Complexity is not for free: the impact of component complexity on additive manufacturing build time

Complexity Is Not For Free: The Impact of Component Complexity on Additive Manufacturing Build Time

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ABSTRACT

'Complexity for free' has often been claimed as one of the main advantages of additive manufacturing. Several authors have promoted the idea that additive manufacturing allows the fabrication of complex geometries without any increase in the cost of production. Many examples have proven how additive manufacturing can fabricate complex and intricate geometries. However, little attention has been given to the impact that shape complexity has on building time and/or material consumption. This paper explores the effect of shape complexity on part cost in Fused Deposition Modelling and challenges the mainstream assumption that additive manufacturing technologies provide 'Complexity for free'. A small scale experiment is presented where different shape complexities were produced and their building time and material consumption analysed. The case for the experiment was a load cell holder for a scientific instrument. Four shape types of the holder namely 'X', 'G1', 'G2' and 'G3' were compared. The results show how shape complexity increases both building time and material consumption and therefore have a negative impact on part cost. These findings also highlight the need for a revision of the idea of 'complexity for free' and in-depth discussion around the concepts of 'simple', 'basic' and 'optimal' design for Fused Deposition Modelling. In addition, other design considerations relating to shape complexity are raised.

KEYWORDS: Design for Additive Manufacturing; Shape Complexity; Design Optimization; Costing

1 INTRODUCTION

Previous studies have promoted AM as a technology in which shape complexity does not have any impact on production cost. Among the first who attempted to define the capabilities of AM, Hague et al. stated that AM could produce any complexity of geometry without any increase in cost [1]. Similarly, Gibson et al. in their influential book on AM suggested that in AM designers can exploit complex geometries without causing any additional increase in time and cost [3]. Furthermore, Comb advocated that complex parts could be created rapidly, inexpensively and practically with AM processes [2]. Although these contributions were significant as they marked the first efforts to define AM opportunities in design, they did not attempt to explore the implications of shape complexity with empirical studies.
Consequently, in the development of generic cost models for AM, shape complexity has not been considered in detail. Xu et al. were among the first to propose a cost model for AM. In their equation for calculating the fabrication time, the authors considered only the volume of the solid part as a geometrical variable [5]. In their generic cost model for AM, Gibson et al. considered shape complexity as a correction factor for calculating the average cross-sectional

area of a part [3]. This correction factor, derived from Pham and Wang [6], took into account the printing time differences between geometries with the same cross-sectional area in laser sintering. Shape complexity was considered as a ratio between the actual part volume and the bounding box. Since this correction factor relates the time difference in scanning cross-sectional areas with different area distribution in laser sintering [6] it may not be valid for FDM where building time is instead affected by the deposition speed of layers [4].

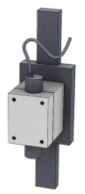
In specific cost models for FDM, shape complexity has been widely neglected. In the cost model for FDM proposed by Mello et al. execution time and material consumption are inputs to be obtained via software simulation [7]. Similarly, in Grujovic et al. in the cost model for FDM applied to the wood industry, building time is estimated via software simulation [8].

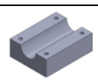
Recently, Urbanic and Hedrick hinted at the problem of shape complexity in FDM, discussing how intricate surfaces increase the building time [4]. According to the authors, the building time in FDM is directly related to the perimeter travel distances and the volume of the component. Because the travel speed of the outer delimiting contour is slower than the speed of the raster infill, components with intricate external surfaces would result in higher building times and therefore prove more expensive. Although this was a first attempt to consider the implications of shape complexity in AM, the paper did not offer an adequate investigation on the issue.

2 METHOD

The study aimed at comparing building time and material consumption of different shape complexities. A real object was selected as the basis for comparison. Although this limited the investigation of each parameter singularly (e.g. perimeter and building time), it allowed testing a more realistic scenario where complexity is influenced by different parameters at the same time. The object selected for the experiment was a load-cell holder for a scientific instrument. The load-cell holder was chosen because of its relatively simple box geometry, which allowed the exploration of numerous alternative shapes. The initial load-cell holder geometry 'B' (Table 1) was originally conceived for machining. It involved cutting a cuboid to the dimensions of 37.5 x 29.5 x 12.5 mm and performing two machining operations: drilling four 2.5 mm diameter holes with centres at 4.5 mm distance from the lateral outer surface and milling a semi-circular recess of 12.5 mm diameter for holding the load cell.

Table 1: Shape 'B', representation of use, Functional surfaces (white) and Design space (black).



Height (mm)	'B'
12.5	
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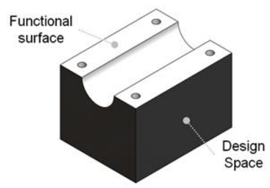


The top and bottom surfaces, the four holes and the semi-circular recess were defined as 'Functional surfaces' and used as fixed geometrical requirements for the design of the other design variations. The remaining volume of the original shape 'B' was defined as 'Design space' and used for altering the shape complexity [9]. Variations were designed using three parameters: shape complexity, height and thickness. Two thicknesses were considered, 1.5

mm, which is the minimum suggested thickness for vertical walls in FDM [10] and 3 mm. The geometries were also tested using the two different part heights 12.5 mm and 25 mm. The shapes were created by thickening and connecting the 4 holes diameters and cutting the semi-circular recess. Figure 1 presents the four different shape types conceived for connecting the holes. 18 design variations were generated using SolidWorks 2016 and saved in STL format with the finest resolution settings as shown in Table 2.

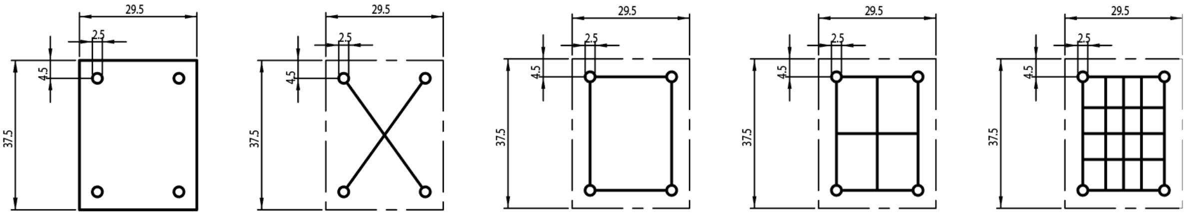
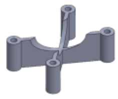
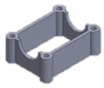
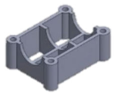
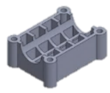
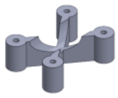
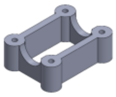
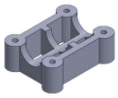
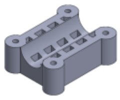
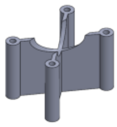
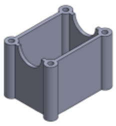
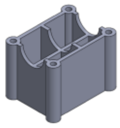
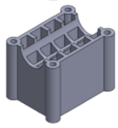
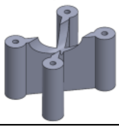
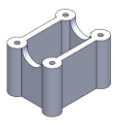
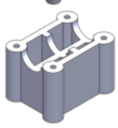
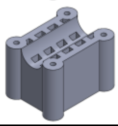


Figure 1: Layout of the shape types. From left to right ‘B’, ‘X’, ‘G1’, ‘G2’ and ‘G3’.

Table 2: Design variations

Thickness (mm)	Height (mm)	‘X’	‘G1’	‘G2’	‘G3’
1.5	12.5				
3	12.5				
1.5	25				
3	25				

Finally, a ‘Shape Complexity Index’ for FDM (C_{FDM}) was proposed in order to determine the geometrical complexity for each design variation. This index (Equation 1) was defined as the ratio between the surface area of the component (SA_C) and the volume of the envelope space between the functional surfaces(V_{es}). The volume of the envelope space between functional surfaces was defined as the volume of design space between functional surfaces.

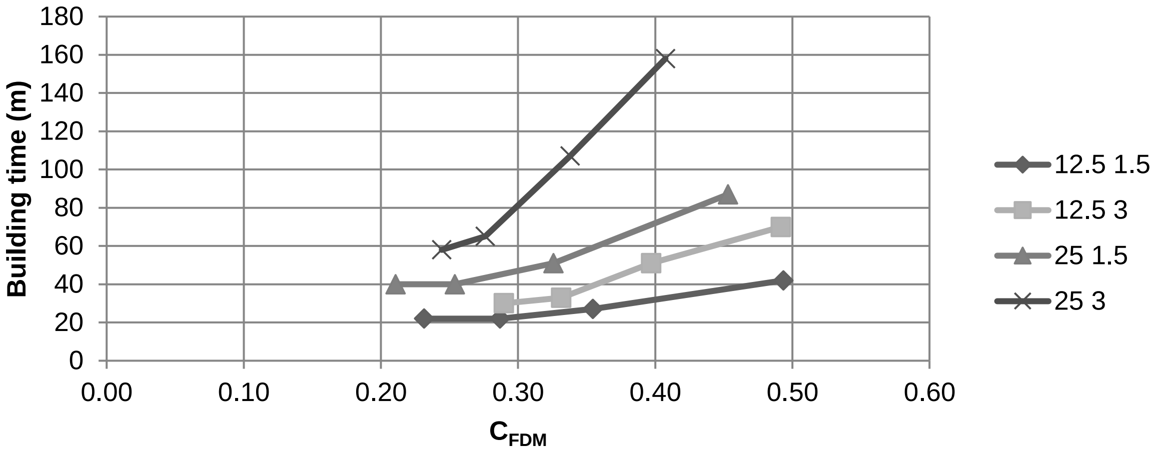
Equation 1: Proposed Shape Complexity Index for FDM

$$C_{FDM} = \frac{SA_c}{V_{bb}}$$

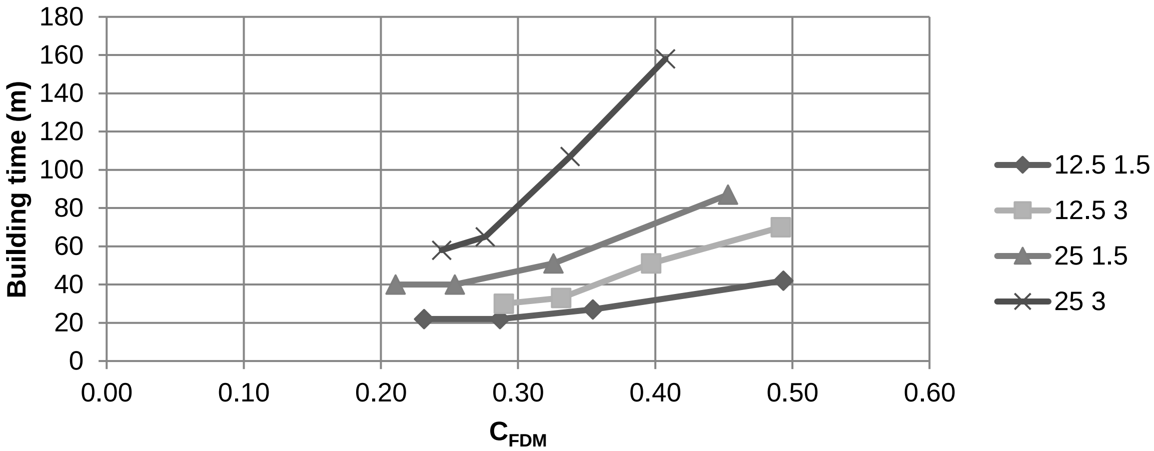
3 RESULTS

A Stratasys Dimension SST 1200es was utilised to fabricate the specimens and acquire data regarding building times and material consumption. A ‘Solid’ model interior (i.e. infill) was chosen for the shape types ‘X’, ‘G1’, ‘G2’ and ‘G3’; while ‘Sparse low density’ was used for the shape type ‘B’. The setting ‘Basic’ was used for the support infill in all the specimens.

The material used was ABS-P43™ Model (Ivory); the starting filament was 1.75 mm in diameter. The process parameters were 0.254 mm layer thickness, 78 °C building chamber temperature, 270 °C head temperature and soluble support type. No machining or polishing was performed on the specimens after support removal. Surface area and volume were taken from the CAD models. The Shape Complexity Indices were calculated using Equation 1 and are reported in in the appendices (Table 3). The data concerning the estimated material usage, estimated support usage and estimated printing time was collected from the software Catalyst EX, version 4.4, build 4339. The measurements of weight (related to the variables ‘Part weight with supports’ and ‘Part weight without supports’) and time (i.e. ‘Real printing time’) were performed using a digital scale (Precisa XB 3200 C) and an online stopwatch (Google stopwatch). The comprehensive results of the experiments are presented in the appendices (**Error! Reference source not found.**).

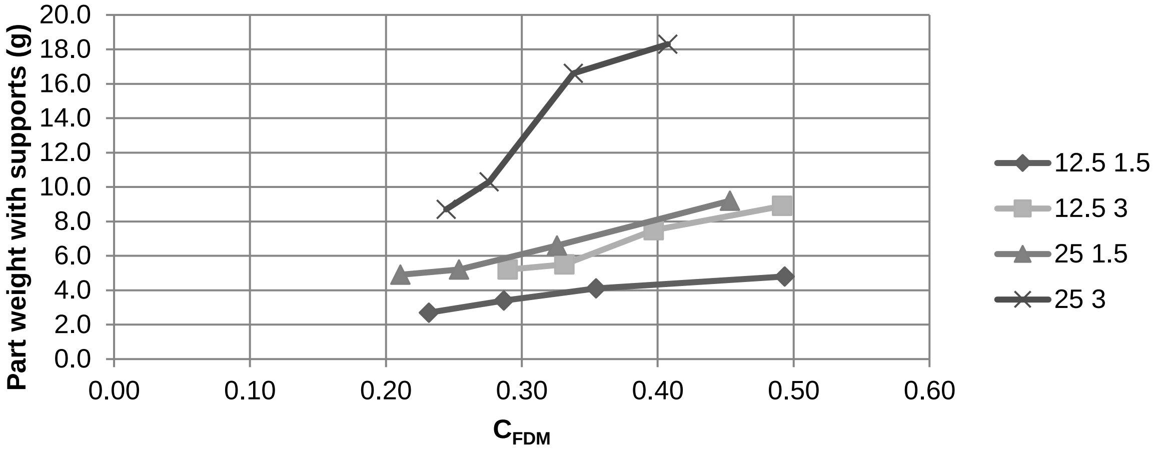


Graph 1 shows the production time in relation to the Shape Complexity Index proposed in this study. For all four combinations of height and thickness, the graph suggests a relationship between the Shape Complexity Index and production time.



Graph 1: Production time and Shape Complexity Index

The part weight including the supports was used to indicate material consumption. Graph 2 presents the relationship between Part weight with supports and the Shape Complexity Index. Similarly to Graph 1, Graph 2 illustrates a nearly linear relationship for all the height and thickness combinations.



Graph 2: Part weight with supports and Shape Complexity Index

4 DISCUSSION AND CONCLUSIONS

The overall results of this study indicate that building time and material consumption are affected by shape complexity. For all the combinations of height and thickness, shape complexity was directly related to an increase in building time and material consumption. Shape complexity also had a remarkable impact. In fact, the building time of the component with the highest Shape Complexity Index was generally twice the building time of the component with the lowest Shape Complexity Index. In the case of the group of components with the greatest height and thickness (height 25mm and thickness 3mm) the production time difference was three times longer. Since building time and material consumption are two key factors for estimating production cost [3], [7], [8], [11], these findings exemplify how shape complexity can have a significant impact on part cost. Therefore, these outcomes challenge the common assumption that in FDM ‘complexity is for free’. If the geometry of the part has an impact on cost, complexity has to be carefully considered.

Moreover, the concepts of ‘optimal’, ‘basic’ or ‘simple’ shape, which are common in conventional manufacturing, are new for FDM (and AM in general). The investigation and characterisation of these concepts would aid the design of cost effective components. An indication of these concepts can be observed by comparing the building time and the material consumption of the original shape type ‘B’ with those of the other shapes. In fact, in terms of manufacturability the components that obtained a shorter building time and a lower material consumption can be considered more efficient shapes. For instance, at thickness 1.5mm and both heights the shape types ‘X’, ‘G1’ and ‘G2’ obtained a shorter building time and a lower material consumption than the equivalent shape type ‘B’. Additionally, the shape type that resulted in the lowest building time and material consumption was the shape type ‘X’ which can be considered as the most efficient design for the load-cell holder. These findings suggest that an ‘optimal’, ‘basic’ or ‘simple’ geometry for FDM exists; and that shape may be different from a shape considered ‘optimal’ for conventional manufacturing technologies.

The Shape Complexity Index is also one of the contributions of this study. Although, the study does not provide large empirical evidence that the index can reliably predict building time and material consumption in FDM. In the case of the load-cell holder, the index showed a linear relationship with the dependent variables under the assumptions of constant thickness and height.

Previous studies showed similar effects in other AM processes [6]. It is possible therefore, that shape complexity may have similar implications in other AM processes where the effect of shape complexity on building time is due to the slower deposition speed of the outer delimiting contour [12]. The findings could be theoretically expanded to all the AM processes based on a vector-scan approach (e.g. SLA and SLS). Conversely, these findings are probably not applicable to processes adopting a line-wise approach (e.g. Material Jetting) or layer-wise (e.g. Light projection VAT Photopolymerisation processes).

Further work is required to expand and validate these findings and develop reliable design guidelines. Three potential research directions can be envisaged. The first direction should expand the results with other AM processes and in particular with laser sintering, vat photopolymerisation and material jetting. The second direction should explore the concepts of ‘optimal’, ‘simple’ or ‘basic’ component for AM and provide design principles and rules to guide process selection and design optimisation. Finally, the third direction should define the variables and quantify the impact of design features and complexity on building time and material consumption.

5 ACKNOWLEDGEMENTS

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7 APPENDICES

Table 3: Design variations with data derived from CAD, CAM and experimental campaign

Shape type	Nominal Height (mm)	Wall thickness (mm)	Surface Area (mm^2)	V_{es}	C_{FDM}	Estimated material usage (cm^3)	Estimated support usage (cm^3)	Estimated printing time (m)	Part weight with supports (g)	Part weight (g)	Actual printing time (m)
B	12.5	N/A	4385.77	11282	0.39	6.909	1.165	40	8.8	6.5	40
B	25	N/A	6453.47	24864	0.26	12.095	1.165	72	12.9	11.3	69
X	12.5	1.5	2613.07	11282	0.23	1.757	0.574	22	2.7	1.6	22
X	12.5	3	5240.48	11282	0.29	4.034	0.737	30	5.2	3.8	30
X	25	1.5	3267.09	24864	0.21	3.735	0.578	41	4.9	3.5	40
X	25	3	6076.38	24864	0.24	8.462	0.737	56	8.7	8.0	58
G1	12.5	1.5	3236.96	11282	0.29	2.222	0.862	22	3.4	2.1	22
G1	12.5	3	3738.15	11282	0.33	4.813	0.987	33	5.5	4.5	33
G1	25	1.5	6312.19	24864	0.25	4.516	0.862	40	5.2	4.3	40
G1	25	3	6863.8	24864	0.28	9.772	0.986	64	10.3	9.3	65
G2	12.5	1.5	4001.3	11282	0.35	2.708	0.863	26	4.1	2.5	27
G2	12.5	3	4478.7	11282	0.40	5.747	1.584	56	7.5	5.5	51
G2	25	1.5	8101.53	24864	0.33	5.736	0.863	51	6.6	5.4	51
G2	25	3	8404.35	24864	0.34	12.277	3.359	127	16.6	11.8	107
G3	12.5	1.5	5566.65	11282	0.49	3.881	0.863	43	4.8	3.7	42
G3	12.5	3	5547.19	11282	0.49	7.614	1.335	76	8.9	7.2	70
G3	25	1.5	11266.89	24864	0.45	8.401	0.863	89	9.2	8.1	87
G3	25	3	10131.69	24864	0.41	16.506	2.062	176	18.3	16.6*	158

* Internal supports were not completely removed.