attempted to improve the mechanical properties and component quality of the ABS parts produced by FDM through statistical design optimization. Their literature review shows that process parameters, including air gap, layer thickness, raster angle, raster width and construction orientations, are the critical factors and must be studied and thoroughly analyzed.

The current status of analysis of FDM indicates that there is a need to develop optimization paradigms for FDM process parameters which will help the FDM community to select the optimum process parameters for best performance of FDM.

This paper demonstrates the use of Desirability Function for Multi Objective Optimization of FDM process parameters.

2. Set up Details

2.1 Printing Details

A 3D Printer with machine size (400*450*450) mm, build size (300*300*300) mm (L*W*H) and nozzle diameter 0.4 mm is used for printing the components.

The components consist of cam levers used for adjustment and locking purposes. These components are manufactured with PLA filaments of 1.75 mm diameter.

2.2 Process Parameters

For the optimization procedure, three important FDM governing process parameters, namely layer thickness, infill % and speed, are selected. To optimize the above process parameters, printing time, length of filament consumed and weight of product are selected as responses.

Table 1 shows the process parameters and their levels. A L_{16} Taguchi array with three fac tors, each with four levels, is used for design of experiment. Table 2 shows the L_{16} array with the measured responses. Fig. 2 shows the components manufactured using this array.

Table 1. Process Parameters and Their Levels

Parameters	**Level 1**	**Level 2**	**Level 3**	**Level 4**
Layer Thickness	0.15	0.2	0.25	0.3
Speed	70	80	90	100
Infill Percentage	55	65	75	85

Fig. 2. Cam Levers Manufactured by FDM

3. Optimization Using Desirability Function

First, the Desirability Function approach transforms the estimated responses to a scale-free value (di), called desirability, to increase the quality characteristic (yi). Desirability (di) is a value between 0 and 1 and increases with increasing desirability of the corresponding response.

The desirability of individuals is combined into an overall desirability value D [11]. In what follows, the equations used to solve optimization problems with desirability are reported.

Table 2. L_{16} Array with Measured Responses

Layer thickness (mm)	Speed (mm /sec)	Infill (%)	Time (Min)	Weight of Product (gm)	Filament length (meter)
0.15	70	55	37	5.98	2.14
0.15	80	65	36	7.12	2.23
0.15	90	75	36	7.09	2.31
0.15	100	85	35	6.95	2.4
0.2	70	65	31	7.21	2.2
0.2	80	55	28	5.69	2.11
0.2	90	85	30	7.02	2.38
0.2	100	75	28	7	2.29
0.25	70	75	28	6.89	2.3
0.25	80	85	27	7.15	2.38
0.25	90	55	23	5.99	2.13
0.25	100	65	23	7.03	2.21
0.3	70	85	26	7.02	2.37
0.3	80	75	23	7.11	2.29
0.3	90	65	21	6.88	2.21
0.3	100	55	20	6	2.13

The goals of any optimization are to maximize, minimize or target a response to find out the optimal processing parameters. In desirability, the goals can be calculated as [11, 12].

I. Maximize the Response Desirability

$di = 0$ if $yi < Li$

$di = ((yi - Li)/(Ti - Li))ri$ if $Li \leqslant yi \leqslant Ti$

$di = 1$ if $yi > Ti$

II. Minimize the Response Desirability

$di = 0$ if $yi > Ui$

$di = ((Ui - yi)/(Ui - Ti))ri$ if $Ti \leqslant yi \leqslant Ui$

$di = 1$ if $yi < Ti$

III. Target the Response Desirability

$di = ((yi - Li)/(Ti - Li))ri$ if $Li \leqslant yi \leqslant Ti$

$di = ((Ui - yi)/(Ui - Ti))ri$ if $Ti \leqslant yi \leqslant Ui$

$di = 0$ if $yi < Li$

$di = 0$ if $yi > Ui$

If the importance is the same for each response, the composite desirability can be computed as:

$$D = (d1 \times d2 \times d3 \times \ldots\ldots \times dn)^{1/n}$$

where:

Di = Desirability for individual responses
D = Composite desirability
n = Total number of responses
yi = Predicted value of response under consideration
Ti = Target value of response under consideration
Li = Lowest value of response under consideration
Ui = Highest value of response under consideration

Based on process parameters and responses in this investigation, and optimization paradigm based on Desirability Function is applied using the Minitab 17 software. The following goals are defined for the various responses for optimization. All the responses are to be minimized. Therefore, targets for optimization are set for the lowest values of these responses. The weights assigned to the responses are: Time = 0.5, Weight = 0.25 and Length = 0.25. For simplicity, an optimization problem with same importance is assigned to all the responses, i.e. 1. Table 3 shows the optimization problem details.

Based on equations of desirability, a composite desirability for each option is calculated. The preference is given to the highest desirability. The remaining preferences are arranged according to their ranks based on desirability values. Based on composite desirability values, the ranks are provided for different options. The optimization plot shown in Fig. 3 is generated based on process parameter settings and goals of optimization. Table 4 shows the ranks of different options. The first rank, which is the best option for process parameters, is: 0.3 mm layer thickness, 100 mm/sec speed and 55 % infill. The last rank is: 0.15 mm layer thickness, 90 mm/sec speed and 75 % infill. The composite desirability for the first rank is 0.9660 and the one for the last rank is 0.0000.

Table 3. Optimization Goals

Response	**Goal**	**Target**	**Upper**	**Weight**	**Importance**
Filament length (m)	Minimize	2.11	2.40	0.25	1
Weight of Product (g)	Minimize	5.69	7.21	0.25	1
Time (min)	Minimize	20.00	37.00	0.5	1

Table 4. Composite Desirability and Ranks

Layer thickness (mm)	Speed (mm/s)	Infill (%)	**Composite Desirability (D)**	**Ranks**
0.15	70	55	0.4864	13
0.15	80	65	0.4845	14
0.15	90	75	0.0000	16
0.15	100	85	0.4287	15
0.2	70	65	0.7037	6
0.2	80	55	0.8847	3
0.2	90	85	0.5564	12
0.2	100	75	0.6417	9
0.25	70	75	0.5772	11
0.25	80	85	0.5969	10
0.25	90	55	0.9599	2
0.25	100	65	0.8217	5
0.3	70	85	0.6589	8
0.3	80	75	0.6967	7
0.3	90	65	0.8461	4
0.3	100	55	0.9660	1

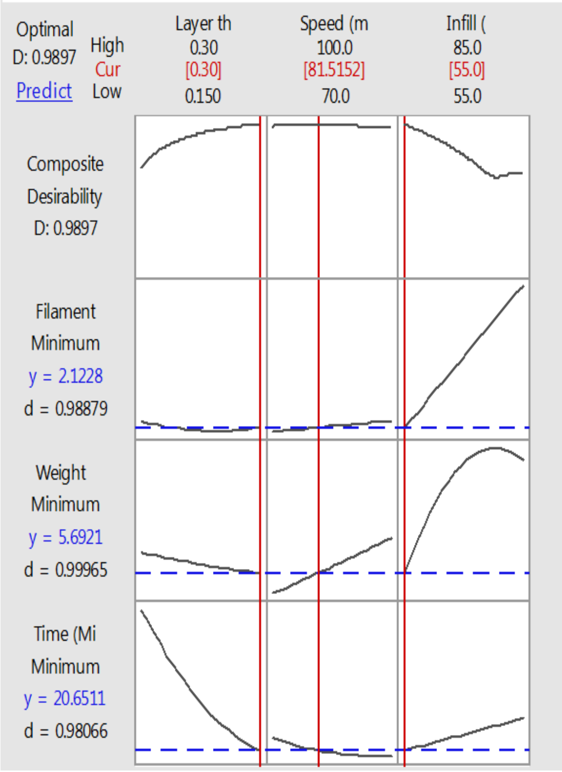

Fig.3 Optimization Plot

Once the optimization is completed, the optimized process parameters found are: Layer thickness = 0.3 mm, Speed = 81.5152 mm/s and Infill % = 55. This is shown in red colour in the optimization plot. For these optimum parameters, the responses are: filament length consumed = 2.12 m, weight of component = 5.69 g, time required for printing = 20.65 min.

The composite desirability for optimum parameters is equal to 0.9897 and that for first rank is equal to 0.9660. Therefore, a significant improvement in composite desirability is found for the optimum parameters. The improvement of 2.45 % in composite desirability as compared to the best rank from the array of L_{16}. With optimized process parameters, the individual desirabilties of responses can be also found from the optimization plot. Desirability for time for printing is 0.9806 with the time of 20.65 minutes. Desirability for length of filament consumed is 0.9887 with a length of 2.12 m. Desirability for weight of product is 0.9996 with weight equal to 5.69 g.

To confirm the predicted values of the responses using optimum process parameters, confirmation experiments are carried out with optimized settings of layer thickness equal to 0.3 mm, speed equal to 81.5152 mm/sec and infill % equal to 55 %. For these optimum parameters, the actual responses are filament length consumed equal to 2.10 m, weight of component equal to 5.68 g, time required for printing equal to 20.01 min. Thus, the match between predicted and actual responses is quite good and this indicates the suitability of Desirability Function for the optimization of processes involving multiple responses.

4. Conclusions

Based on the obtained results, the following conclusions can be drawn.

1. The Desirability Function approach is a very useful technique to optimize process parameters for manufacturing processes with multiple responses.
2. For the FDM process under investigation, the optimum parameters are Layer thickness = 0.3 mm, Speed = 81.5152 mm/sec, and Infill % = 55 %.
3. For these optimum parameters, the predicted responses are: filament length consumed = 2.12 m, weight of component = 5.69 g, and time required for printing = 20.65 min.
4. For these optimum parameters, the actual responses are: filament length consumed = 2.10 m, weight of component = 5.68 g, time required for printing = 20.01 min.

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