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Optimization of Build Time and Model Volume for A FDM Maxum Modeler Using Response Surface Methodology

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Abstract - **Layout optimization is one of the key issues in optimization of any RP Process. Layout optimization for the FDM Maxum modeler is attempted by deriving, analyzing and validating models for build time and model material using response surface methodology technique. The exact relationship between the various crucial process parameters viz. contour width, orientation about particular axis, raster angle and air gap for estimation of build time and model volume are established. Also, the effect of various spatial orientations on the build time and model material volume has been observed and analyzed. This work makes a maiden attempt in the direction of actual spatial visualizations for response estimations of a FDM modeler.**

Keywords - Layout optimization, Build time, Model volume, Contour width, Orientation, Air gap, Raster angle, Response surface methodology

1. INTRODUCTION

Layered manufacturing (LM) offers numerous advancements over the conventional manufacturing processes for prototyping purpose. Qualitative and quantitative optimization of layered manufacturing processes has been a subject of great interest to the researchers. Optimization of build time, support volume, model volume and production cost are the key aspects of quantitative optimization whereas qualitative optimization encompasses optimization of surface quality, dimensional accuracy and mechanical properties. Models have been derived and analyzed for basic conical primitives of Constructive Solid Geometry (CSG) using the Response surface methodology technique for a FDM maxum modeler.[8-9]

This work exhaustively evaluates the effect of contour width, raster angle, orientation and air gap on the build time and model volume requirements for conical primitives. It also establishes basic design principles for evaluation of different spatial orientations for build time and model volume optimization for FDM maxum modeler in particular and FDM process in general.

This paper proposes a novel method of estimation and optimization of build time and model volume requirements for different feasible orientations at the design stage itself using RSM and its corresponding validation. These estimates combined with support material and production cost estimations can be very useful in the overall quantitative optimization of the given FDM process.

2. LITERATURE REVIEW

The driving force in the global market is the advancement in manufacturing processes. New and innovative technologies have been discovered to fabricate products. LM is an advanced manufacturing technique whose success is based on optimal process parameters and technique selection for the desired end results which vary with the end user priorities. Optimization of build time and model volume can go a long way in enhancing the quantitative effectiveness of any layered manufacturing (LM) process. The aim of this study is to understand the dependence of build time and model material on different process parameters and to arrive at optimum part orientation in FDM process. [8-9]

Espalin et al. [3] investigated build process variation for FDM in making contours and rasters using variable layer thicknesses and road widths and evaluated its effect on surface roughness, production times and mechanical properties. They used this to develop a unique FDM process which enabled multiple material depositions (F.G.M.). Vilalpando et al.[2] proposed a method to create reconfigurable internal structure to balance mechanical properties, material usage and build time. A. Sheriff El-Gizawy et al. [2] used polyeterimide (ULTEM 9085) with FDM and characterized the mechanical properties and internal structure evolved using classical lamination theory. Panda et al.[7] considered the effect of five important process parameters viz. layer thickness, orientation, raster angle, raster width and air gap on tensile, flexural and impact strength using central composite design and empirical model development.

After validation using ANOVA theoretical parameter settings to simultaneously affect all three response optimization are suggested [4, 7, 10]. Jacobs [4] gave some basic guidelines for best orientation for part build which are still followed. Choi et al. [1] proposed a virtual reality system for modeling and optimization of RP processes and by building a mathematical model for build-time estimation in SLS systems. Zhe [15] presented relationships between the build orientation and the maximum stress, maximum strain, and young's modulus for SLS, FDM and Objet (SLA), decision criteria for selecting the best orientation of the minimum strain and maximum external load through case studies. Mishra et al. have also reviewed the build orientations for different RP processes [6].

Model material and build time estimation is one of the critical responses in the quantitative optimization of the LM processes. A number of researchers have carried work in improving the effectiveness and efficiency of FDM processes. A lot of work has been done in the direction of qualitative improvements. However, from detailed literature review it can be easily concluded that there are research gaps in the quantitative aspect of the FDM process optimization. This work makes an attempt in the direction of quantitative layout optimization by optimizing the model material volume and build time requirements for FDM process. .

3. RESPONSES

3.1) Build Time: Contrary to the common belief that reducing the machine time or the actual component manufacturing time, also called build time, the total time involved is called process time. However for the ease of estimation we can very safely assume build time to be one of the best indicators of the process time. We can very safely say that decreasing the build time would definitely contribute to reducing the overall process time. Build time is a critical factor for optimization of any LM technique. Build time is the time a part spends on a machine during its creation assuming no bottlenecks. Though build time is frequently used measure of process time/process speed, yet these two terms are not the same. Process time give an indication of the overall product completion time. Several factors need attention for the process time evaluation. These mainly include: model preparation, file generation, system preparation, part build time, post build operations and post processing operations. [3][8-9]

3.2) Model Material Volume: The model volume is the amount of model material required for the model manufacture. FDM Maxum uses Acrylobutadienestyrene (ABS). Though it would vary with the prototype requirements of the end user but in general an efficient designer would always try to optimize its quantity for prototype production.

4. EXPERIMENTAL DESIGN

Experiments were carried on Insightv9.1 for FDM Maxum modeler. Based on previous experimentations and trial experimental designs, the parameters listed in Table 1 are kept fixed during entire experimentation and the machine parameters listed in Table 2 are treated as process parameters. The design methodology adopted was response surface methodology. The scheme of experimentation followed to evaluate the effect of spatial orientation is given in table 3. The RSM table used is a 30 run full factorial design table for 4 process parameters and is given in table 4 and Table 6 for build time and model material volume respectively. Tables 5 and 7 respectively give the RSM model specifications derived for the build time and model material volume respectively

Two responses build time and model material volumes are evaluated in all possible orientations of given build volume of the modeler. The experiment is designed using RSM and models corresponding to different orientations, i.e., rotations about different axis (x- axis, Y- axis, Z-axis, x- axis with minimum Z height and Y-axis with minimum Z-height) are derived. The graphs corresponding to them are plotted and compared for all the other spatial orientations for the same component and the optimal conditions are concluded.

Table 1: Fixed Parameters

Contour and Raster Air Gap	0.0000
Raster Fill Control	Start Angle
Part Fill Style	Perimeter/Rasters
Part Interior Style	Solid-Normal
Visible Surface	Normal Rasters
Support Style	Sparse
Part Material	ABS P400
Slice Height	0.1778
Support Material	Soluble P400 SR
Nozzle	T12

Table 2: Process Parameters and their Levels

	PARMETERS	LEVEL 1	LEVEL 2	LEVEL 3
1	Contour Width (A)	0.4290	0.5415	0.6540
2	Orientation (D)	0	15	30
3	Raster Angle (E)	0	15	30
4	Air Gap (F)	-0.0254	0	0.0254

Table 3: Scheme of Experimentation

Response		**Spatial Rotation about**				
Type	**Primitive**	**x axis(θx)**	**Y-axis(θy)**	**z axis(θz)**	**y with min z (θxz)**	**y with min z (θyz)**
Build Time	Cone	B.T.1	B.T.2	B.T.3	B.T.4	B.T.5
Model Material Volume	Cone	M.V.1	M.V.2	M.V.3	M.V.4	M.V.5

Table 4: Variation of Build time with different spatial orientations for FDM Maximum

		Factor 1	Factor 2	Factor 3	Factor 4	Response 1,B.T. 4 Θx	Response 1,B.T. 4 θy	Response 1,B.T. 4 θz	Response 1,B.T. 4 θxz	Response 1 ,B.T. 4 θyz
Std	Run	A:contour width	B:air gap	C:raster angle	D:orientation	Build time	Build time	Build time	Build time	Build time
		mm	mm	deg	deg	Hours	hours	hours	hours	hours
18	1	0.654	0	15	15	2.2	2.217	2.067	1.15	1.533
20	2	0.5415	0.0254	15	15	2.2	2.217	2.067	1.133	1.517
7	3	0.429	0.0254	30	0	2.067	2.067	2.067	1.283	1.283
10	4	0.654	-0.0254	0	30	2.25	2.25	2.083	1.133	2.1
29	5	0.5415	0	15	15	2.2	2.217	2.083	1.167	1.55
16	6	0.654	0.0254	30	30	2.233	2.217	2.05	1.267	2.2
3	7	0.429	0.0254	0	0	2.083	2.083	2.083	1.1	1.1
15	8	0.429	0.0254	30	30	2.233	2.233	2.067	1.283	2.233
8	9	0.654	0.0254	30	0	2.05	2.05	2.05	1.267	1.25
23	10	0.5415	0	15	0	2.083	2.083	2.083	1.167	1.15
6	11	0.654	-0.0254	30	0	2.1	2.1	2.1	1.317	1.317
11	12	0.429	0.0254	0	30	2.217	2.217	2.067	1.1	2.083
12	13	0.654	0.0254	0	30	2.217	2.2	2.05	1.083	2.05
1	14	0.429	-0.0254	0	0	2.1	2.1	2.1	1.15	1.15
22	15	0.5415	0	30	15	2.217	2.233	2.083	1.3	1.583
9	16	0.429	-0.0254	0	30	2.267	2.267	2.12	1.15	2.133
19	17	0.5415	-0.0254	15	15	2.233	2.233	2.1	1.183	1.6
21	18	0.5415	0	0	15	2.2	2.217	2.083	1.1	1.533
13	19	0.429	-0.0254	30	30	2.283	2.283	2.1	1.35	2.3
2	20	0.654	-0.0254	0	0	2.083	2.083	2.083	1.133	1.133
26	21	0.5415	0	15	15	2.2	2.217	2.083	1.167	1.55
30	22	0.5415	0	15	15	2.2	2.217	2.083	1.167	1.55
24	23	0.5415	0	15	30	2.233	2.25	2.083	1.167	2.15
14	24	0.654	-0.0254	30	30	2.267	2.25	2.083	1.317	2.267
28	25	0.5415	0	15	15	2.2	2.217	2.083	1.167	1.55
5	26	0.429	-0.0254	30	0	2.12	2.12	2.12	1.35	1.35
25	27	0.5415	0	15	15	2.2	2.233	2.083	1.167	1.55
17	28	0.429	0	15	15	2.2	2.217	2.1	1.167	1.567

4	29	0.654	0.0254	0	0	2.05	2.05	2.05	1.083	1.083
27	30	0.5415	0	15	15	2.2	2.217	2.083	1.167	1.55

Table 5: Build Time RSM Model Specifications for different orientations

Orientation	Transform	Lambda	Process order	Pure err	Pred R-Square	Adjusted R-Squared	F-value	Model
x axis(θx)	Power	2.08	Modified	0	0.9825	0.9883	407.83	Significant
Y-axis(θy)	Power	3	Quadratic	0	0.9538	0.9838	119.49	Significant
z axis(θz)	Power	-3	Linear	0	0.8431	0.8937	61.97	Significant
x with min z (θxz)	Power	0.97	Quadratic	0	0.9918	0.9962	549.96	Significant
y with min z (θyz)	Power	1.21	Modified	0	0.9968	0.9975	1961.38	Significant

Table 6: Variation of Model material requirements with different spatial orientations for FDM Maximum

	Factor 1	Factor 2	Factor 3	Factor 4	Response 2 (ONLY X)	Response 2 (ONLY Y)	Response 2 (ONLY Z)	Response 2 (ONLY X Min Z)	Response 2 (ONLY Y Min Z)
Run	A:contour width	B:air gap	C:raster angle	D:orientation	Model material	Model material	Model material	Model material	Model material
	mm	mm	deg	deg	cc	cc	cc	cc	cc
1	0.654	0	15	15	7.515	7.515	7.486	7.668	7.659
2	0.5415	0.0254	15	15	7.122	7.12	7.091	7.253	7.251
3	0.429	0.0254	30	0	7.078	7.078	7.078	7.256	7.256
4	0.654	-0.0254	0	30	7.948	7.948	7.928	8.121	8.072
5	0.5415	0	15	15	7.517	7.517	7.486	7.664	7.658
6	0.654	0.0254	30	30	7.132	7.132	7.104	7.279	7.264
7	0.429	0.0254	0	0	7.078	7.078	7.078	7.241	7.241
8	0.429	0.0254	30	30	7.104	7.102	7.076	7.255	7.238
9	0.654	0.0254	30	0	7.104	7.104	7.104	7.282	7.281
10	0.5415	0	15	0	7.486	7.486	7.486	7.663	7.255
11	0.654	-0.0254	30	0	7.926	7.926	7.926	8.144	8.144
12	0.429	0.0254	0	30	7.092	7.094	7.078	7.241	7.212
13	0.654	0.0254	0	30	7.125	7.125	7.105	7.264	7.24
14	0.429	-0.0254	0	0	7.961	7.961	7.961	8.149	8.151
15	0.5415	0	30	15	7.517	7.517	7.486	7.682	7.674
16	0.429	-0.0254	0	30	7.981	7.982	7.962	8.149	8.12
17	0.5415	-0.0254	15	15	7.971	7.971	7.943	8.139	8.128
18	0.5415	0	0	15	7.513	7.513	7.486	7.666	7.628
19	0.429	-0.0254	30	30	7.987	7.987	7.959	8.172	8.138
20	0.654	-0.0254	0	0	7.928	7.928	7.928	8.121	8.12
21	0.5415	0	15	15	7.517	7.517	7.486	7.664	7.658
22	0.5415	0	15	15	7.517	7.517	7.486	7.664	7.658
23	0.5415	0	15	30	7.513	7.513	7.486	7.666	7.64

24	0.654	-0.0254	30	30	7.953	7.953	7.926	8.141	8.108
25	0.5415	0	15	15	7.517	7.517	7.486	7.664	7.658
26	0.429	-0.0254	30	0	7.961	7.961	7.961	8.171	8.172
27	0.5415	0	15	15	7.517	7.513	7.486	7.664	7.658
28	0.429	0	15	15	7.517	7.517	7.487	7.666	7.658
29	0.654	0.0254	0	0	7.105	7.105	7.105	7.266	7.266
30	0.5415	0	15	15	7.517	7.517	7.486	7.664	7.658

Table 7: Model Material volume RSM Model Specifications for different orientations

Orientation	Transform	Lambda	Process order	Pure err	Pred R-Square	Adjusted R-Squared	f-value	Model
x axis(θx)	Power	2.69	Modified	0	1	1	1.93E+05	Significant
Y-axis(θy)	Power	1.9	Modified	0	1	1	1.93E+05	Significant
z axis(θz)	Power	-0.47	Modified	0	1	1	2.24E+06	Significant
x with min z (θxz)	Power	-1.96	Modified	0	1	1	3.20E+05	Significant
y with min z (θyz)	Power	2.31	Quadratic	0	0.8966	0.9611	52.17	Significant

RSM model details are tabulated in Table 5 and 7.The model are found to be significant with relevant f- and p-values. All the residuals are clustered in the straight line implying that errors are normally distributed for the normal plot of residuals. In all the plots of actual vs predicted model values. the points are clustered around a straight line indicating that the predicted value are in close adherence to the actual values.

Figures 1-8 denote the variation of build-time model volume w.r.t. changes in contour width, air gap, raster angle and orientation respectively.

5. RESULTS AND DISCUSSIONS

Convulsive to the model formation for C1PS1, models have been made for every component corresponding to all parameter settings by experimental observation and modeling. The same have been analyzed and the following conclusions have been drawn:

5.1 **Effect of each individual parameter:** It is established by this experimentation that the build time slightly decreases with the increasing contour width, decreases with increasing air gap, increases slightly with increase in raster angle and shows considerable increase with increase in angle of orientation w.r.t. a given axis.
Again, model material volume slightly increases with the increasing contour width, decreases with increasing air gap, decreases slightly with increase in raster angle and shows fluctuating behavior with increase in angle of orientation w.r.t. a given axis.

5.2 **Best spatial Orientation:** It is observed from the data and the corresponding graphs obtained from the RSM models that for conical primitives the least build time corresponds to the rotation about x- axis keeping minimum z- height. This is followed by the orientations about y axis keeping minimum z- height, rotation about z- axis, rotation about x-axis and the maximum time is obtained corresponding to the rotation about y axis.

Again the least model volume corresponds to the rotation about z- axis. This is followed by the orientations about y axis, rotation about x- axis , rotation about y-axis keeping minimum z- height and the maximum model material required corresponds to the rotation about x axis keeping minimum z- height.

The graphs demonstrating effects of change in the parameters and the spatial orientation for all components as per technique of experimentation are plotted and presented.

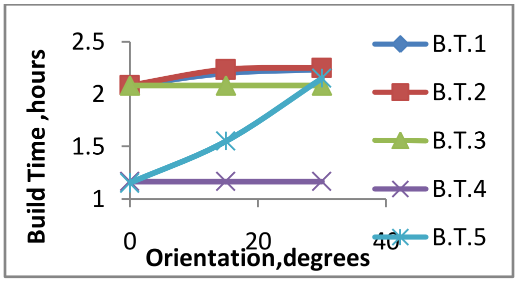


Figure 1: B.T. variation with Orientation

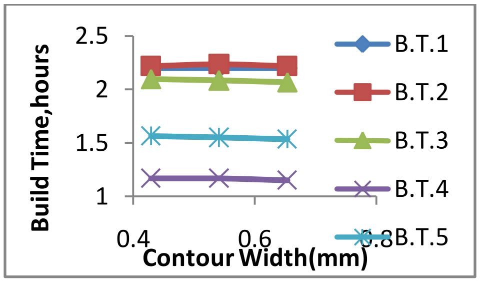


Figure 2: B.T. variation with contour width

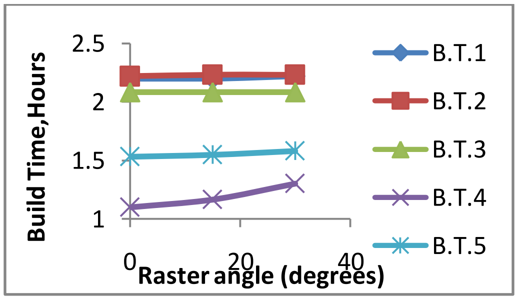


Figure 3: B.T. variation with raster angle

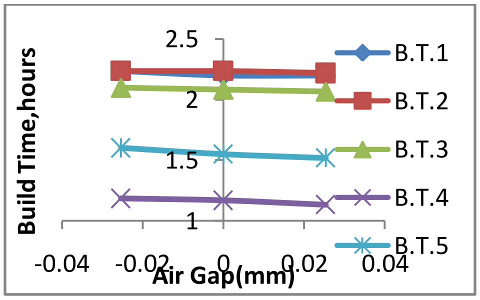


Figure 4: B.T. variation with air gap

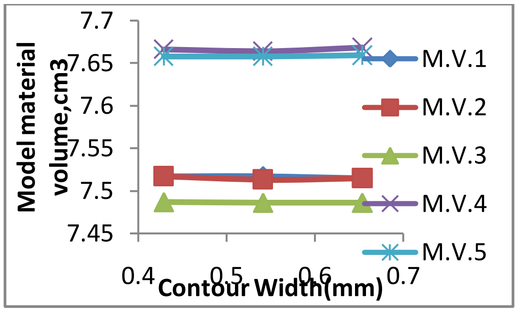


Figure 5: M.M variation with contour width

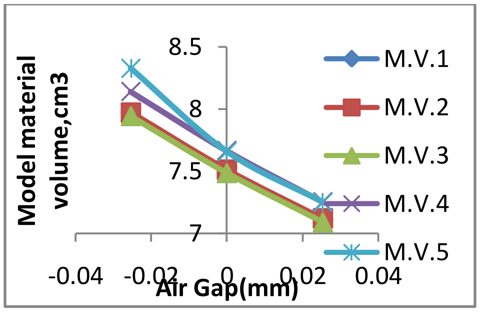
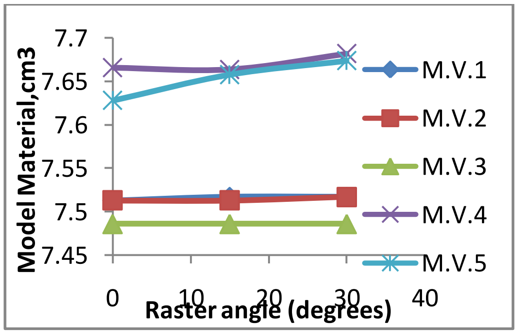


Figure 6: M.M variation with air gap



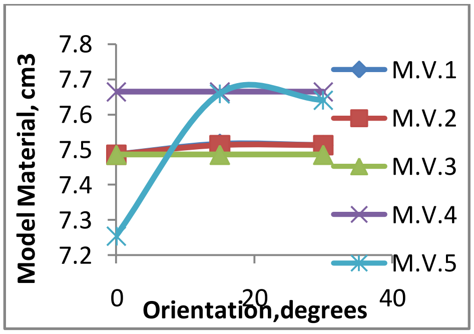


Figure 7: M.M variation with raster angle **Figure 8: M.M variation with orientation**

Conclusions: This work experimentally builds models for relationship between build time and model material volume required with contour width, air gap, raster angle and angle of orientation. It demonstrates how the build time and model material requirements vary with variation in the orientation technique for conical primitives for a FDM maxum modeler.

This work can be easily extended to multi objective process optimization using GRA or Fuzzy logic or any other suitable multi objective optimization technique.

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