Experimental optimization of fused deposition modeling process parameters: a Taguchi process approach for dimension and tolerance control

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Abstract

Additive manufacturing (AM) or 3D printing is an industrial revolution, challenging traditional manufacturing models, but is still in the development phase after more than 30 years of discrete existence in prototyping labs. AM is an advanced manufacturing technology that fabricates parts layer by layer from one from a digital model (CAO) that manages a digital stereolithography (STL) file. From standard NF ISO 17296-2, there are 7 families of the most used processes, such as FDM (Fused Deposition Modeling) was developed by S. Scott Crump, unction by the temperature setting of the machine (around 200 ° C), necessary for the melting of the material and deposited by a thin-layer nozzle that can range from 0.08 to 3 mm thick. Due to the nature of the FDM process many benefits appear but making functional parts using FDM has proved to be a difficult task. The difficulty comes from the influence of processing parameters such as: Platform temperature, Extruder temperature, Layer thickness, Number of shells, Infill density, print speed, Infill pattern and Number of solid layers on the final characteristics of the pieces. Our work presented provides an experimental study to analyze the effect of each processing parameter on the dimensional accuracy and time of manufacture of FDM parts. In general, 18 test samples were made using various treatment parameters. In order to analyze dimensional tolerances of these samples they were measured and compared to a 3D CAD model.

Keywords:
Additive manufacturing; Fused Deposition Modeling; Optimization of Processing Parameters; Taguchi method; dimensional tolerances.

1. Introduction

The engineering profession constantly reinvents itself through innovations and technologies so the world changes the industry also to meet the new expectations of consumers. It focuses on personalization and responsiveness. Additive manufacturing [1] is an industrial revolution that challenges traditional manufacturing models and disrupts the relationship between the manufacturer and the consumer. This process of shaping by adding material is a real economic and environmental opportunity.

Additive manufacturing or 3D printing the most popular term with the public is still in the development phase after more than 30 years of discreet existence in prototyping laboratories. The first technology was invented in France and the patent was filed on July 16, 1984 under the name "device to realize a model of industrial part" [2], based on the same technic, the Americans also deposited theirs on August 8, 1984 [3]. So additive manufacturing is not a new technology, manufacturers have been using it for more than 30 years mainly for prototyping [4,5].

Today, the 3D printing market offers different types of machines. So not so easy to locate, especially as each device has its own technology to make the object in volume. But whatever the used method, the volume object is always a layer-by-layer succession from a numerical model (CAD) [6] which manages a digital stereolithography (STL) file [7]. Based on the standard NF ISO 17296-2 [8], there are seven families of processes to use the most. The FDM [9] " fuse deposition Modeling " is the most popular method. It builds parts layer by layer ranging from 0.08 to 3mm thick, heating a thermoplastic filament (PLA, ABS) [12]] at over 200 °C and extruding it through a small nozzle of diameters (0.4mm, 0.6mm, 0.8mm, 1.00mm and 1.20mm) by 3D CAD model usually in STL format as shown in Figure 1. The filament usually has a circular section with specific diameters for each FDM system. The most used diameters are either 3.0mm or 1.75mm. After which the platform goes down and the printer proceeds in the same way for the following layers. The second machine works a little differently SLA [2,3] or stereolithography apparatus is the first AM technique ever invented. The third method of AM is polyjet technology [10], it works on photopolymerization and looks like a lot our major conventional inkjet. In the end the SLS technology "Selective Laser Sintering" [11] placed in a tank, a thin layer of powder material will agglomerate in the heat of a powerful laser pointed at specific locations. The fused powder assembles is solidified. It is called sintering.

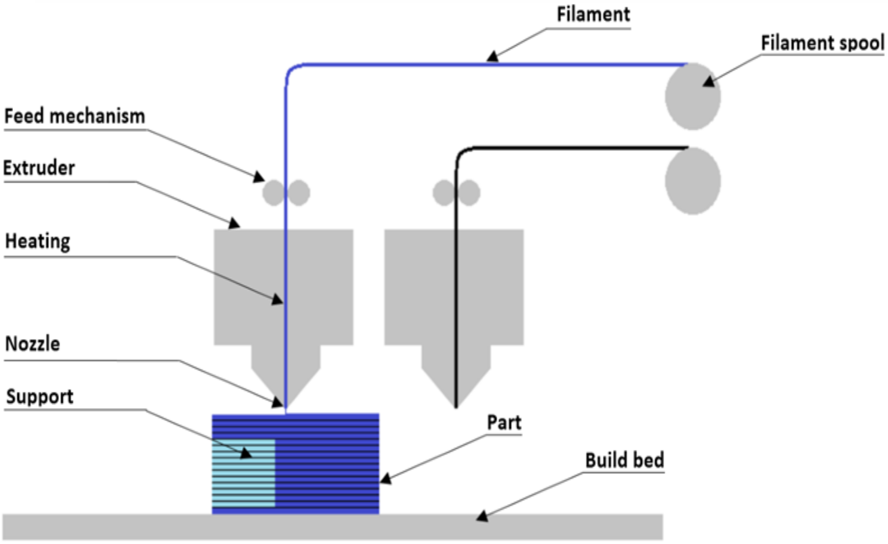

Figure 1. FDM process schematic.

From this revolution of the AM there are still limitations and many problems of 3D printing; the most common are problems of FDM technology.

In this paper, we will optimize one from these problems. This problem is created from the parameterization of the printing that can involve the time of the printing, the consumption of the raw material and the deviations of the dimensional tolerance of the manufactured parts. These parameters are requiring the availability of the reference to ensure that the processed additive manufacturing parts conform to the required design features, in particular geometric design features.

2. Material and methods:

2.1 Experimental work

The FDM printer used to make the samples is 3DP WORKBENCH, from 3DP Platform Industries, using 1.75 mm diameter PLA filaments and a 0.6 mm diameter nozzle. This FDM printer has a print volume measuring 1000 x 1000 x 500 mm with a positioning accuracy of 0.07 mm. The components are printed in the XYZ orientation at the center of the construction platform.
The samples used in this study to evaluate print time, raw material consumption and dimensional accuracy [18-19], they are modeled on the basis of ASTM D5418-07 [13] and 35mm length width 12.5 and height 3.5 as shown in figure 2. The sample used was drawn using SolidWorks 2016 and exported as an STL file. The STL file was prepared in FDM Simplify3d [14] to define all process parameters on all samples and generate the G code that created the toolpath.

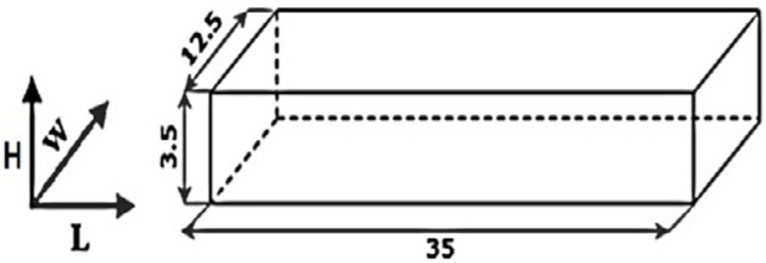

Figure 2. Created specimens' CAD model (in mm)

2.2 Experimental design:

To understand the influence of the modification of the processing parameters on the printing time, the consumption of the raw material and the dimensional accuracy of a printed part. An evaluation of optimization the control parameters that can influence the dimensional accuracy of the reference component has been completed. In this research, the treatment parameters studied are: Platform temperature, Extruder temperature, Layer thickness, Number of shells, Infill density, Print speed, Number of solid layers, and Infill pattern which was presented in Figure 3. Each of the parameters considered was assigned to only three levels Platform temperature that assigned two levels of control as shown in Table I. Some research work focuses on a single parameter, such as the building direction [20], while others focus on 3 or 4 treatment parameters at the same time. Effects as in [21], [22] and [23] where the effect of building direction, layer height, raster angle and other parameters are analyzed at the same time.

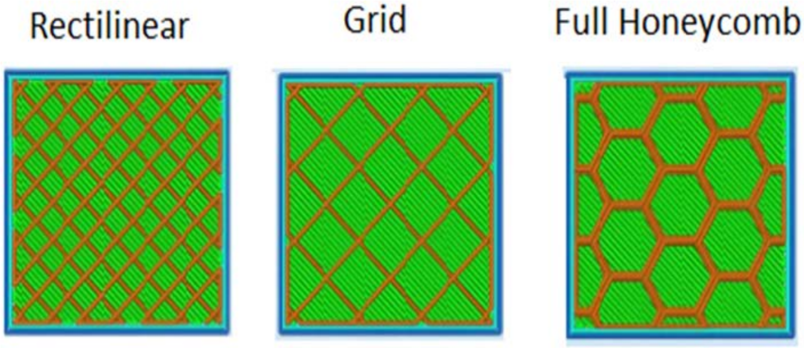

Figure 3. Infill patterns shape schematic

Table 1. Parameters and levels of varying Processing Parameters

Symbols	factors	Units	Levels
A	Platform temperature	°C	70 80
B	Extruder temperature	°C	190 200 210
C	Layer thickness	mm	0.15 0.3 0.5
D	Number of shells	--	1 2 3
E	Infill density	%	25 50 75
F	print speed mm/s	mm/s	50 65 80
G	Infill pattern 'H=1 D=2 L=3'	--	H D L
H	Number of solid layers 'U/L'	--	2 3 4

The values of the processing parameters that were used in Table 1 to establish a Taguchi's experience plan that were widely used in process optimization and product design studies [15-16] .Table 2 shows the values of treatment parameters that were used to establish a total of 18 samples. Thus, only one value was changed at a time in each printed sample.

The samples were measured using a three-dimensional measuring machine (MMT) that was programmed to perform the measurements automatically to avoid errors during the measurement process that may occur when measured manually. For the location of the samples in the MMT table were used a fixture to fix the reference components in place to allow for repeatability and ease of measurement.

Table 2. L18 Orthogonal array, Sample processing parameters specification

essai	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
1	70	190	0.15	1	25	50	1	2
2	70	190	0.3	2	50	65	2	3
3	70	190	0.5	3	75	80	3	4
4	70	200	0.15	1	50	65	3	4
5	70	200	0.3	2	75	80	1	2
6	70	200	0.5	3	25	50	2	3
7	70	210	0.15	2	25	80	2	4
8	70	210	0.3	3	50	50	3	2
9	70	210	0.5	1	75	65	1	3
10	80	190	0.15	3	75	65	2	2
11	80	190	0.3	1	25	80	3	3
12	80	190	0.5	2	50	50	1	4
13	80	200	0.15	2	75	50	3	3
14	80	200	0.3	3	25	65	1	4
15	80	200	0.5	1	50	80	2	2
16	80	210	0.15	3	50	80	1	3
17	80	210	0.3	1	75	50	2	4
18	80	210	0.5	2	25	65	3	2

3. Results and Analysis:

Experimental results for dimensional accuracy, time of printing and material consumption were recorded and analyzed

3.1 Dimensional Accuracy and Repeatability:

The dimensional deviation of length L that was calculated represents the dimensional accuracy achievable by the FDM process. The average dimension, the measuring range and the deviation for each characteristic are shown in Table 3. This table shows the measurement results taken for the 18 samples.

The width measurement W were averaged into a single width value for each sample achievable by the FDM process. The results of these measurements are presented in Table 4.

The dimensional difference of the height H that was calculated shows the dimensional accuracy achievable by the FDM process. Which have been averaged into a single height value for each sample. The results of these measurements are presented in Table 5.

Table 3. Samples measurements length results (in mm).

essai	**LA**	**LB**	**Average**	**error**
1	34,896	34,865	34,880	0,120
2	34,7975	34,719	34,758	0,242
3	34,707	34,671	34,689	0,311
4	34,782	34,809	34,795	0,205
5	34,752	34,809	34,780	0,220
6	34,757	34,807	34,782	0,218
7	34,845	34,832	34,839	0,162
8	34,881	34,834	34,857	0,143
9	34,910	34,772	34,841	0,159
10	34,878	34,772	34,825	0,176
11	34,699	34,692	34,695	0,305
12	34,755	34,728	34,742	0,258
13	34,712	34,779	34,746	0,255
14	34,764	34,723	34,743	0,257
15	34,934	34,890	34,912	0,089
16	34,805	34,724	34,764	0,236
17	35,118	35,057	35,087	-0,087
18	34,720	34,714	34,717	0,283

Table 4. Samples measurements width results (in mm).

essai	**WA**	**WB**	**Average**	**error**
1	12,434	12,381	12,408	0,092
2	12,372	12,357	12,365	0,135
3	12,224	12,210	12,217	0,283
4	12,324	12,310	12,317	0,183
5	12,365	12,361	12,363	0,137
6	12,342	12,362	12,352	0,148
7	12,316	12,319	12,318	0,183
8	12,371	12,340	12,356	0,145
9	12,451	12,323	12,387	0,113
10	12,203	12,209	12,206	0,294
11	12,290	12,252	12,271	0,229
12	12,342	12,279	12,311	0,189
13	12,245	12,240	12,243	0,258
14	12,366	12,355	12,360	0,140
15	12,486	12,448	12,467	0,033
16	12,401	12,284	12,343	0,157
17	12,553	12,479	12,516	-0,016
18	12,300	12,344	12,322	0,178

Table 5. Samples measurements height results (in mm).

essai	**HA**	**HB**	**Average**	**error**
1	3,338	3,464	3,401	0,099
2	3,404	3,412	3,408	0,092
3	3,263	3,250	3,256	0,244
4	3,247	3,234	3,240	0,260
5	3,335	3,363	3,349	0,151
6	3,261	3,232	3,247	0,253
7	3,251	3,255	3,253	0,247
8	3,401	3,409	3,405	0,095
9	3,220	3,155	3,187	0,313
10	3,420	3,424	3,422	0,078
11	3,426	3,426	3,426	0,074
12	3,368	3,302	3,335	0,165
13	3,240	3,243	3,241	0,259
14	3,396	3,404	3,400	0,100
15	3,307	3,325	3,316	0,184
16	3,255	3,285	3,270	0,230
17	3,332	3,327	3,329	0,171
18	3,171	3,203	3,187	0,313

The first note for all results is that all errors have positive values, which shows that the machine tends to create larger objects than expected. Platform temperature has little or no influence on dimensional error, as shown in Figure 4-a. From Figure 4-b, it is clear that Extruder temperature has a significant effect on dimensional accuracy; when the extrusion temperature increases, the error increases for the height and the opposite for the width and length. In the figure 4-C, we can see that a more average layer height generally gives lower results. In addition to that, we can that when the layer height was 0.3 mm, the error was small in thickness even if the height of the layer is relatively large or small, which is explained by H = 3.50 mm an integer multiple of 0.3 mm. This explains the jump of error when the layer is slightly decreased to 0.15 mm or increased to 0.50 mm. All that shows the importance of the height of the layer on the dimensional accuracy [17]. Infill density and print speed has little influence on dimensional geometry in a margin of 0.05mm in length and 0.025mm in width and height, as shown in Figures 4-e and 4-f. it can be seen that when using a single shell it gives weaker results which was presented in Figure 4-d. In addition, we can see that when we increase the number of shells the error remains a little stable. The use of Infill pattern rectilinear has a significant influence on the dimensional geometer compared to Infill pattern grid which has a small dimensional error, as shown in Figure 4-g. Number of solid layers that have been shown in Figure 4-h has a great influence on length and height compared to width and when we increase the number of solid layers the error increases.

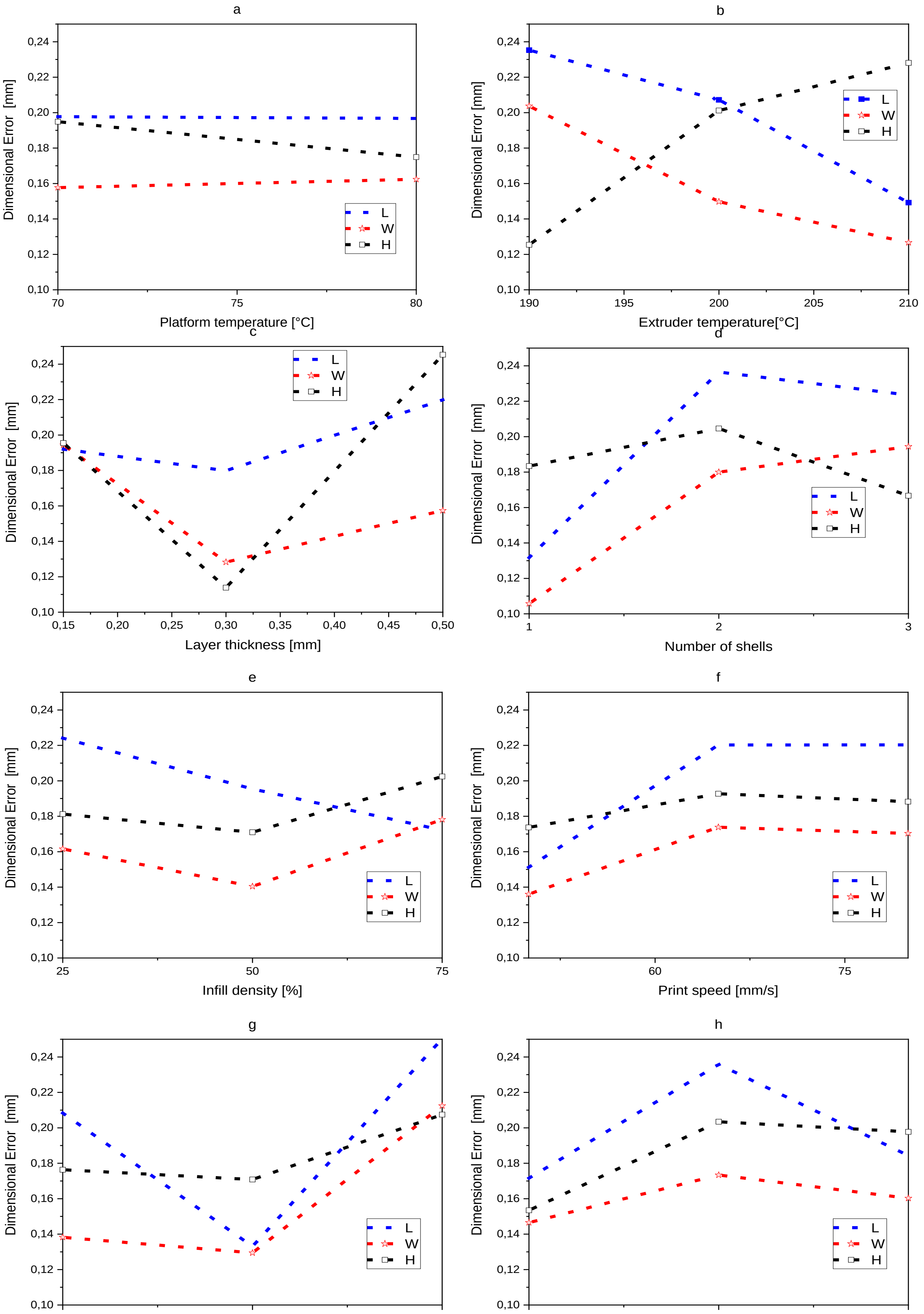

Figure 4.The dimensional error [mm] caused by (a) Platform temperature, (b) extrusion temperature, (c) layer height, (d) Number of shells, (e) infill precentage, (f) printing speed, (g) infill patterns and (h) Number of solid layers

3.2 Print time and material consumption:

Print Time T calculated represent the time required to print each sample by the FDM process. Consumption of PLA material represents the mass of material needed to construct each sample. Table VI shows the results of Print Time and Material Consumption taken for the 18 samples.

Table 6. Print time and material consumption

essai	**print time (min)**	**weight of the plastic (g)**
1	4	1,07
2	3	2,00
3	2	2,35
4	5	1,58
5	3	1,96
6	2	2,25
7	4	1,79
8	4	1,50
9	2	2,32
10	6	1,97
11	2	1,67
12	3	2,36
13	7	1,86
14	3	1,99
15	2	2,07
16	5	1,64
17	4	2,20
18	2	1,93

The first remark is that the Platform temperature and Extrude temperature has little or no influence on print time and material consumption as shown in Figures 5-a and 5-b. From Figure 5-c, it is clear that layer height has a significant effect on print time and consumption; as the layer height increases, the consumption increases and the printing time decreases, and the opposite when the layer height decreases. Then Figure 5-e shows that Infill density is also influencing the results, when the percentage of filling increases the consumption and the time of printing increases. The Number of shells has little influence on the results, as shown in Figure 5-d. print speed has an influence just on the time of the impression which was decreased when the print speed increases, and has little effect on the consumption of the material ; as Figure 5-f shows. Number of solid layers and Infill pattern have no effect on the time of printing that remains stable, but they do influence the consumption of the raw material as shown in Figures 5-g and 5-h.

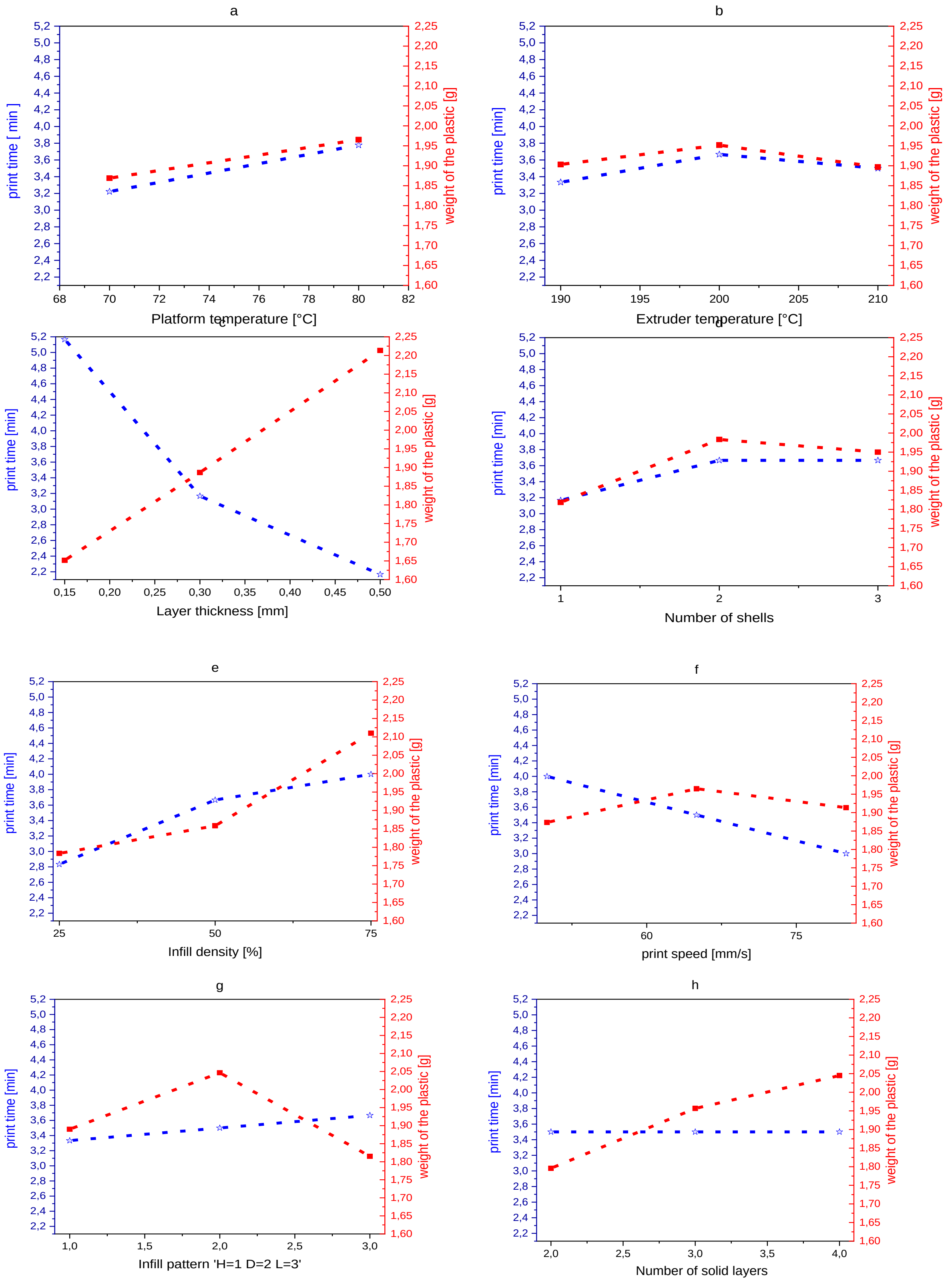

Figure 5. Print time (min) and material consumption (g) caused by (a) Platform temperature, (b) extrusion temperature, (c) layer height, (d) Number of shells, (e) infill percentage, (f) printing speed, (g) infill patterns and (h) Number of solid layers

4. CONCLUSION:

This paper examines the effect of FDM processing parameters on the final geometry of printed parts, material consumption and printing time. The study examines the influence of eight processing parameters which are: Platform temperature, Extruder temperature, Layer thickness, Number of shells, Infill density, Print speed, Infill pattern and Number of solid layers. Using Taguchi's experimental design method is a new approach developed to model and optimize print parts by FDM. The 18 reference components were constructed based on the experimental design and measurements that were made on the samples.

Generally, to improve the dimensional accuracy we need a higher Extruder temperature, higher Infill density, average Layer thickness, lower print speed, low number of shells, low number of solid layers and Infill pattern grid which less dimensional error. The dimensions may be preferable when comparing several dimensions at the same time, so that the error in the width and its changes is a little negligible compared to the errors of the other dimensions if the error has been described as a percentage error.

It has been demonstrated that the time of printing is significantly influenced by Layer thickness, Infill density and printing speed; less significantly by Extruder temperature, Number of shells, Infill pattern and Number of solid layers. For decreased printing time, higher printing speed and higher layer height are required in addition to low infill density. To decrease the consumption of the material; Infill density more reliable, small layer height and low Number of solid layers are required.

Future work in the field of research on the FDM process, the process of additive manufacturing shows a maximum of knowledge in making engineering applications with high quality parts, accuracy and high properties with low consumption and reduced printing time.

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