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Effect of varying spatial orientations on build time requirements for FDM process: A case study

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A B S T R A C T

In this research, effect of varying spatial orientations on the build time requirements for fused deposition modelling process is studied. Constructive solid geometry cylindrical primitive is taken as work piece and modeling is accomplished for it. Response surface methodology is used to design the experiments and obtain statistical models for build time requirements corresponding to different orientations of the given primitive in modeller build volume. Contour width, air gap, slice height, raster width, raster angle and angle of orientation are treated as process parameters. Percentage contribution of individual process parameter is found to change for build time corresponding to different spatial orientations. Also, the average of build time requirement changes with spatial orientation. This paper attempts to clearly discuss and describe the observations with an aim to develop a clear understanding of effect of spatial variations on the build time for Fused Deposition Modelling process. This work is an integral part of process layout optimization and these results can effectively aid designers specially while tackling nesting issues.

1. Introduction

Rapid Prototyping (RP)/Generative Manufacturing (GM) is around 3 decade old technology which enables quick transition from concept to physical models [1]. GM answers the need of manufacturing which is environment friendly with minimal wastage of material. Though material availability and data transfer techniques have hindered widespread use of GM as an end product technology in the past yet these have been dealt with effectively during recent times [2]. It has established itself as an efficient means for fast, easy and effective prototype production of intricate and complicated geometry parts [3]. GM applications extend from prototyping to end product manufacturing [4]. It is increasingly finding shining role in defence, aerospace, medical, polymer, and many other fields [5]. Especially, in defence support applications, GM proves itself a game changing landmark technology owing to its versatility and flexibility to produce custom engineered designs and products [6–8]. Busachi et al. [7] reported results of GM methodological studies carried out at various defence support systems in UK. Kalvala et al. [8] utilized friction assisted solid state lap seam welded joints with GM techniques and explained their probable utilization in defence applications. Several GM techniques like selective laser sintering [9], fused deposition modelling [10], three dimensional printing [11], laser engineered net shaping [12], etc. are in practice for fabrication of layered components directly from computer drawings of the part [5].

Fused Deposition Modelling (FDM) is one of GM techniques having unique advantage of variety of raw materials and modelers it offers [13]. It has the capability to produce intricate and complex shapes with reasonable time and cost requirements [5]. FDM has been widely used for various defence applications by different military manufacturers including EOIR technology, RLM industries, Sheppard air base, Tiberius arms, etc. [14]. These applications vary from prototypes, end products, guns, design modifications, etc. Several authors successfully fabricated various functional components using FDM by investigating the effect of various process parameters like raster width, air gap, slice height, etc. [15–17]. Srivastava et al. [15] experimentally investigated the effect of various process parameters upon responses with an aim to achieve layout optimization. Vasudevarao et al. [16] proposed an experimental design to determine significant factors and their interactions for optimal surface finish of parts fabricated via Fused

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Deposition Modelling process. Sood et al. [17] carried out parametric appraisal of the factors affecting the various mechanical properties of components fabricated by FDM process.

Majority of published research mainly focuses on the evaluation of effects of process parameters namely raster parameters, air gap; slice height, etc. on the build time and mechanical properties of fabricated components. In addition to these process parameters, spatial orientation significantly affects the build time which in turn affects the FDM layout process performance. Interestingly, investigations on effect of spatial orientation on build time for layout optimization of FDM process are almost untouched. Present work investigates effect of varying spatial orientation of components within the build volume in addition to other process parameters upon the build time (BT) requirements for FDM process.

2. Experimental procedure

2.1. Materials

Material used for current experimentation is Acrylonitrile Butadiene Styrene (ABS) having chemical formula ($C_8H_8 \cdot C_4H_6 \cdot C_3H_3N$)n. It is a thermoplastic used in making light weight, rigid, molded products like piping, musical instruments, golf club heads, automotive body parts, wheel covers, protective head gear, furniture buffer, air soft BBs, toys etc. An interesting application of an ABS variant has been reported in defence industry by Tiberius Arms, a group that produces different versions of their guns from cost effective ABS with the help of uPrint modeller which is an another high end FDM modeller [14]. It is a copolymer derived by polymerizing styrene and acrylonitrile in the presence of polybutadiene. Its composition varies from 15 to 35% acrylonitrile, 5–30% butadiene and 40–60% styrene which results in a long chain of polybutadiene crisscrossed with shorter chains of poly (styrene-co-acrylonitrile). Being polar, nitrile groups from neighboring chains attract each other and bind the chains together, making ABS stronger than pure polystyrene. ABS can be used in the temperature range of −25 °C to 60 °C. Model material and support material used for the current work are two variants of ABS namely ABS P430 and ABS SR30 respectively [18].

In order to arrive upon definite and meaningful design principles, components chosen are cylindrical primitives of constructive solid geometry (CSG) [19]. There are seven basic primitives of CSG namely cylindrical, conical, spherical, pyramidal, prismatic, cubical and cuboidal. It is a matter of general understanding of CAD that all the rest of shapes can be obtained by performing Boolean operations on these primitives and thus the design principles proposed for them can be thought of as generally applicable. Though the design principles for cylindrical workpiece are established in current case study, this work can similarly be extended for six remaining primitives also. In the present work, experiments are carried out for cylindrical primitives having.stl size $X = 20$ mm, $Y = 69.999$ mm, $Z = 20$ mm. Five different spatial orientations in the given build volume are considered for cylindrical primitives to arrive upon best orientation. These are absolute rotation about *x*-axis, absolute rotation about *y*-axis, absolute rotation about *z*-axis, rotation about *x*-axis keeping minimum *z* height and rotation about *y*-axis keeping minimum *z*-height. Fig. 1 presents the different spatial orientations of cylindrical primitives at varying angles.

Modeller used in the current experimentation is Fortus 250mc which is one of the most advanced and versatile Stratasys systems that offers cost effective printing of FDM parts with appreciable efficiency [20]. It pairs fine layer resolution with a larger build envelope which imparts power to fine-tune most aspects of prototype production. It is an office friendly high end FDM system which optimizes parts for strength, print time and aesthetics [21]. It is based on FDM technology. There are five basic steps involved in the FDM process which include [22]:

- Step 1 Formulation computer aided design (CAD) model from the component drawing
- Step 2 Converting CAD model of the drawing into.stl format, i.e., tessellated to enable it to be used as an input in to insight software
- Step 3 Dividing the tessellated.stl file into thin layers, i.e., slicing
- Step 4 Constructing layers for actual physical model generation
- Step 5 Cleaning and finishing model

Its working is explained as follows: A plastic filament is uncoiled from a roll and supplies material to an extrusion nozzle which can be used depending on requirement. The nozzle is heated to melt the material and can be moved in both horizontal and vertical directions by an automated computational mechanism, directly controlled by a computer-aided manufacturing (CAM) software package. The model or part is produced by extrusion of thermoplastic material to form layers as the material hardens immediately after extrusion from the nozzle [23]. The technical specifications of this modeller are tabulated in Table 1.

2.2. Selection of process parameters

There are four classes of parameters which are found to affect the FDM process. These are operation specific, modeller specific, geometry specific and material specific parameters [24]. Operation specific parameters include slice thickness, road width, head speed, raster angle, temperature of extruding material, envelope temperature, contour width, raster width, single/multi fill contours and air gap. Modeller specific parameters include nozzle diameter, filament feed rate, roller speed, flow rate and filament diameter. Geometry specific parameters include fill vector length, support structures and orientation. Material specific properties include physical properties, binder, viscosity, chemical composition and flexibility [2,25].

Previous experimentations, trial experiments and literature survey reflect that BT requirement of FDM modeler is mainly affected by six process parameters namely contour width (CW), slice height (SH), orientation (O), raster angle (RA), raster width (RW) and air gap (AG). These parameters are therefore selected as process parameters owing to their larger effect on BT as compared to others.

2.3. Response Surface Methodology (RSM) based experimentation

RSM technique is an extremely powerful statistical tool adopted for experimental design and building of empirical models in order to reduce experimental runs. This work utilizes central composite RSM design which has several advantages over other RSM designs. One of the biggest advantages of CCD is tremendous reduction in the number of runs as compared to full factorial designs [26]. Six process parameters namely SH, O, CW, RA, RW, and AG at three levels each were chosen for experimentation. Their details are summarized in Table 2.

Based on previous research work, rests of the parameters are kept constant throughout the experimentation primarily due to their lesser effect on the output as compared to chosen process parameters [5]. The constant parameters and their values are listed in Table 3.

Build time (BT) is a critical factor for optimization of any GM technique and is taken as the response for current experimentation. Though build-time is frequently used as a measure of process time/process speed, yet these two terms are not the same. Process time

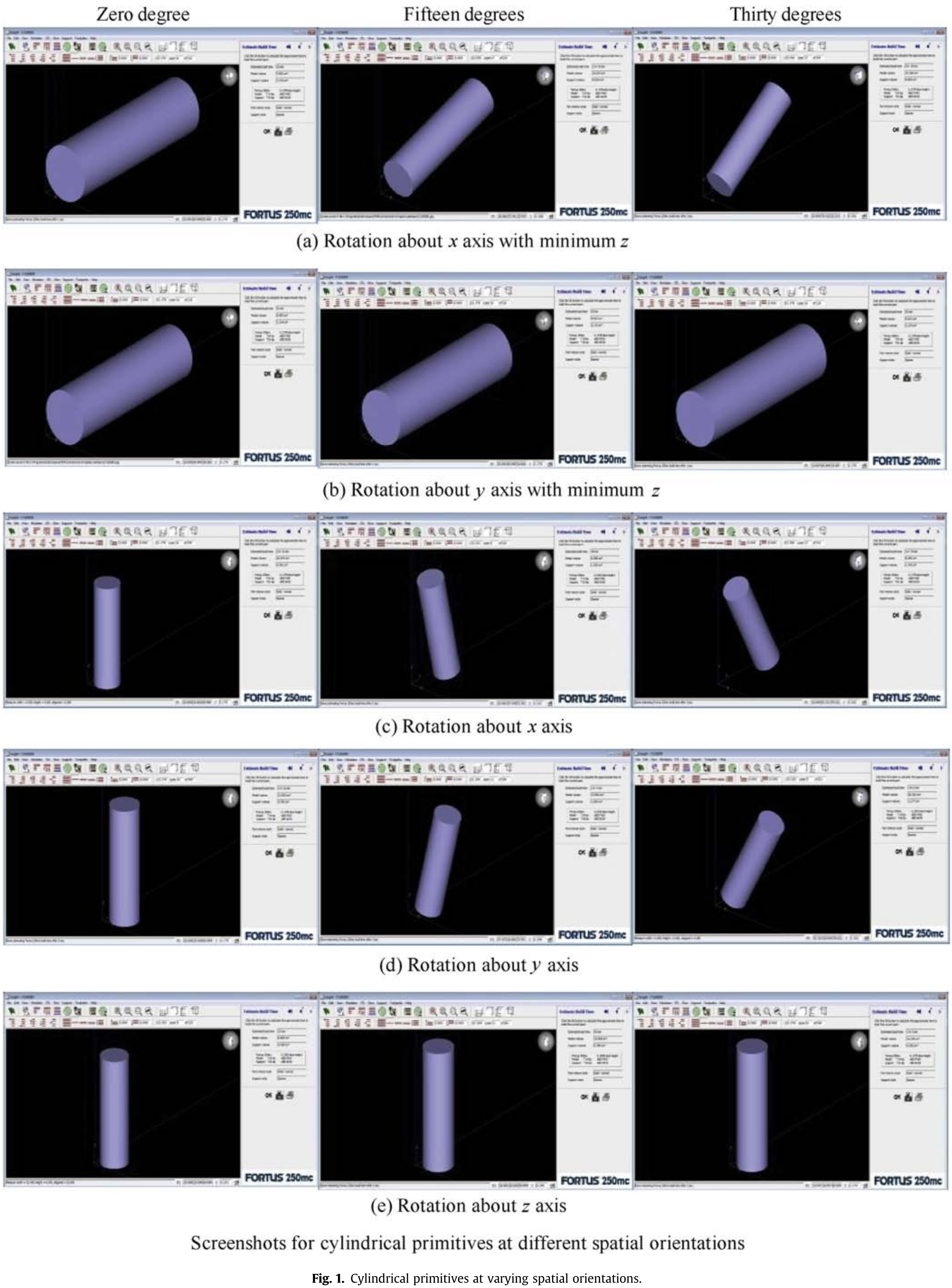

Fig. 1. Cylindrical primitives at varying spatial orientations.

Table 1
Technical specifications of Fortus 250mc modeler.

Characteristic	Specifications
Build envelope	10 × 10 × 12 inch
Layer thickness	0.007, 0.010 and 0.013 inches
Model material	ABS P430
Support material	ABS SR30
Powered by	Insight
Support structures	Soluble

gives an indication of the overall product completion time while BT is the time which a part spends on a machine during its creation assuming no bottlenecks. Several factors need attention for the process time evaluation. These mainly include: model preparation/file generation, system preparation, part build time, post build operations/post processing operations [27]. In this work, only part build time is studied. 86 run central composite RSM design table for six process parameters and single response was used for this experimentation (see Table 4). Empirical relationship among BT and input process parameters for various spatial orientations is determined and validated using analysis of variance (ANOVA), predicted versus actual plots and normal probability plot of residuals.

3. Results and discussions

Table 4 presents the observation table for BT corresponding to 86 run RSM design for each spatial orientation. The readings for BT are noted directly from FDM control center.

3.1. RSM model details

Models corresponding to each spatial orientation are derived, analyzed and validated using RSM technique by DesignExpert7 software. The details of RSM model for cylindrical primitives for varying spatial orientations are presented in Table 5.

The model was found to be significant with enough large F values. F-value for the model are sufficiently large which implies that model as a whole has statistically significant predictive capability.There is only 0.01% probability that such a high F-value can occur due to noise factors. Fig. 2 shows the normal probability plot of residuals for build time. 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.

The final model equations for build-time for each spatial orientation in Terms of Actual Factors are given in Table 6. It can be easily observed from the model equations (1–5) that the interaction terms are not very significant in any of the model thereby implying that we can neglect these interaction terms safely.

3.2. Effect of process parameters on build time

Fig. 4(a)–(f) denotes BT variation of build-time with respect to the changes in process parameters. It is noted that B.T. invariably reduces with increase in slice height. It invariably reduces with increasing air gap. It depends slightly on contour width as only minor reduction can be seen corresponding to increasing contour width. The dependence on RW is also minor. BT invariably increases with increase in raster angle. It invariably increases with increase in angle of rotation about any particular axis (orientation) though it remains constant in cases where rotational symmetry about any particular axis is displayed.

Percentage contribution of each process parameter is estimated. These results are summed up in Table 7. It can be easily observed that the percentage contribution of process parameters changes with changing spatial orientation. However air gap, slice height and orientation angle contribute majorly towards the changes in build time. Variation in slice height has maximum affect for almost each spatial orientation followed by air gap and orientation. Contour width and raster angle are the least significant factors in most of the cases.

Table 2
Process Parameters and their Levels.

S. No.	Parameters	Acronym	Definition	Level 1	Level 2	Level 3
1	Slice height/mm	SH	It is based on the material and tip size used in modeler.	0.1778	0.254	0.3302
2	Contour width/mm	CW	It is the material bead width used for contours.	0.4	0.48	0.56
3	Air gap/mm	AG	It sets the distance between part & supports when creating containment supports.	−0.1	0.4	0.9
4	Raster width/mm	RW	It is the material bead width used for rasters.	0.4	0.48	0.56
5	Raster angle/(°)	RA	It is for rasters on the bottom part of layer.	0	15	30
6	Orientation/(°)	O	It refers to the inclination of part in a build platform with respect to specific axis.	0	15	30

Table 3
Fixed parameters and their levels.

S. No.	Parameter	Definition	Levels
i.	Part interior style	It controls the density of material fill of the rasters.	Solid normal
ii.	Visible surface style	This refers to the visible regions of the part curves.	Normal
iii.	Support style	It is chosen from the type of support that surrounds component.	Sparse
iv.	Part fill style	It decides the fill pattern utilized to build a solid model.	one contour/ rasters
v.	Part X Shrink Factor	It is the value of shrinkage factor applied in X direction.	1.007
vi.	Part Y shrink factor	It is the value of shrinkage factor applied in Y direction.	1.007
vii.	Contour to raster air gap	It is the gap of air space between inner most contour & raster fill outermost edge.	0
viii.	Support self-supporting angle	It is used to control beginning of support creation on angled walls and surfaces & is the minimum angle of part walls built without support.	50
ix.	Contour base oversize	It is the distance that base will extend beyond the part contour extremes.	1.27
x.	Contour base layers	It is the number of base layers built to construct the base.	8
xi.	Support tip	It is the nozzle through which extrusion head extrudes the semi-liquid material to build part support.	T16

Table 4
86 run Central Composite RSM Design Table of Build time Observations for Cylindrical Primitives corresponding to varying spatial orientations.

Primitive 1- Cylinder								Build Time Observations (Hours)				
Std	Run	Factor 1 SH/ mm	Factor 2 CW/ mm	Factor 3 AG/ mm	Factor 4 RW/ mm	Factor 5 RA/(°)	Factor 6 O/(°)	Rot.about *x* axis with min *z*	Rot about *y* axis with min *z*	Rot about *x* axis	Rot about *y* axis	Rot about *z* axis
13	1	0.1778	0.4	0.9	0.56	0	0	0.933	0.917	1.767	1.767	1.767
27	2	0.1778	0.56	−0.1	0.56	30	0	1.883	1.883	2.133	2.133	2.133
72	3	0.254	0.48	0.4	0.56	15	15	1.3	0.75	1.0167	1.017	0.867
30	4	0.3302	0.4	0.9	0.56	30	0	0.517	0.517	0.517	0.517	0.517
60	5	0.3302	0.56	−0.1	0.56	30	30	1.617	0.883	1.133	1.133	0.95
53	6	0.1778	0.4	0.9	0.4	30	30	2.533	1.05	1.567	1.583	1.15
28	7	0.3302	0.56	−0.1	0.56	30	0	0.867	0.867	0.95	0.95	0.95
9	8	0.1778	0.4	−0.1	0.56	0	0	1.7	1.7	2.167	2.167	2.167
11	9	0.1778	0.56	−0.1	0.56	0	0	1.683	1.683	2.133	2.133	2.133
61	10	0.1778	0.4	0.9	0.56	30	30	2.483	0.983	1.5	1.5	1.083
39	11	0.1778	0.56	0.9	0.4	0	30	2.533	0.917	1.5	1.517	1.167
45	12	0.1778	0.4	0.9	0.56	0	30	2.483	0.883	1.433	1.45	1.083
38	13	0.3302	0.4	0.9	0.4	0	30	1.3	0.483	0.75	0.767	0.55
84	14	0.254	0.48	0.4	0.48	15	15	1.333	0.783	1.067	1.067	0.917
52	15	0.3302	0.56	−0.1	0.4	30	30	1.95	1.2	1.483	1.483	1.3
82	16	0.254	0.48	0.4	0.48	15	15	1.333	0.783	1.067	1.067	0.917
19	17	0.1778	0.56	−0.1	0.4	30	0	2.617	2.617	2.967	2.967	2.967
69	18	0.254	0.48	−0.1	0.48	15	15	1.9	1.35	1.717	1.717	1.55
43	19	0.1778	0.56	−0.1	0.56	0	30	3.4	1.683	2.433	2.45	2.133
73	20	0.254	0.48	0.4	0.48	0	15	1.333	0.717	1.067	1.067	0.917
46	21	0.3302	0.4	0.9	0.56	0	30	1.267	0.467	0.7	0.733	0.517
5	22	0.1778	0.4	0.9	0.4	0	0	0.917	0.917	1.15	1.15	1.15
34	23	0.3302	0.4	−0.1	0.4	0	30	2.017	1.12	1.5	1.517	1.317
20	24	0.3302	0.56	−0.1	0.4	30	0	1.2	1.2	1.3	1.3	1.3
48	25	0.3302	0.56	0.9	0.56	0	30	1.2	0.417	0.7	0.717	0.517
41	26	0.1778	0.4	−0.1	0.56	0	30	3.433	1.717	2.483	2.483	2.183
26	27	0.3302	0.4	−0.1	0.56	30	0	0.933	0.933	0.967	0.967	0.967
21	28	0.1778	0.4	0.9	0.4	30	0	1.05	1.05	1.15	1.15	1.15
1	29	0.1778	0.4	−0.1	0.4	0	0	2.367	2.367	3.033	3.033	3.033
32	30	0.3302	0.56	0.9	0.56	30	0	0.467	0.467	0.517	0.517	0.517
79	31	0.254	0.48	0.4	0.48	15	15	1.333	0.783	1.067	1.067	0.917
37	32	0.1778	0.4	0.9	0.4	0	30	2.55	0.917	1.517	1.517	1.15
35	33	0.1778	0.56	−0.1	0.4	0	30	4.133	2.333	3.25	3.25	2.983
8	34	0.3302	0.56	0.9	0.4	0	0	0.45	0.45	0.55	0.55	0.55
36	35	0.3302	0.56	−0.1	0.4	0	30	1.933	1.083	1.467	1.489	1.3
76	36	0.254	0.48	0.4	0.48	15	30	1.8	0.783	1.15	1.167	0.917
10	37	0.3302	0.4	−0.1	0.56	0	0	0.833	0.833	0.967	0.967	0.967
23	38	0.1778	0.56	0.9	0.4	30	0	1.033	1.033	1.183	1.183	1.183
33	39	0.1778	0.4	−0.1	0.4	0	30	4.167	2.367	3.3	3.3	3.033
14	40	0.3302	0.4	0.9	0.56	0	0	0.467	0.467	0.517	0.517	0.517
81	41	0.254	0.48	0.4	0.48	15	15	1.333	0.783	1.067	1.067	0.917
7	42	0.1778	0.56	0.9	0.4	0	0	0.917	0.917	1.167	1.167	1.167
75	43	0.254	0.48	0.4	0.48	15	0	0.767	0.767	0.917	0.917	0.917
71	44	0.254	0.48	0.4	0.4	15	15	1.383	0.817	1.12	1.12	0.967
58	45	0.3302	0.4	−0.1	0.56	30	30	1.683	0.933	1.15	1.167	0.967
74	46	0.254	0.48	0.4	0.48	30	15	1.35	0.817	1.067	1.083	0.917
44	47	0.3302	0.56	−0.1	0.56	0	30	1.6	0.783	1.133	1.15	0.95
47	48	0.1778	0.56	0.9	0.56	0	30	2.467	0.867	1.433	1.45	1.083
65	49	0.1778	0.48	0.4	0.48	15	15	2.033	1.233	1.633	1.633	1.433
17	50	0.1778	0.4	−0.1	0.4	30	0	2.65	2.65	3.033	3.033	3.033
2	51	0.3302	0.4	−0.1	0.4	0	0	1.12	1.12	1.317	1.317	1.317
42	52	0.3302	0.4	−0.1	0.56	0	30	1.683	0.833	1.15	1.167	0.967
51	53	0.1778	0.56	−0.1	0.4	30	30	4.15	2.617	3.3	3.317	2.967
3	54	0.1778	0.56	−0.1	0.4	0	0	2.333	2.333	2.967	2.967	2.967
56	55	0.3302	0.56	0.9	0.4	30	30	1.233	0.5	0.733	0.733	0.55
55	56	0.1778	0.56	0.9	0.4	30	30	2.517	1.033	1.533	1.55	1.167
59	57	0.1778	0.56	−0.1	0.56	30	30	3.4	1.883	2.483	2.5	2.133
12	58	0.3302	0.56	−0.1	0.56	0	0	0.783	0.783	0.95	0.95	0.95
66	59	0.3302	0.48	0.4	0.48	15	15	1.033	0.6	0.767	0.767	0.667
18	60	0.3302	0.4	−0.1	0.4	30	0	1.25	1.25	1.317	1.317	1.317
40	61	0.3302	0.56	0.9	0.4	0	30	1.233	0.45	0.733	0.75	0.55
68	62	0.254	0.56	0.4	0.48	15	15	1.317	0.767	1.05	1.05	0.9
62	63	0.3302	0.4	0.9	0.56	30	30	1.267	0.517	0.717	0.717	0.517
24	64	0.3302	0.56	0.9	0.4	30	0	0.5	0.5	0.55	0.55	0.55
80	65	0.254	0.48	0.4	0.48	15	15	1.333	0.783	1.067	1.067	0.917
54	66	0.3302	0.4	0.9	0.4	30	30	1.3	0.55	0.75	0.75	0.55
57	67	0.1778	0.4	−0.1	0.56	30	30	3.433	1.917	2.533	2.55	2.167
31	68	0.1778	0.56	0.9	0.56	30	0	0.983	0.983	1.083	1.083	1.083
6	69	0.3302	0.4	0.9	0.4	0	0	0.483	0.483	0.55	0.55	0.55
49	70	0.1778	0.4	−0.1	0.4	30	30	4.2	2.65	3.367	3.367	3.033
16	71	0.3302	0.56	0.9	0.56	0	0	0.417	0.417	0.517	0.517	0.517
86	72	0.254	0.48	0.4	0.48	15	15	1.333	0.783	1.067	1.067	0.917

Table 4 (*continued*)

Primitive 1- Cylinder								Build Time Observations (Hours)				
Std	Run	Factor 1 SH/ mm	Factor 2 CW/ mm	Factor 3 AG/ mm	Factor 4 RW/ mm	Factor 5 RA/(°)	Factor 6 O/(°)	Rot.about *x* axis with min *z*	Rot about *y* axis with min *z*	Rot about *x* axis	Rot about *y* axis	Rot about *z* axis
22	73	0.3302	0.4	0.9	0.4	30	0	0.55	0.55	0.55	0.55	0.55
64	74	0.3302	0.56	0.9	0.56	30	30	1.2	0.467	0.717	0.717	0.517
4	75	0.3302	0.56	−0.1	0.4	0	0	1.083	1.083	1.3	1.3	1.3
70	76	0.254	0.48	0.9	0.48	15	15	1.167	0.617	0.883	0.883	0.733
83	77	0.254	0.48	0.4	0.48	15	15	1.333	0.783	1.067	1.067	0.917
78	78	0.254	0.48	0.4	0.48	15	15	1.333	0.783	1.067	1.067	0.917
77	79	0.254	0.48	0.4	0.48	15	15	1.333	0.783	1.067	1.067	0.917
25	80	0.1778	0.4	−0.1	0.56	30	0	1.917	1.917	2.183	2.183	2.183
15	81	0.1778	0.56	0.9	0.56	0	0	0.867	0.867	1.083	1.083	1.083
63	82	0.1778	0.56	0.9	0.56	30	30	2.467	0.983	1.483	1.483	1.083
50	83	0.3302	0.4	−0.1	0.4	30	30	2.033	1.25	1.5	1.517	1.317
67	84	0.254	0.4	0.4	0.48	15	15	1.367	0.8	1.233	1.067	0.933
29	85	0.1778	0.4	0.9	0.56	30	0	0.983	0.983	1.1	1.1	1.1
85	86	0.254	0.48	0.4	0.48	15	15	1.333	0.783	1.067	1.067	0.917
Average								1.648	**1.062**	1.3879	1.39	1.25

Table 5
RSM Model Specifications for cylindrical primitives.

Significance	Transform	Lambda	Model	Pure error	*R*-Sqrd	Adjus *R*-Sqrd	*F*-Value	*P*-Value
Rotation about *x* axis with minimum *z*								
Significant	Power	0.09	Quadratic	0	0.9989	0.9984	1959.3	<0.0001
Rotation about y axis with minimum *z*								
Significant	Power	−0.09	Quadratic	0	0.9994	0.9992	3871.52	<0.0001
Rotation about x axis								
Significant	Power	1	Quadratic	0	0.9857	0.979	148.05	<0.0001
Rotation about *y* axis								
Significant	Power	1	Quadratic	0	0.986	0.9795	151.44	<0.0001
Rotation about *z* axis								
Significant	Power	1	Quadratic	0	0.9846	0.9774	137.04	<0.0001

3.3. *Effect of varying spatial orientations on build time*

Fig. 4(a–f) denote BT variation of build-time with respect to varying spatial orientations. For cylindrical primitives, rotation about y axis keeping minimum z height gives the least value of build-time followed by rotations about z axis. This is followed by rotations about x and y axis both of which result in same BT requirements. Rotations about x axis for minimum z height requires maximum amount of BT.

4. Conclusions

This work successfully develops significant and meaningful RSM models for build time in terms of various process parameters. Effects of varying spatial orientation have been established and numerous critical and important conclusions can be drawn from this research. The same scheme of experimentation can be easily applied to six remaining CSG primitives and results can be compiled to provide universally acceptable principles for orientation of a given component in the modeller build volume. Following are the important conclusions that can be drawn from this case study:

1) Spatial orientation has large impact on Build Time in FDM process.
2) Percentage contribution of process parameters varies with the changing spatial orientations. SH and AG are found to have maximum percentage contribution in almost every spatial orientation. CW is least significant in each case.
3) Effect of individual process parameter upon BT variation can be summed up as:
   a) BT invariably reduces with increase in SH and AG while it increases increases with increase in RA.
   b) B.T. depends slightly on CW and RW as only minor reduction can be seen corresponding to increasing CW and RW respectively.
   c) B.T. invariably increases with increase in angle of rotation about any particular axis (O) though it remains constant for components which display rotational symmetry about any particular axis.
4) Effect on changes on spatial rotations on the build time is studied. It is established that for cylindrical primitives' rotations about y axis with minimum z height amounts to least BT requirements.
5) Design rules established in this research can easily be extended to other GM processes with suitable process specific adjustments which can highly benefit GM professionals.
6) Though we have focused on achieving minimum build-time yet it should always be kept in mind that an inferior part can never compete with its superior counterpart even if the latter takes twice as much time. Therefore build-time should always be considered as one of the options and should always be weighed against other design objectives.

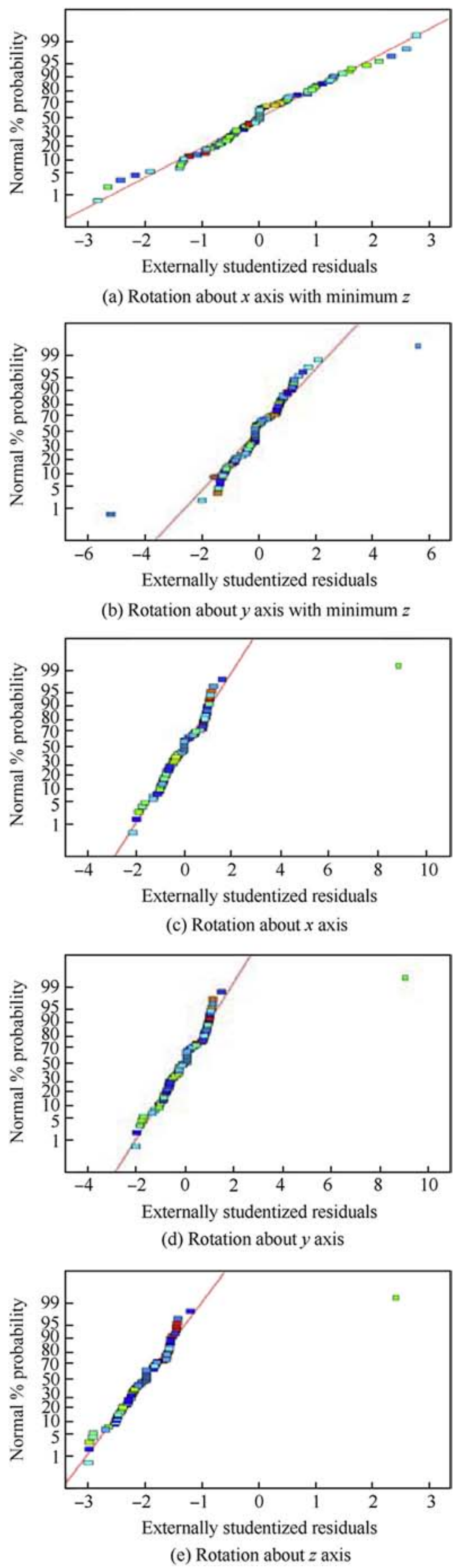

Fig. 2. Normal plot of residuals (BT).

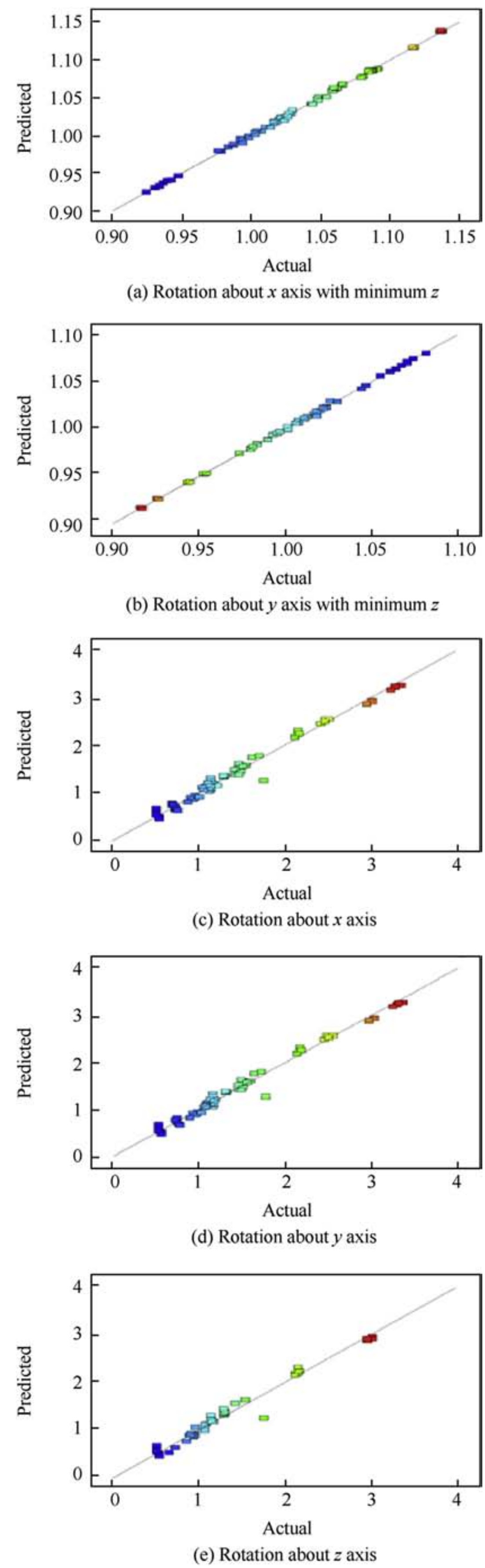

Fig. 3. Predicted versus Actual (BT).

Table 6
RSM model equations of Build Time in terms of process parameters.

Rotation about *x* axis with minimum *z*	
$(BT)^{0.09} = +1.32222 - 1.11049 \times SH - 0.062003 \times CW - 0.17505 \times AG - 0.24029 \times RW + 3.13085E-004 \times RA + 3.02984E-003 \times O - 0.17253 \times SH \times CW + 0.053502 \times SH \times AG + 0.043939 \times SH \times RW - 5.47135E-005 \times SH \times RA - 8.64021E-004 \times SH \times O - 6.90451E-003 \times CW \times AG - 0.036362 \times CW \times RW + 2.80592E-005 \times CW \times RA + 2.78495E-004 \times CW \times O + 0.13109 \times AG \times RW - 2.32985E-005 \times AG \times RA + 1.03047E-003 \times AG \times O - 1.28127E-004 \times RW \times RA + 1.32610E-003 \times RW \times O - 1.08977E-005 \times RA \times O + 1.42762 \times SH^2 + 0.10471 \times CW^2 + 0.042355 \times AG^2 + 0.095321 \times RW^2 + 2.88277E-006 \times RA^2 - 4.78955E-005 \times O^2$	Equation 1
Rotation about *y* axis with minimum *z*	
$(BT)^{-0.09} = +0.72803 + 1.03958 \times SH - 0.010619 \times CW + 0.17581 \times AG + 0.16348 \times RW - 5.87611E-004 \times RA - 4.77410E-005 \times O + 0.22999 \times SH \times CW - 8.93997E-003 \times SH \times AG + 0.034250 \times SH \times RW - 5.40105E-005 \times SH \times RA - 5.80317E-005 \times SH \times O + 0.014314 \times CW \times AG + 0.059633 \times CW \times RW - 9.92108E-007 \times CW \times RA - 5.52752E-005 \times CW \times O - 0.14080 \times AG \times RW - 3.31951E-005 \times AG \times RA + 1.23998E-005 \times AG \times O + 8.42779E-005 \times RW \times RA + 1.18986E-005 \times RW \times O - 2.94801E-007 \times RA \times O - 1.44853 \times SH^2 - 0.058417 \times CW^2 - 0.054850 \times AG^2 - 0.047556 \times RW^2 + 7.90155E-006 \times RA^2 + 2.72555E-006 \times O^2$	Equation 2
Rotation about *x* axis	
$(BT)^1 = +10.88518 - 26.32600 \times SH - 11.86108 \times CW - 4.73475 \times AG - 5.11682 \times RW - 1.93627E-003 \times RA + 0.017724 \times O + 2.47601 \times SH \times CW + 5.16732 \times SH \times AG + 8.98643 \times SH \times RW + 3.66360E-003 \times SH \times RA - 0.025098 \times SH \times O - 0.065625 \times CW \times AG - 1.46973 \times CW \times RW + 8.22917E-003 \times CW \times RA + 6.92708E-003 \times CW \times O + 3.63438 \times AG^{*} RW - 1.38750E-003 \times AG \times RA - 3.45833E-004 \times AG \times O - 8.22917E-003 \times RW \times RA - 6.97917E-003 \times RW \times O + 7.65278E-005 \times RA \times O + 23.21960 \times SH^2 + 11.92550 \times CW^2 + 0.93929 \times AG^2 + 0.49582 \times RW^2 + 8.10324E-006 \times RA^2 - 1.40786E-004 \times O^2$	Equation 3
Rotation about *y* axis	Equation 4
$(BT)^1 = +8.92739 - 27.30323 \times SH - 1.21700 \times CW - 4.76334 \times AG - 7.00453 \times RW - 3.53203E-003 \times RA + 0.014974 \times O + 2.22738 \times SH \times CW + 5.15133 \times SH\ AG + 8.96848 \times SH\ RW + 1.76345E-003 \times SH \times RA - 0.024565 \times SH \times O - 0.066797 \times CW \times AG - 1.56494 \times CW \times RW + 7.72135E-003 \times CW \times RA + 7.01823E-003 \times CW \times O + 3.62305 \times AG \times RW - 1.58958E-003 \times AG \times RA - 3.60417E-004 \times AG \times O - 9.02344E-003 \times RW \times RA - 6.60156E-003 \times RW \times O + 6.90972E-005 \times RA \times O + 25.46337 \times SH^2 + 0.99243 \times CW^2 + 0.99141 \times AG^2 + 2.53149 \times RW^2 + 1.01562E-004 \times RA^2 - 4.51042E-005 \times O^2$	
Rotation about *z* axis	Equation 5
$(BT)^1 = +9.20620 - 27.63578 \times SH - 2.30616 \times CW - 4.82632 \times AG - 6.75211 \times RW - 4.98971E-003^{*} RA - 5.06044E-003 \times O + 2.29915 \times SH \times CW + 5.33095 \times SH \times AG + 9.32733 \times SH \times RW + 9.11800E-003 \times SH \times RA + 9.58279E-003 \times SH \times O - 0.025391 \times CW \times AG - 1.72119 \times CW \times RW + 8.68490E-003 \times CW \times RA + 9.12760E-003 \times CW \times O + 3.67227 \times AG \times RW - 1.32292E-003 \times AG \times RA - 1.52708E-003 \times AG \times O - 8.68490E-003 \times RW \times RA - 9.12760E-003 \times RW \times O + 4.18750E-005 \times RA \times O + 25.36111 \times SH^2 + 2.14965 \times CW^2 + 0.95503 \times AG^2 + 2.22778 \times RW^2 + 6.33680E-005 \times RA^2 + 6.33680E-005 \times O^2$	

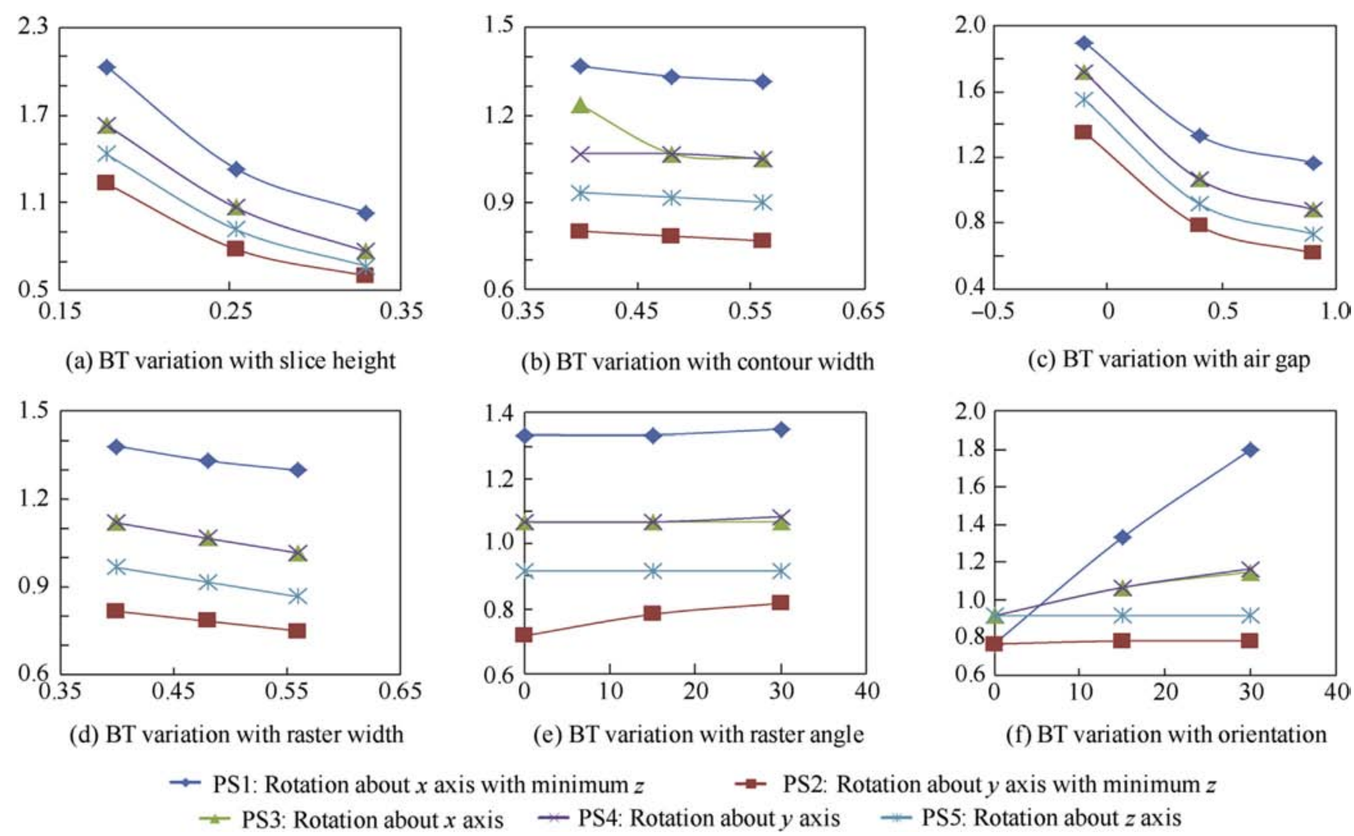

Fig. 4. BT variation with process parameters and spatial orientations.

Table 7
Variation in Percentage Contribution of Process Parameters with changes in BT corresponding to varying spatial orientations.

Percentage contribution of process parameter	SH	CW	AG	RW	RA	O	Average BT required
Rotation about x axis with minimum z height	34.24	0.09	21.28	1.40	0.19	39.33	1.648
Rotation about y axis with minimum z height	44.2	0.172	49.9	2.72	1.11	0.0001	1.062
Absolute rotation about x axis	46.5	0.08	36.5	3.27	0.0001	2.24	1.388
Absolute rotation about y axis	46.4	0.064	36.5	3.25	0.0023	2.45	1.390
Absolute rotation about z axis	43.0	0.054	40.6	3.63	0.017	0.018	1.250

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