Experimental Evaluation of FDM Process for Production Cost Optimization

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Abstract

Optimization of production cost is the ultimate objective for any effort in the direction of quantitative effectiveness improvement of any layered manufacturing (LM) process. This work exhaustively evaluates the effect of various process parameters including contour width, raster width, raster angle, slice height, orientation and air gap on the production cost requirements for basic constructive solid geometry (CSG) primitives. Models have been derived and evaluated analytically and graphically using response surface methodology (RSM) technique to deduce the effect of aforementioned parameters on the production cost estimation for a Fortus 250mc modeler. This work: (i) establishes relationship between support volume, model material volume, build time and production cost for a Fortus 250mc modeler (ii) establishes basic design principles for production cost estimation in a given build volume (iii) evaluates different spatial requirements for production cost estimation for Fortus 250 mc modeler in particular and FDM process in general.

Keywords

Production cost, Model volume, Support volume, Build time, Contour width, Raster width, Air gap, Raster angle, Orientation, Slice height, Layout optimization.

I. Introduction

Rapid prototyping (RP) is the most promising emerging engineering trend. Optimization of layout for RP processes can go a long way in increasing the worth and effectiveness of any RP process. This encompasses two aspects:

A. Quantitative Aspect

Optimization of build time, support volume, model volume and production cost.

B. Qualitative Aspect

Optimization of surface quality, dimensional accuracy and mechanical properties.

Production cost models have been derived and analyzed for seven basic CSG primitives used in CSG including Sphere, Cylinder, Cube, Prism, Pyramid, Cuboid and Cone based on the understanding that rest of the components can be arrived at by applying Boolean operations on these primitives.

This paper proposes a novel method of optimization and evaluation of production cost with a view to achieve quantitative optimization for different feasible orientations subject to different process parameter levels at the design stage itself by virtue of model estimation using RSM and its corresponding validation. These estimates combined with build time, support material and model material estimations can be used for overall quantitative optimization of the FDM process.

II. Literature Review

RP is an advanced manufacturing technique whose success is based on optimal process parameters and technique selection for the desired end results which vary with user priorities. The aim of this study is to understand the dependence of production cost on different process parameters and to arrive at optimum part orientation for production cost in FDM process.

Zhang et al.[2] presented layout optimization using simulated annealing techniques for solid ground curing process and illustration the effectiveness of system developed using various examples. Dani et al.[1] proposed a methodology for selection of optimal part orientation for the connecting rod by considering parameters support volume, production cost, build time and model material volume. Nezhad et al. [3] presented a Pareto Based Optimization Algorithm to determine the best part orientation in Stereolithography systems. The objective functions are minimum build time and minimum support volume under desired surface finish. The optimization is done using Genetic Algorithm (GA). At each GA step, the surface finish is achieved applying adaptive layer thickness method.

The algorithm is developed by MATLAB. The codes are run for some case studies. Espalin et al. [4] 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.[5] proposed a method to create reconfigurable internal structure to balance mechanical properties, material usage and build time. A. Sheriff El-Gizawy et al. [6] 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. Jacobs [8] gave some basic guidelines for best orientation for part build which are still followed. Choi et al. [9] 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 [10] 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. [11] have also reviewed the build orientations for different RP processes.

Minimization of production cost is the ultimate objective for the quantitative optimization of any RP process. A little work has been done in the direction of overall production cost estimation. This paper makes a maiden attempt to present the production cost as a function of support volume, build time, model material for a Fortus 250 mc modeler. Models have been derived and analyzed for production cost estimation in the current study.

III. Production Cost

Production cost for any component made on Fortus 250mc modeler is a total of three distinct components:
(i) Machine Cost = (Machine cost + Labor cost+ Running cost+ Annual Maintenance cost) per hour X Build time
(ii) Support material cost = (Cost of support material spool / Volume of material per spool) X Volume of Support material used
(iii) Model material cost (Cost of model material spool / Volume of material per spool) X Volume of model material used
On detailed discussion with Design Tech engineers (suppliers of FDM systems to NSIT) and the Stratasys experts, the above equations can be rewritten as:
(i) Machine Cost = 150 X Build time (in rupees)
(ii) Support material cost = 17 X Volume of Support material used (in rupees)
(iii) Model material cost = 17.6 X Volume of model material used (in rupees)
(iv) Production cost = (i) + (ii) + (iii)

IV. Experimental Design

1. Modeler: We have carried out our experiments on Insightv9.1 for Fortus 250 mc modeler.
2. Fixed parameters: Based on previous experimentations and trial experimental designs, we rounded upon following parameters as the fixed parameters [Table 1].
3. Process parameters: Based upon trial experimentations and the work of previous researchers, we concluded that the following machine parameters can be taken as the process parameters for optimization of production cost [Table 2].

Table 1: Fixed Parameters

S.No.	Parameter	Comments
i.	Part interior style	Solid normal
ii.	Visible surface style	Normal
iii.	Support style	Sparse
iv.	Model Material	ABS P430
v.	Support Material	ABS SR30
vi.	Part fill style	one contour/rasters
vii.	Part X Shrink Factor	1.007
viii.	Part Y shrink factor	1.007
ix.	Contour to raster air gap	0
x.	support style	Sparse
xi.	Support self supporting angle	50
xii.	Contour base oversize	1.27
xiii.	Contour base layers	8
xiv.	Invert material	yes
xv.	Support tip	T16

Table 2 : Process Parameters

S.No.	Parameters	Level 1	Level 2	Level 3
1	Slice height(mm)	0.1778	0.254	0.3302
2	Contour width(mm)	0.4	0.48	0.56
3	Air gap(mm)	-0.1	0.4	0.9
4	Raster width(mm)	0.4	0.48	0.56
5	Raster angle(degrees)	0	15	30
6	Orientation(degrees)	0	15	30

d. Design Methodology: The design methodology adopted was response surface methodology (RSM). The RSM table that was used was a 86 run table full factorial design table for 6 process parameters and is given in table 4.The scheme of experimentation followed to evaluate the effect of spatial orientation is given in Table 3.

Table 3: Scheme of Experimentation

Primitive		Spatial Rotation about				
		x axis(θx)	Y-axis(θy)	z axis(θz)	y with min z (θxz)	y with min z (θyz)
S.No.	Type					
1	Cylinder	C1PS3	C1PS4	C1PS5	C1PS1	C1PS2
2	Cone	C2PS1	C2PS2	C2PS3	C2PS4	C2PS5
3	Cube	C3PS1	C3PS2	C3PS3	C3PS4	C3PS5
4	Sphere	C4PS1	C4PS2	C4PS3	C4PS4	C4PS5
5	Cuboid	C5PS1	C5PS2	C5PS3	C5PS4	C5PS5
6	Pyramid	C6PS1	C6PS2	C6PS3	C6PS4	C6PS5
7	Prism	C7PS3	C7PS4	C7PS5	C7PS1	C7PS2

Note: CnPSm implies the evaluations for nth component at mth spatial orientation (1-5)

V. Response

Three responses namely build time, model volume and support volume are obtained and used for production cost estimation in all possible orientations in the given build volume of the modeler with respect to six different process parameters. The experiment has been designed using response surface methodology and models corresponding to each parameter setting (CnPSm) have been derived. The graphs of these settings are made and compared for all the other parameter settings for the same component and the optimal conditions are concluded.

VI. Results

The model obtained using RSM for C1PS1 (cylinder with absolute rotation about x-axis keeping minimum z-height) is discussed.
Cylinder with absolute rotation about x-axis keeping minimum Z height, C1PS1:

Std	**Run**	**Factor 1 A: Slice Height**	**Factor 2 B: Counter..mm**	**Factor 3 C Air Gap in mm**	**Factor 4 D: Raster in mm**	**Factor 5 E: Raster a... degrees**	**Factor 6 F: Orientation degrees**	**Production cost in rupees**
13	1	0.1778	0.4	0.9	0.56	0	0	345.212
27	2	0.1778	0.56	-0.1	0.56	30	0	801.819
72	3	0.254	0.48	0.4	0.56	15	15	524.868
30	4	0.3302	0.4	0.9	0.56	30	0	306.592
60	5	0.3302	0.56	-0.1	0.56	30	30	831.821
53	6	0.1778	0.4	0.9	0.4	30	30	645.309
28	7	0.3302	0.56	-0.1	0.56	30	0	643.904
9	8	0.1778	0.4	-0.1	0.56	0	0	758.169
11	9	0.1778	0.56	-0.1	0.56	0	0	754.931
61	10	0.1778	0.4	0.9	0.56	30	30	667.241
39	11	0.1778	0.56	0.9	0.4	0	30	650.743
45	12	0.1778	0.4	0.9	0.56	0	30	666.537
38	13	0.3302	0.4	0.9	0.4	0	30	477.787
84	14	0.254	0.48	0.4	0.48	15	15	525.265
52	15	0.3302	0.56	-0.1	0.4	30	30	922.664
82	16	0.254	0.48	0.4	0.48	15	15	525.265
19	17	0.1778	0.56	-0.1	0.4	30	0	951.136
69	18	0.254	0.48	-0.1	0.48	15	15	865.604
43	19	0.1778	0.56	-0.1	0.56	0	30	1091.86
73	20	0.254	0.48	0.4	0.48	0	15	522.486
46	21	0.3302	0.4	0.9	0.56	0	30	501.483
5	22	0.1778	0.4	0.9	0.48	0	0	316.227
34	23	0.3302	0.4	-0.1	0.4	0	30	950.359
20	24	0.3302	0.56	-0.1	0.4	30	0	734.441
48	25	0.3302	0.56	0.9	0.56	0	30	483.14
41	26	0.1778	0.4	-0.1	0.56	0	30	1101.32
26	27	0.3302	0.4	-0.1	0.56	30	0	666.8
21	28	0.1778	0.4	0.9	0.4	30	0	340.206
1	29	0.1778	0.4	-0.1	0.4	0	0	901.186
32	30	0.3302	0.56	0.9	0.56	30	0	293.83
79	31	0.2540	0.48	0.4	0.48	15	15	525.265
37	32	0.1778	0.4	0.9	0.4	0	30	649.718
35	33	0.1778	0.56	-0.1	0.4	0	30	1243.25
8	34	0.3302	0.56	0.9	0.4	0	0	257.258
36	35	0.3302	0.56	-0.1	0.4	0	30	919.085
76	36	0.2540	0.48	0.4	0.48	15	30	623.467
10	37	0.3302	0.4	-0.1	0.56	0	0	645.346
23	38	0.1778	0.56	0.9	0.4	30	0	346.123
33	39	0.1778	0.4	-0.1	0.4	0	30	1253.92
14	40	0.3302	0.4	0.9	0.56	0	0	292.125
81	41	0.2540	0.48	0.4	0.48	15	15	525.265
7	42	0.1778	0.56	0.9	0.4	0	0	324.875
75	43	0.2540	0.48	0.4	0.48	15	0	387.069
71	44	0.2540	0.48	0.4	0.4	15	15	535.474
58	45	0.3302	0.4	-0.1	0.56	30	30	859.166
74	46	0.2540	0.48	0.4	0.48	30	15	528.245
44	47	0.3302	0.56	-0.1	0.56	0	30	827.825
47	48	0.1778	0.56	0.9	0.56	0	30	668.903
65	49	0.1778	0.48	0.4	0.48	15	15	626.93
17	50	0.1778	0.4	-0.1	0.4	30	0	948.585

2	51	0.3302	0.4	-0.1	0.4	0	0	731.481
42	52	0.3302	0.4	-0.1	0.56	0	30	857.952
51	53	0.1778	0.56	-0.1	0.4	30	30	1246.24
3	54	0.1778	0.56	-0.1	0.4	0	0	895.065
56	55	0.3302	0.56	0.9	0.4	30	30	460.609
55	56	0.1778	0.56	0.9	0.4	30	30	648.22
59	57	0.1778	0.56	-0.1	0.56	30	30	1092.68
12	58	0.3302	0.56	-0.1	0.56	0	0	624.618
66	59	0.3302	0.48	0.4	0.48	15	15	486.426
18	60	0.3302	0.4	-0.1	0.4	30	0	756.198
40	61	0.3302	0.56	0.9	0.4	0	30	459.937
68	62	0.2540	0.56	0.4	0.48	15	15	523.921
62	63	0.3302	0.4	0.9	0.56	30	30	502.988
24	64	0.3302	0.56	0.9	0.4	30	0	269.296
80	65	0.2540	0.48	0.4	0.48	15	15	525.265
54	66	0.3302	0.4	0.9	0.4	30	30	478.464
57	67	0.1778	0.4	-0.1	0.56	30	30	1101.99
31	68	0.1778	0.56	0.9	0.56	30	0	368.083
6	69	0.3302	0.4	0.9	0.4	0	0	266.632
49	70	0.1778	0.4	-0.1	0.4	30	30	1259.27
16	71	0.3302	0.56	0.9	0.56	0	0	280.062
86	72	0.2540	0.48	0.4	0.48	15	15	525.265
22	73	0.3302	0.4	0.9	0.4	30	0	281.472
64	74	0.3302	0.56	0.9	0.56	30	30	483.711
4	75	0.3302	0.56	-0.1	0.4	0	0	711.802
70	76	0.2540	0.48	0.9	0.48	15	15	428.163
83	77	0.2540	0.48	0.4	0.48	15	15	525.265
78	78	0.2540	0.48	0.4	0.48	15	15	525.265
77	79	0.2540	0.48	0.4	0.48	15	15	525.265
25	80	0.1778	0.4	-0.1	0.56	30	0	796.622
15	81	0.1778	0.56	0.9	0.56	0	0	345.018
63	82	0.1778	0.56	0.9	0.56	30	30	668.748
50	83	0.3302	0.4	-0.1	0.4	30	30	953.75
67	84	0.254	0.4	0.1	0.48	15	15	537.074
29	85	0.1778	0.4	0.9	0.56	30	0	360.176
85	86	0.254	0.48	0.4	0.48	15	15	525.265

Table 5: RSM Model Specifications for C1PS1

Transform	Lambda	Process order	Pure error	R-Squared	Adjusted R-Squared
Power	0.44	Quadratic-manual	0	0.9994	0.9992

RSM model details are tabulated in Table 5. The model was found to be significant with F value of 3881.83 and p-value < 0.0001. fig. 2 shows the normal probability plot of residuals for production cost. It is evident that all the residuals are clustered in the straight line implying that errors are normally distributed. Fig. 3 shows the plot of actual vs predicted model values. Since the points are clustered around a straight line,the predicted value are in close adherence to the actual values. Normal plot of residuals and Predicted versus Actual graphs are attached below.

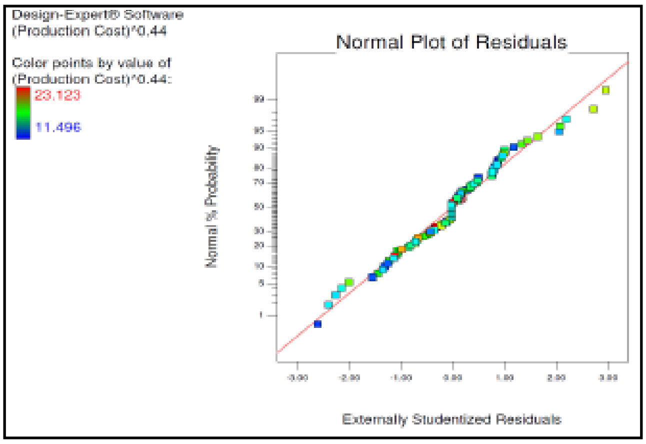


Fig. 2: Normal Plot of Residuals

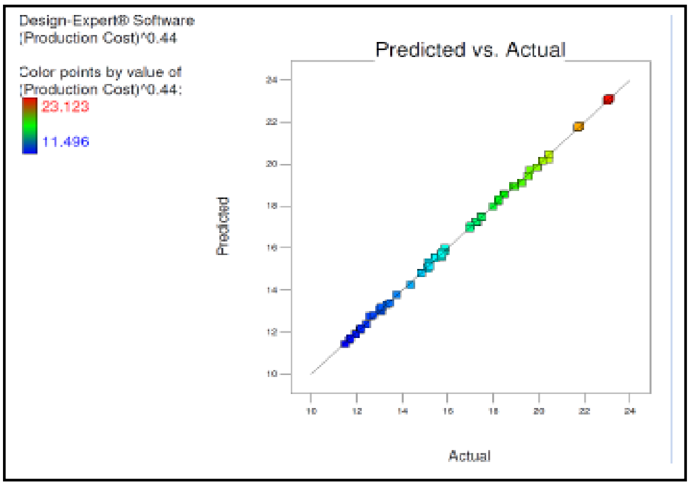


Fig. 3: Predicted Versus Actual

The Final model Equation for production cost in terms of Actual Factors:

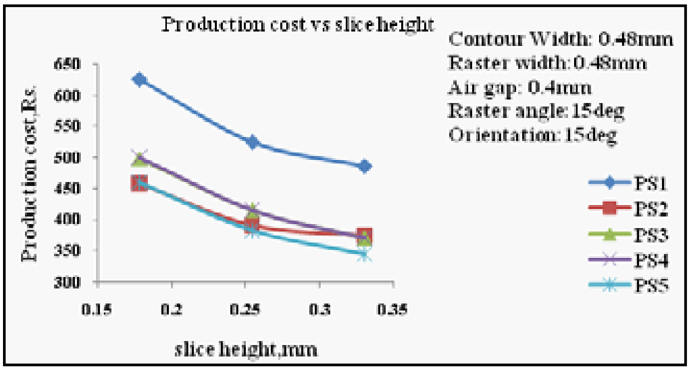
(Production Cost)0.44 = +31.45478 -42.85180 * Slice Height -7.77648 * Contour Width -15.60226 * Air Gap -17.97944 * Raster Width +0.016106 * Raster angle +0.20604 * Orientation -10.54927 * Slice Height * Contour Width +3.05787 * Slice Height * Air Gap +10.63133 * Slice Height * Raster Width -0.015105 * Slice Height * Raster angle -0.21749 * Slice Height * Orientation +0.42824 * Contour Width * Air Gap -0.34614 * Contour Width * Raster Width +2.23925E-003 * Contour Width * Raster angle -0.012791 * Contour Width * Orientation +9.47308 * Air Gap * Raster Width -1.44613E-003 * Air Gap * Raster angle +0.040707 * Air Gap * Orientation -3.23383E-003 * Raster Width * Raster angle -7.18748E-004 * Raster Width * Orientation -3.57559E-004 * Raster angle * Orientation +64.17364 * Slice Height^2 +10.24168 * Contour Width^2 +5.01845 * Air Gap^2 +9.58921 * Raster Width^2 -7.47649E-006 * Raster angle2 -1.66988E-003 * Orientation^2

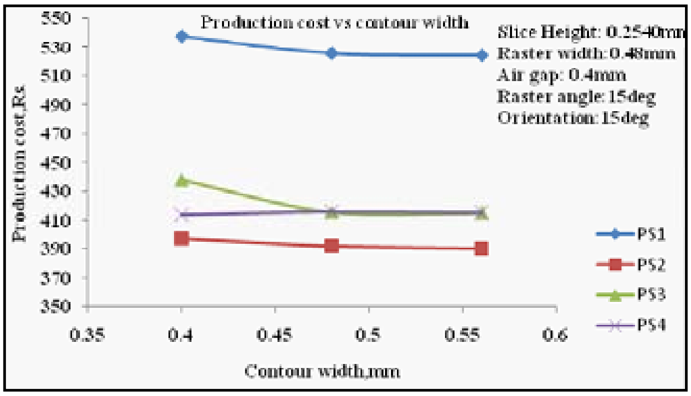
Figs. 4-9 denote the variation of production cost with respect to the changes in slice height, contour width, air gap, raster width raster angle and orientation respectively for the rotation of cylinder with about x-axis keeping z height minimum.

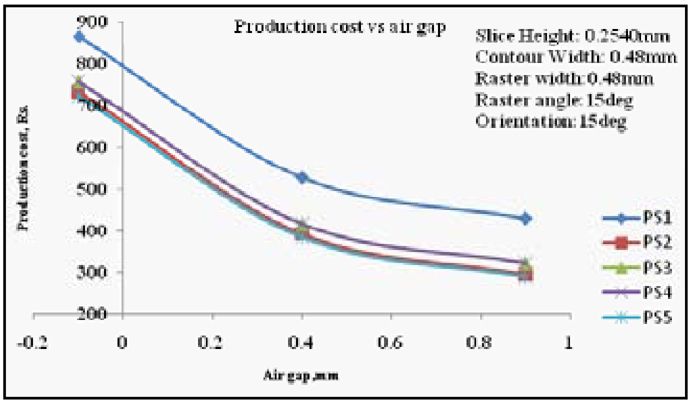
Convulsive to the model formation for C1PS1, models have been made for every component corresponding to all parameter settings by experimental observation and modeling. The same have been analyzed and the following conclusions have been drawn:

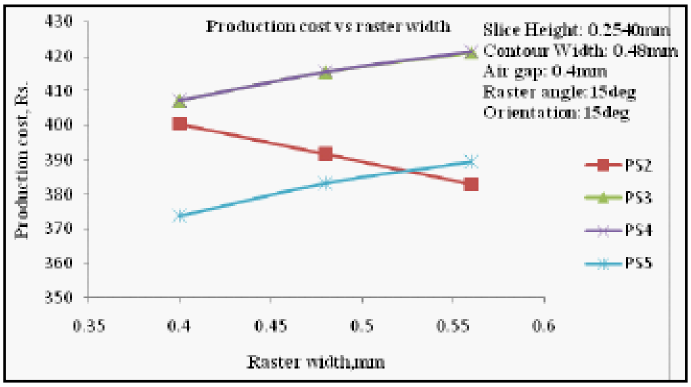
1. Effect of each individual parameter on the production cost.
2. Best spatial Orientation for each component.

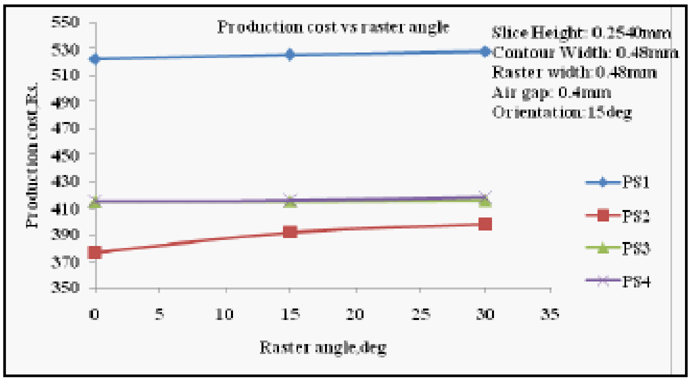
The graphs demonstrating effects of change in the parameters and the spatial orientation for all components as per technique of experimentation have been summarized in the Table 6.











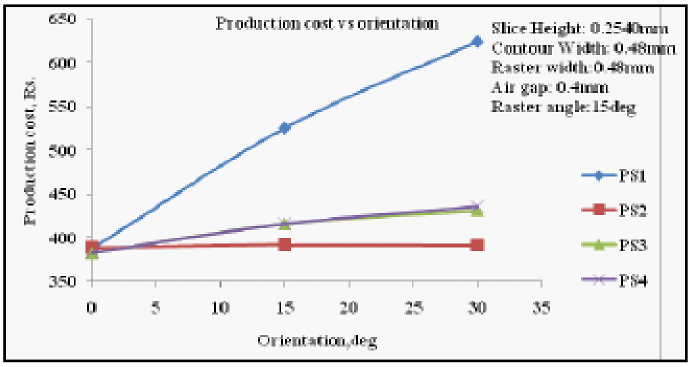
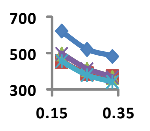
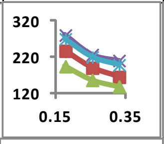
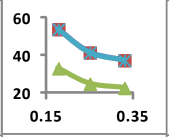
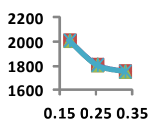
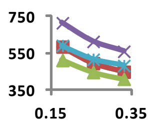
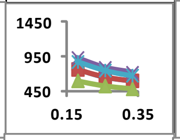
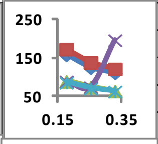
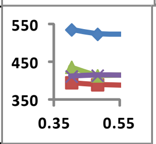
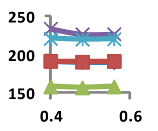
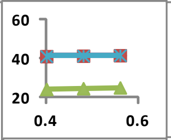
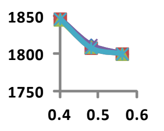
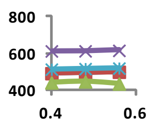
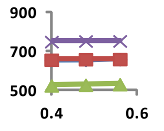
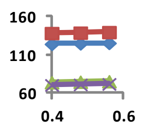
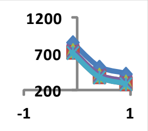
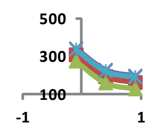
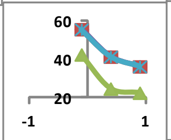
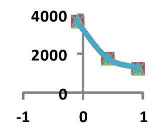
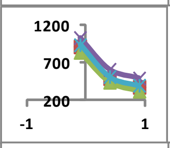
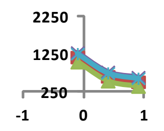
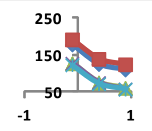
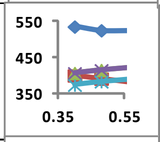
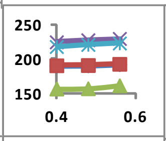
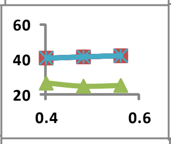
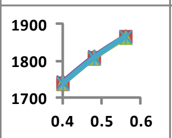
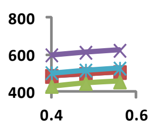
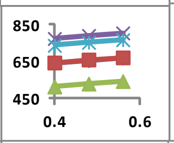
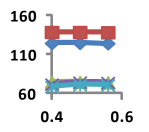
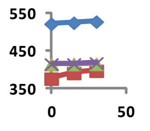
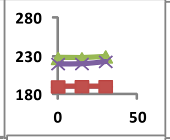
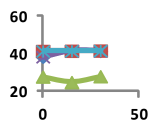
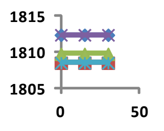
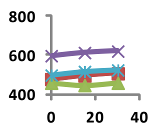
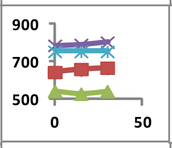
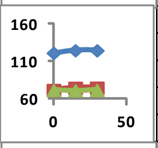
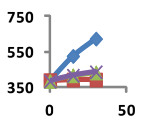
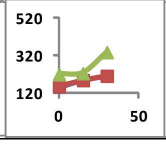
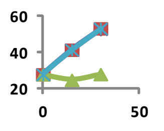
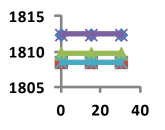
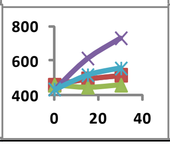
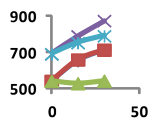
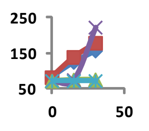


Table 6: Graphical representation for the production cost variation with changes in process parameters and spatial orientation

	COMPONENT 1 PARAMETER SETTING 1-5	COMPONENT 2 PARAMETER SETTING 1-5	COMPONENT 3 PARAMETER SETTING 1-5	COMPONENT 4 PARAMETER SETTING 1-5	COMPONENT 5 PARAMETER SETTING 1-5	COMPONENT 6 PARAMETER SETTING 1-5	COMPONENT 7 PARAMETER SETTING 1-5	FIXED PARAMETERS
SLICE HEIGHT								C.W.: 0.48 mm R.W.: 0.48 mm A.G.: 0.4 mm R.A: 15 deg O : 15 deg
CONTOUR WIDTH								S.H.: 0.254 mm R.W.: 0.48 mm A.G.: 0.4 mm R.A.: 15 deg O : 15 deg
AIR GAP								S.H.: 0.254 mm R.W.: 0.48 mm C.W.:0.48mm R.A.: 15 deg O : 15 deg
RASTER WIDTH								S.H.: 0.254 mm C.W.: 0.48 mm A.G.: 0.4 mm R.A.: 15 deg O : 15 deg
RASTER ANGLE								S.H.: 0.254 mm R.W.: 0.48 mm A.G.: 0.4 mm R.A.: 15 deg O : 15 deg
ORIENTATION								S.H.: 0.254 mm R.W.: 0.48 mm A.G: 0.4 mm R.A.: 15 deg C.W.:0.48mm

VII. Conclusion

Table 7: Dependence of Production cost (P.C.) on individual Process parameters for primitives

Serial No.	Slice Height (S.H.)	Contour Width (C.W.)	Air Gap (A.G.)	Raster width (R.W.)	Raster angle (R.A.)	Orientation (0)
Primitive 1	P.C. invariably decreases with increase in S.H.	P.C. decreases with increase in C.W. for PS 1,2,3 and remains constant for PS 4,5.The increase is more b/n 0.4-0.48 as compared to 0.48-0.56	P.C. invariably decreases with increase in A.G. Decrease b/n -0.1-0.4 is greater than that b/n 0.4-0.9	P.C. decreases with increase in R.W. for PS1,2 and increases R.W. for PS3,4,5	P.C. increases slightly with increase in R.A.	P.C. increases appreciably for increase in O b/n 0-15 and slightly lesser b/n 15-30.
Primitive 2	P.C. invariably decreases with increase in S.H.	P.C. decreases slightly with increase in C.W.	P.C. invariably decreases with increase in A.G. Decrease b/n -0.1-0.4 is greater than that b/n 0.4-0.9	P.C. increases slightly with increase in R.W.	P.C. increases slightly or remains constant with increase in R.A.	P.S. increases with increasing O for PS1,2,4 and remains constant for PS3,5
Primitive 3	P.C. invariably decreases with increase in S.H.	P.C. increases slightly or remains constant with increase in C.W.	P.C. invariably decreases with increase in A.G. Decrease b/n -0.1-0.4 is greater than that b/n 0.4-0.9	P.C. increases slightly with increase in R.W for PS1,2,4,5 but shows fluctuation for PS3	P.C. increases slightly or remains constant with increase in R.A.	P.C. increases slightly with increase in R.W for PS1,2,4,5 but shows fluctuation for PS3

Primitive 4	P.C. invariably decreases with increase in S.H.	P.C. decreases with increase in C.W. The increase is more b/n 0.4-0.48 as compared to 0.48-0.56	P.C. invariably decreases with increase in A.G.	P.C. invariably increases with increase in A.G.	P.C. does not vary with R.A.	P.C. does not vary with O.
Primitive 5	P.C. invariably decreases with increase in S.H.	P.C. increases slightly with increase in C.W.	P.C. invariably decreases with increase in A.G. Decrease b/n -0.1-0.4 is greater than that b/n 0.4-0.9	P.C. invariably increases with increase in R.W.	P.C. increases slightly with increase in R.A. for PS1, 2, 4, 5 but shows fluctuation for PS3	P.C. increases slightly with increase in O for PS1,2,4,5 but shows fluctuation for PS3
Primitive 6	P.C. invariably decreases with increase in S.H.	P.C. increases slightly or remains constant with increase in C.W.	P.C. invariably decreases with increase in A.G. Decrease b/n -0.1-0.4 is greater than that b/n 0.4-0.9	P.C. invariably increases with increase in R.W.	P.C. increases slightly with increase in R.A. for PS1,2,4,5 but shows fluctuation for PS3	P.C. increases slightly with increase in O for PS1,2,4,5 but shows fluctuation for PS3
Primitive 7	P.C. invariably decreases with increase in S.H.	P.C. increases slightly or remains constant with increase in C.W.	P.C. invariably decreases with increase in A.G. Decrease b/n -0.1-0.4 is greater than that b/n 0.4-0.9	P.C. increases slightly or remains constant with increase in R.W.	P.C. increases slightly or remains constant with increase in R.A.	P.C. invariably increases with increase in R.W.

Table 8: Variation of Production Cost (P.C.) With Spatial Orientation for Primitives

Process Parameters	Effect on M.V.	Rotation about x axis(θx)	Rotation about y axis (θy)	Rotation about z axis(θz)	Rotation about x axis with minimum z (θxz)	Rotation about y axis with minimum z (θyz)
B.T. Variation: Scale 0-5 where 0 implies no variation and 5 implies maximum variation. Values: Scale 1-5 where 1 implies least value and 5 implies maximum value.						
Primitive 1						
Slice height	Values	5	2	3	4	1
	Variation	5	2	3	4	1
Contour width	Values	5	2	3	4	1
	Variation	4	1	3	2	0
Air gap	Values	5	2	3	4	1
	Variation	5	2	3	4	1
Raster width	Values	5	2	3	4	1
	Variation	5	2	3	4	1
Raster angle	Values	5	2	3	4	1
	Variation	4	1	2	3	0
Orientation	Values	5	2	3	4	1
	Variation	4	1	2	3	0
Primitive 2						
Slice height	Values	2	3	1	5	4
	Variation	2	3	1	5	4
Contour width	Values	2	3	1	5	4
	Variation	2	3	1	5	4
Air gap	Values	2	3	1	5	4
	Variation	2	3	1	5	4
Raster width	Values	2	3	1	5	4
	Variation	2	3	1	5	4

Raster angle	Values	2	3	1	5	4
	Variation	1	2	0	4	3
Orientation	Values	2	3	1	5	4
	Variation	1	2	0	3	0
Primitive 3						
Slice height	Values	2	3	1	2	3
	Variation	2	2	1	2	2
Contour width	Values	2	3	1	2	3
	Variation	2	3	1	2	3
Air gap	Values	3	2	1	3	2
	Variation	3	2	1	3	2
Raster width	Values	3	2	1	3	2
	Variation	3	2	1	3	2
Raster angle	Values	2	3	1	2	3
	Variation	2	3	1	2	3
Orientation	Values	2	3	1	2	3
	Variation	2	3	1	2	3
Primitive 4						
Slice height	Values	1	1	1	1	1
	Variation	1	1	1	1	1
Contour width	Values	1	1	1	1	1
	Variation	1	1	1	1	1
Air gap	Values	1	1	1	1	1
	Variation	1	1	1	1	1
Raster width	Values	1	1	1	1	1
	Variation	1	1	1	1	1
Raster angle	Values	1	1	1	1	1
	Variation	1	1	1	1	1
Orientation	Values	1	1	1	1	1
	Variation	1	1	1	1	1
Primitive 5						
Slice height	Values	2	3	1	5	4
	Variation	2	3	1	5	4
Contour width	Values	2	3	1	5	4
	Variation	2	3	1	5	4
Air gap	Values	2	3	1	5	4
	Variation	2	3	1	5	4
Raster width	Values	2	3	1	5	4
	Variation	2	3	1	5	4
Raster angle	Values	2	3	1	5	4
	Variation	2	3	1	5	4
Orientation	Values	2	3	1	5	4
	Variation	2	3	1	5	4
Primitive 6						
Slice height	Values	2	3	1	5	4
	Variation	2	3	1	5	4
Contour width	Values	2	3	1	5	4
	Variation	2	3	1	0	4
Air gap	Values	2	3	1	5	4
	Variation	2	3	1	5	4
Raster width	Values	2	3	1	5	4
	Variation	2	3	1	5	4

Raster angle	Values	2	3	1	5	4
	Variation	2	3	1	5	4
Orientation	Values	2	3	1	5	4
	Variation	2	3	1	5	4
Primitive 7						
Slice height	Values	4	5	2	3	1
	Variation	3	4	2	5	1
Contour width	Values	4	5	3	2	1
	Variation	3	4	2	0	1
Air gap	Values	4	5	3	2	1
	Variation	4	5	3	2	1
Raster width	Values	4	5	3	2	1
	Variation	4	5	3	2	1
Raster angle	Values	4	5	3	2	1
	Variation	3	0	2	0	1
Orientation	Values	4	5	2	3	1
	Variation	3	4	2	5	1

This study experimentally builds the model for the production cost with respect to:

i) All six crucial process parameters and from the results the following can be safely concluded [Table 7]:

1. P.C. invariably decreases with increase in slice height.
2. P.C. shows a fluctuating and relatively inappreciable change with contour width.
3. P.C. invariably decreases corresponding to increasing air gap.
4. P.C. increases slightly or remains constant corresponding to increasing raster width.
5. P.C. increases slightly or remains constant with increase in raster angle in general though the increase is minor. Also, there is a fluctuation around the middle value in many cases implying no clear trend.
6. P.C. increases with increase in angle of rotation from any axis (orientation) in general. However, there is a fluctuation around the middle value in many cases implying no clear trend.

ii) Every feasible spatial orientation and from the results the following can be safely concluded [Table 8]:

1. For cylindrical primitives, rotation about θz gives the least value of production cost followed by rotations θyz, θx ,θy, θxz.
2. For conical primitives, rotation about θz gives the least value of production cost followed by rotations θx & θy, θyz, θxz.
3. For cubical primitives, θz gives the least value of production cost followed by rotations θx & θy & θyz & θxz.
4. For spherical primitives, rotational symmetry is exhibited and production cost corresponding to θx & θy & θyz & θxz & θz are equal.
5. For cuboidal primitives, rotation about θz gives the least value of production cost followed by rotations θx, θy,θyz, θxz
6. For pyramidal primitives, rotation about θz gives the least value of production cost followed by rotations θx, θy,θyz, θxz.
7. For prismatic primitives, rotation about θyz gives the least value of production cost followed by rotations θz & θxz, θy& θx.

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