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MULTI-CRITERIA ANALYSIS OF FDM ADDITIVE MANUFACTURING PROCESS FOR COMPONENTS WITH CYLINDRICAL GEOMETRY

Mircea Dorin VASILESCU, Doru-Alexandru LUCA

Abstract: *This work was carried out as a continuation of previous studies related to the influence of positioning of gear-type or tubular parts. The authors considered expanding the investigation process by approaching in parallel the modified psychological experimental analysis, but also considering the economic, environmental and dimensional aspects and the surface quality for stepped cylindrical parts. To make the parts, a material was used that has as its basic structure poly lactic acid which is modified to be able to work at high printing speed. To establish the optimal constructive orientation that can influence the manufacturing process of the parts, the printing surface was considered. Based on the present study, it was observed that making the parts in a vertical position best satisfies the environmental and constructive criteria and was positioned in the same place at a short distance from the economic point of view from the horizontal printing position.*
Keywords: *Additive manufacturing, PLA, 3D Modelling, 3D Printing, Dimensional measurements.*

1. INTRODUCTION

The additive manufacturing process by depositing plasticized material can be a first option, due to both the reduced consumption of electricity obtained from renewable solar and/or wind resources, respectively hydraulic, but also due to the relatively low emissions from the production process of smooth or stepped cylindrical parts. The advantage of making such parts is given by several technological elements that are worth analyzing, one of which is the reduction of the processing process that is used in the case of conventional processing processes. In the case of adopting the method, the decision that can be made is multiple and has both dimensional, constructive, and environmental implications. The production of these elements from an additive point of view involves studying both the surface quality in relation to which conventionally and additively made mechanical components enter [1]. The most used additive manufacturing processes that have a relatively low energy consumption level are divided into two large categories. The first ones that use a thermal source, filament deposition by thermal modeling (FDM) [2-4], respectively those that use laser beam photopolymerization (SLA) [5], or those that use the laser for localized melting of granular material particles (SLM or SLS) [6]. All of these are based on a process of moving the energy system along linear trajectories and generate layers of material based on the GCODE programming language. A special system is the one that uses an LED matrix assembly that ensures the hardening of the resin layer simultaneously on the entire printing surface [7].

The authors considered, from the study of specialized literature [9], but also of the automatic orientation programs specific to some software for generating layers for making references. Some of these recommend an orientation other than the vertical one, for optimizing printing. It must be mentioned that both professional and free software were analyzed. The multi-criteria analysis tried to harmonize most of the previously mentioned observations and subsequently in other research activities, to develop an interface that would have as a starting point for automatic orientation for printing reference the results of the present study.

In the work undertaken, the authors propose a solution for using psychological experiment [8] in which it is proposed to replace the consultation of specialists with the qualitative or quantitative determination of the value of environmental [10] or economic, technological conditions that can influence the development of a manufacturing process such as additive manufacturing. Given this adopted methodology, it can be observed that a subjective factor related to the knowledge of the manufacturing process better or less well by them will be replaced with quantifiable elements that are much more precise and closer to the phenomenological reality of the process. For this study it is take into consideration the solution of an exploratory variant considering the new types of PLA materials that have appeared on the market, but also considering the technological printing system with very good energy efficiency compared to those previously studied by the authors and in the specialized literature investigated.

2. MATERIALS AND METHODS

2.1 Material

From the basic data of the temperature at the e level of the material chosen for the printing process, it can be seen from Figure 1 that it is optimized in a very narrow temperature range (200ºC to 210ºC). This parameter greatly differentiates this type of filament from other similar existing ones and products of renowned companies. Also, for the printing surface a temperature between 0°C and 60°C is recommended, respectively in the workspace it is recommended to be a temperature of approx. half of bed printing surface. From bibliographic reference the recommended printing speed is 200 mm/sec, and the material is recommended for educational projects, low-stress printed pieces, and functional components.

2.2 Printer

To do experimental research, an ANYCUBIC KOBRA 2 PRO, type cartesian printer, was used, equipped with a single nozzle for material extrusion Figure 2.

Fig. 1. ANYCUBIC white PLA in silica bag

Fig. 2. ANYCUBIC KOBRA 2 PRO printer

From the data sheet of the printer the dimensions are 220x220x250 mm. The printing speed is max. 250 mm/sec and medium 150 mm/sec. It has an accelerated speed of 250 mm/s^2, and an accuracy of printing ±0,1 mm. An important aspect that makes this printer a semi-professional is the direct material extrusion with a row of two gears for pushing the filament. Finally, the extrusion nozzle is at the level of those of the E3D VULCANO, thus having a long thermal transfer length of the temperature. The recommended ambient temperature when the printer is not in use is between 8°C and a maximum of 40°C. Also, from a humidity point of view, it should be 20% to 80%.

From a constructive point of view, the printer has a vertical feed system with two trapezoidal screws on the sides, a precision guidance system on all axes with very good linearity and, most importantly, a material extrusion system of the highest quality, both kinematic and thermal. If we add to this the optimization of the material used for printing to achieve the desired parts, we reach the area of a semi-professional printer from a kinematic point of view.

2.3 Slicer

The authors of the study opted to use the IDEAMAKER 5.2.0 program due to considerations related to certain facilities that it allows, and which optimize both the printing process and the dimensional one.

As can be seen from the generation step of layer number 185 at a height of 37.08 mm, the portion generated with yellow is a perfectly closed contour inside the part. Also, the density chosen for the interior was 20% Figure 3. The part was oriented on the printing surface in a vertical position with the largest step at the base and the smallest at the top. This will determine the lowest material consumption, as no support is required in the printing process. The printing time is 1 hour and 53 minutes with a consumption of 5160 mm of thread and a mass of 15.4 grams.

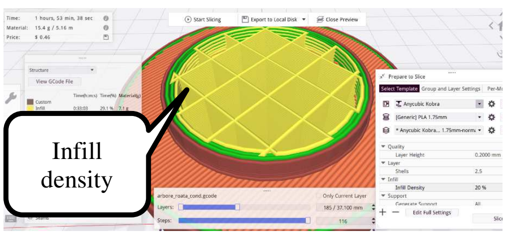


Fig. 3. Slicer line layer 185

A second aspect that can be seen from Figure 3 is the interpenetration of the inner third layer with the continuous layer of the third layer. This will determine a better resistance to the mark on its periphery. It should be noted that there are few slicers that have such an option for generating print lines.

A major advantage of the layer generation program for creating the axis is that it shows the recommended areas for supporting the volume generated during the layering process. In Figure 4, in petrol blue, it is possible to observe the areas that are recommended to be provided with support elements.

The need for support and the logic for generating lines during the printing process can be clearly seen in Figure 5, where blue is the structure generated for support, brown is the outer layer of the section, and yellow shows the radial network generated to create the body of the part.

2.4 Measuring devices

The devices used for dimensional measuring were a caliper with an accuracy of the measuring dimension of 0.01 mm, but also those for gas emissions during the printing process that were presented in the study. In this study the specific aspects of both calibration and comparison of measured values with individual emission measurement sensors were presented Figure 6.

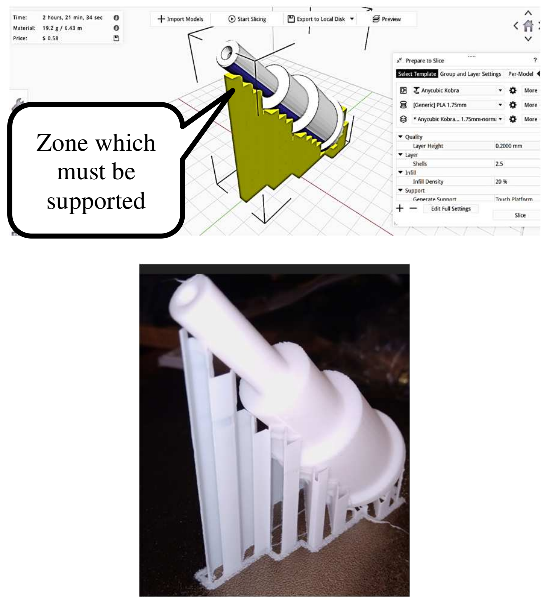


Fig. 4. Surface which needs support top slicer solution, bottom printed solution

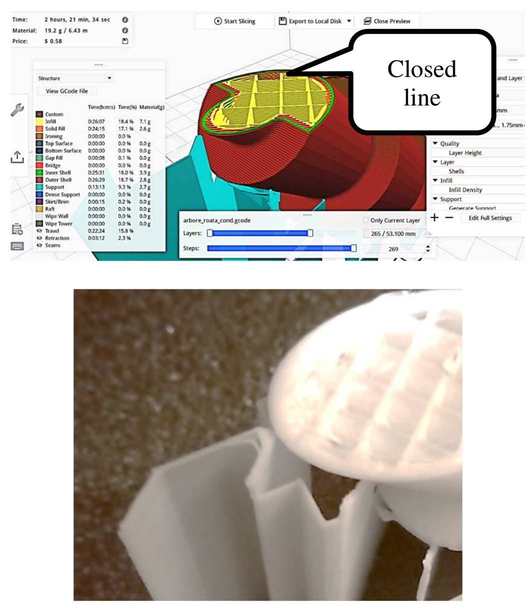


Fig. 5. Structure for generating the layer with support, top slicer solution, bottom printed solution

The initial parameters of the space in which the printer is located were determined by measuring together with the entire assembly, printer turned on, filament inserted into the nozzle and before loading the program for printing. From the level for CO_2 this is 654 ppm, the TVOC is 0.517 ppm, and the HCHO is 0.070 ppm. The humidity is 44% and the printing space temperature in the space in which the printer is put is 25°C.

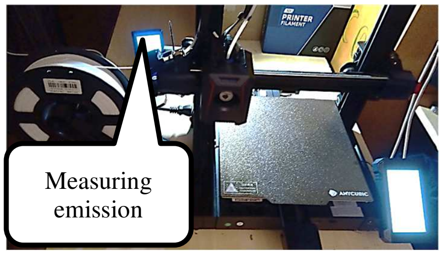


Fig. 6. Measuring gas emissions in space for printing processes.

2.5 Method

The method used in the study is an assembly of steps in which in first position is the generation of the cylindrical element in report with the CAD generation. For generations it is used INVENTOR EDUCATIONAL SOLUTION Figure 7. The software has a great advantage in that it permits to mark the dimensional value directly in 3D CAD space. It is possible to observe that there are four cylindrical parts.

The study of the optimum position in printing solution is conducting with an experiment type psychological in which was assigned value from 1 to 5, 1 is assigned for the lower quality and 5 for the largest quantity. This quantification method was considered for each of the quantitative or qualitative physical quantities considered in this study.

3. RESULTS AND DISCUSSIONS

3.1 Mass of the printed axis

The analysis of the mass of material involved in the printing process was carried out considering both the results obtained based on the values determined by the layer generation program, but also by weighing them using a pharmaceutical balance with milligram measurement accuracy (precision is 0,1 grams for small than 500 grams mass), the maximum mass that can be measured is 2 kilograms. The data were centralized and based on them the comparative graph between the two sets of values was made, being graphically represented in Figure 8.

An important aspect that can affect this correlation is the amount of dye and its mass weight. Considering the rule for carrying out the experiment, we will give the lowest value for the shortest mass (90°) and the highest value, i.e. 5 units, for the greater mass (45°) Table 1.

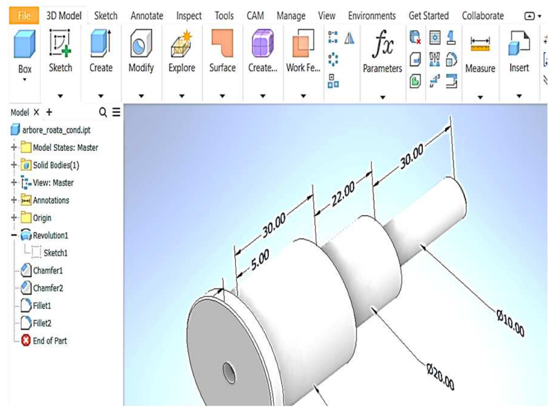


Fig. 7. Dimension for cylindrical structure generated.

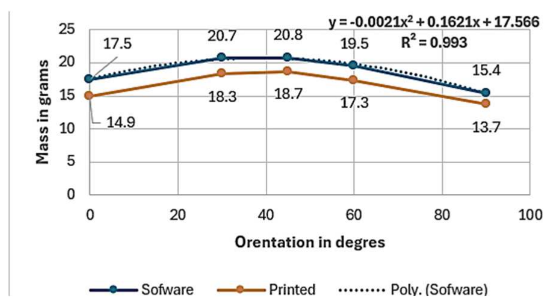


Fig. 8. Mass for cylindrical structure generated.

Table 1

Ranking according for printing time.

Printing angle	Software mass [grams]	Printed mass [grams]	Value
0°	17,5	14,9	2
30°	20,7	18,3	4
45°	20,8	18,7	5
60°	19,5	17,3	3
90°	15,4	13,7	1

It should be noted that the program for slice generation determines for each orientation the thread length that is consumed Figure 9.

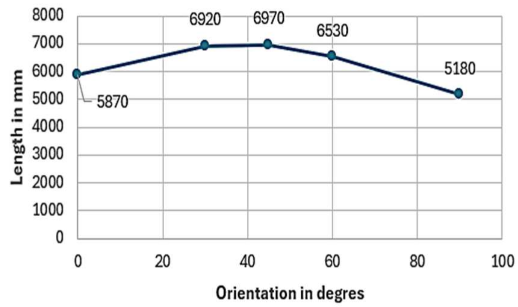


Fig. 9. Thread length is used for cylindrical structure generated.

In this point it is possible to determinate if there is a correlation between the calculated value, but also the ratio between the measured and calculated mass values.

The evolution of the length of the thread used to manufacture the shaft is like that of the mass determined by weighing. Consequently, we did not consider this technological component as a factor involved in determining the importance of orientation. However, an improvement that can be made to the constructive solution of such a printer is the introduction of a system for continuously determining the length of thread that is consumed during the process.

At the same time, the amount of material used to make the supports is not a quantity that can be quantified as an important factor, as it is included in the total mass of the additively manufactured part.

3.2 Time used for printed axis

The duration of the additive manufacturing process is a very important factor considering both its implications in the economic process of determining the costs of using the equipment, energy consumption and, to a lesser extent, salary remuneration.

In Figure 10, it is possible to observe that the longest time to create the part, both calculated by the layer generation program and measured by the printer during the printing process, is for the part orientation at 45^o relative to the surface on which the printing is performed, and the shortest is for the horizontal positioning, followed at a short distance by the vertical generation.

Considering the rule for carrying out the experiment, we will give the lowest value for the shortest duration and the highest value, i.e. 5 units, for the longest duration Table 2.

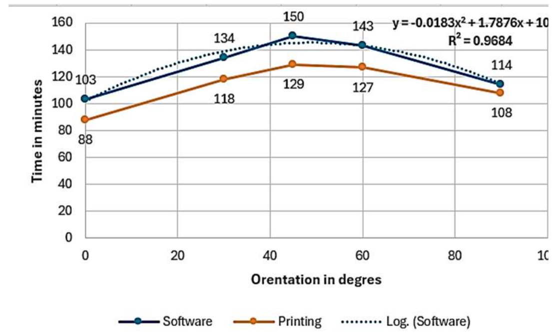


Fig. 10. Printing time for cylindrical structure.

Table 2

Ranking according for printing time.

Printing angle	**Software time [minutes]**	**Printing time [minutes]**	**Value**
0^o	103	88	1
30^o	134	118	3
45^o	150	129	5
60^o	143	127	4
90^o	114	108	2

From the analysis of the printing time, it seems that there are deviations between the duration calculated by the program and the duration achieved during the printing process. Consequently, we recommend for each type of material, but also type of printer, due to considerations of the extrusion assembly, that for a calculation as close as possible to reality, an in-depth study be carried out.

3.3 Analysis of the manufacturing process from an economic point of view

Based on the information obtained from the analysis of the previously mentioned factors, a first ranking of the importance of orientation in relation to the economic component of manufacturing the analysed item can be established. The analysis is done by summing the unit values assigned to the previously analysed factors and the data were centralized in Table 3.

Table 3

Ranking according for the minimum economical value.

Printing angle	**Mass**	**Time**	**Sum**	**Obs.**
0^o	2	1	3	
30^o	4	3	7	

45º	5	5	10	
60º	3	4	7	
90º	1	2	3	
Total	15	15	30	

From a strict economic point of view the best value by far is obtained by positioning the axis horizontally and vertical positioning. The 60º and 30º positionings are tied for third place, and the last fifth position is for the 45º positioning.

3.4 Analysis of the manufacturing process from an ecological point of view

To determine whether there are large differences between the first two orientations that were determined by the previous economic study to be the most cost-effective, we performed measurements of the environmental parameters in the printing area during the printing process. From an experimental point of view, the vertical sample was printed first and then, after cooling it at the end of the printing, the horizontally arranged sample was made.

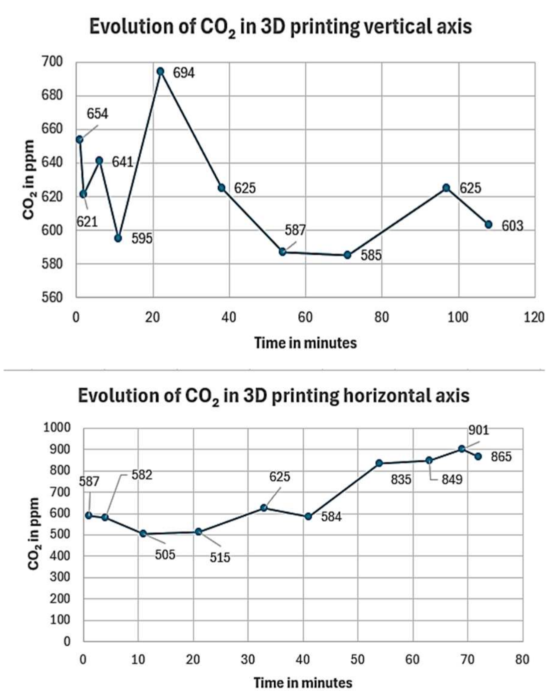


Fig. 11. CO_2 emission top for vertical position, bottom for horizontal position.

This aspect is very important because both the temperature and humidity parameters, respectively the gas emissions resulting from the first printing, modify the initial parameters. At the same time, the determinations were made at time intervals that are specific to the cross-sectional areas during the additive manufacturing process, which determine both emissions and environmental changes.

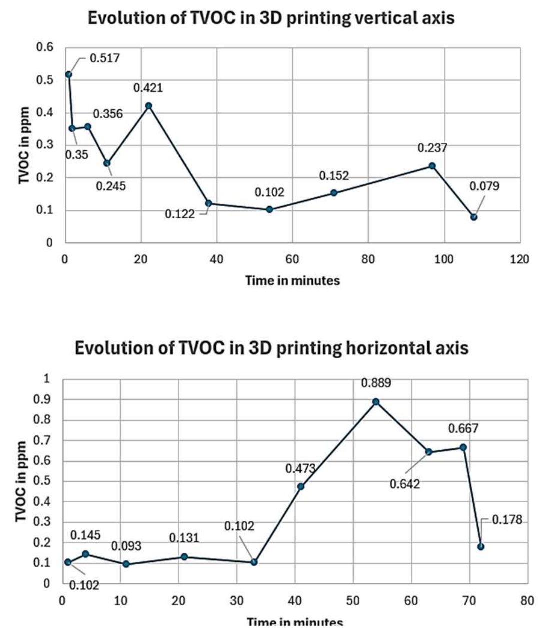


Fig. 12. TVOC emission top for vertical position, bottom for horizontal position.

From the analysis of the data in Figure 11, it can be observed on the one hand that the larger the printing surface, the higher the emission level, in the case of the area from 10 to 40 minutes for the vertical position, but also a maintenance of relatively slightly increasing emissions from minute 20 onwards, considering that the horizontal orientation.

The same evolution has the emissions for TVOC Figure 12 and HCHO Figure 13 as detailed for CO_2.

From the analysis of the emission values related to all three types of gases analyzed, the vertical variant is more efficient, producing a lower level of them than the horizontal one. Consequently, from the point of view of this analysis criterion, it can be concluded that the best solution is vertical printing.

At the same time, if by the law of similarities, it was observed that the emissions increase as a value with the printing surface, the other three positioning options have a larger printing surface compared to the horizontal one, so they retain their positions that were assigned to them in the first comparison criterion.

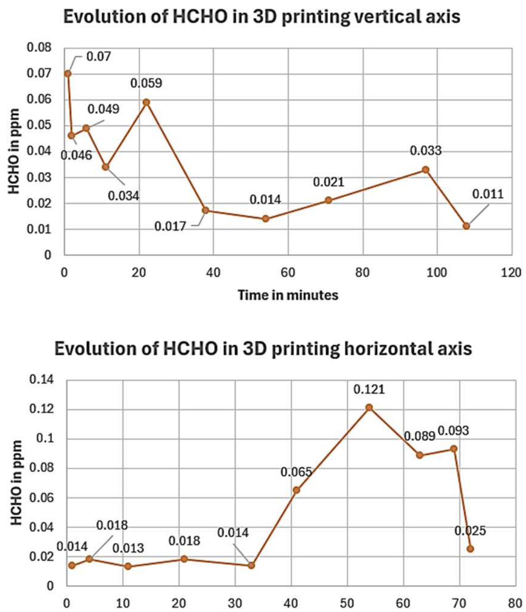


Fig. 13. HCHO emission top for vertical position, bottom for horizontal position.

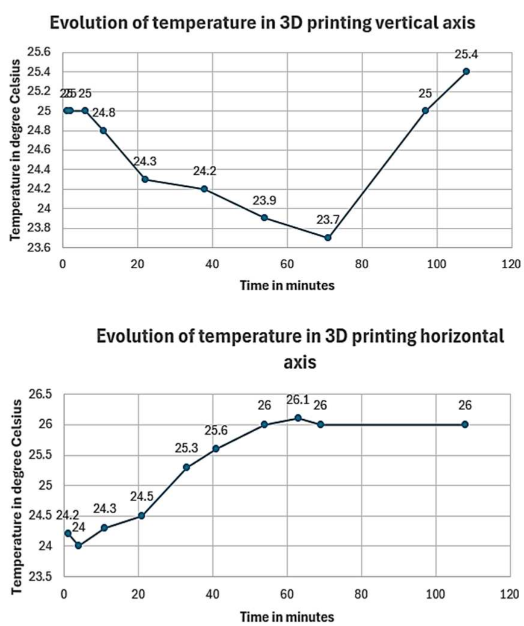


Fig. 14. Temperature evolution top for vertical position, bottom for horizontal position.

From the point of view of the evolution of temperature Figure 14, and humidity Figure 15, it can be observed that the temperature level is increasing, and the humidity is slightly decreasing, which favors the thermal process by reaching the optimal environmental level, but also the reduction of humidity favors the achievement of a more stable behavior of the material used for printing.

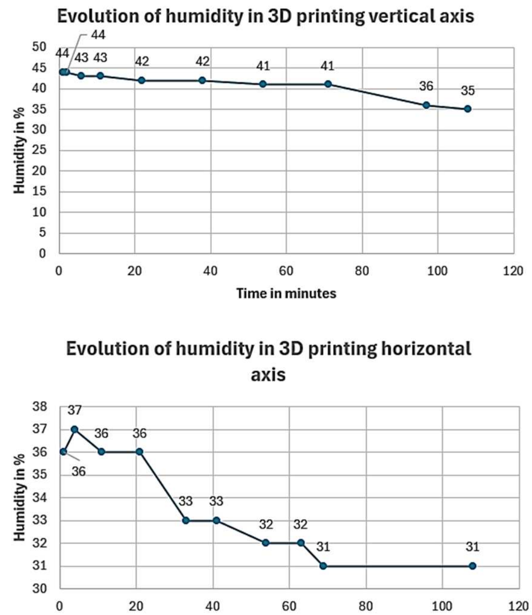


Fig. 15. Humidity evolution top for vertical position, bottom for horizontal position.

The ranking analysis is done by summing the unit values assigned to the previously analyzed factors and the data were centralized in Table 4.

Table 4

Ranking according for the minimum ecological value.

Printing angle	Vertical	Horizontal	Value 90°	Value 0°
CO_2	694	901	1	2
TVOC	0,517	0,889	1	2
HCHO	0,07	0,121	1	2
Temperature	25,4	26,1	1	2
Humidity	44	37	2	1
Total			6	9

From a strict ecological point of view the best value by far is obtained by positioning the axis in vertical orientation.

3.5 Layer number used for generation

An important factor to consider in the analysis is the number of layers considered. This is a constructive factor and from the point of view of the printing process has for the case of the present study a first thickness of 0.28 mm, and for the other layers a thickness of 0.20 mm. If we consider this previously mentioned aspect with the formula marked in bold at the top of the table Figure 16, we can determine the maximum height of each of the five orientations considered. For the psychological analysis we will not take it into account, as it is correlated with the qualitative analysis of the surfaces generated in the additive manufacturing process.

		0.28+(layer-1)*0.2
Orientation in grd.	Layer number	Heigth in mm
0	179	35.88
30	314	62.88
45	385	77.08
60	431	86.28
90	435	87.08

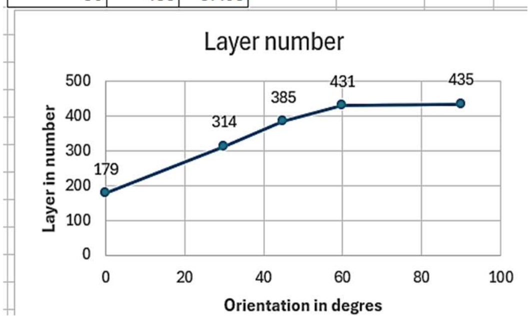


Fig. 16. Layer analysis for cylindrical structure.

3.6 Dimensional measurements and errors

The study continued the dimensional side, with the dimensional sizes being determined on each of the manufactured axes by measuring with an accuracy of 10 microns. Measurements were made both according to the generated diametrical areas, but also according to those of the height of the cylindrical areas. The results for vertical position were centralized in Figure 17. It should be noted that the measurements were made for two perpendicular diameters, determining the deviation between the nominal value and the measured one. The same principle was also used according to the height of the cylindrical areas.

From the measurement sheet for vertical positioning, it can be seen that from the point of view of the diametric values, there are differences from the nominal value but they are in agreement with the value of the latter and as can be seen from the graph on the bottom right the deviation increases according to a polynomial equation of degree 3 as the diameter increases. From the point of view of the changes in the nominal heights in the vertical direction, all have values below the nominal height value, which means that due to the pressing forces of the extruded material on the previous layer compression occurs.

		Direction		Deviation	
	Nom.Val.	X	Y	X	Y
Diameter	10	9.79	9.79	-0.21	-0.21
	20	19.70	19.64	-0.30	-0.36
	30	29.51	29.49	-0.49	-0.51
	36	35.47	35.44	-0.53	-0.56
Length	5	4.60	4.63	-0.40	-0.37
	30	29.62	29.59	-0.38	-0.41
	22	21.62	21.70	-0.38	-0.30
	30	29.55	29.51	-0.45	-0.49
		85.39	85.43		micron
		1.69	1.65	1.67	3.84
					0.77

Diam	Dev.
10	-0.21
20	-0.33
30	-0.50
36	-0.55

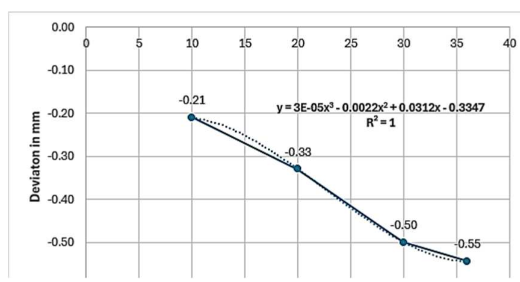
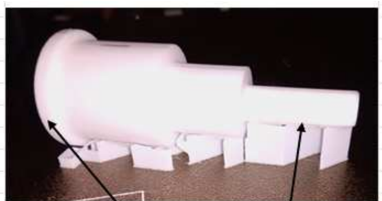


Fig. 17. Data sheet for vertical cylindrical structure generated top printed ax, middle data sheet, bottom diameter deviation graph.

This was determined by calculating the height of the layers according to the generation program and the height resulting from the printing process. The compression value per layer compared to its thickness of 0.20 mm is 0.77 microns, and per layer of 3.88 microns, the average height reduction is 1.67 mm.

For the horizontal positioning solution, it can be observed that according to the direction of the cylindrical areas, the measured values show a deviation that transforms the surface from a cylinder into an oval with a horizontal diameter greater than its value in the vertical plane Figure 18.

The ovality is due to the same pressing force that was studied for positioning in the vertical plane. Considering also the fact that the cylindrical surface on the base plane area shows a deformation in some flat areas, but also nonlinearities on the cylindrical surface, it will lead us to state that the horizontal printing variant of the analysed parts is not recommended for additive manufacturing.



		Direction		Deviation	
Diameter	Nom.Val.	X	Y	X	Y
	10	9.79	9.87	-0.21	-0.13
	20	19.63	19.72	-0.37	-0.28
	30	29.47	29.55	-0.53	-0.45
	36	35.44	35.52	-0.56	-0.48
Length	5	4.95	4.97	-0.05	-0.03
	30	29.80	29.71	-0.20	-0.29
	22	21.88	21.82	-0.12	-0.18
	30	29.58	29.62	-0.42	-0.38

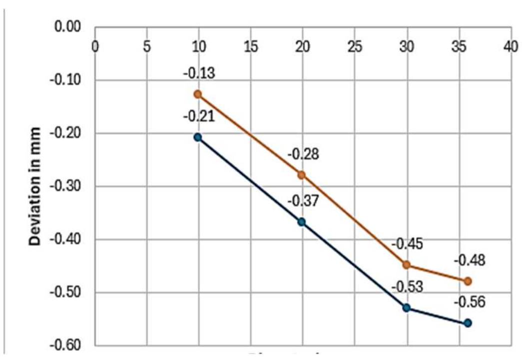


Fig. 18. Data sheet for horizontal cylindrical structure generated top printed ax, middle data sheet, bottom diameter deviation graph.

4. CONCLUSION

The study undertaken by the authors considered putting together three different concepts to determine symmetry axis references for the family of symmetry axis references which is the optimal solution. The authors managed to bring together both the economic and the ecological concept, respectively the quality concept of FDM additive manufacturing.

The analysis for economic criteria permits us to observe that both for material consumption and the optimal solution is for the vertical position. From the time used for generating the axis, the horizontal solution is advantageous. Overall, however, both solutions are in the same position.

However, if we take the ratio of emissions and environmental conditions (temperature and humidity) the best value is obtained for vertical orientation. The other orientations will generate higher values depending on the surface on which the printed start is made.

In the case of analyzing the quality of the printed part, the authors limited in this stage of the study only to the dimensional factor and the circularity of the generated sections. This was considered considering that there are studies that, as we have shown in the introduction to this analysis, have addressed the aspects of surface roughness, but also of axis deformation in the printing process. Considering the dimensional aspects analyzed, it was very clear that the vertical position is the best for creating axial parts with a circular section.

The study undertaken will be extended with the analysis of deviations in shape and position in the other research.

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Analiza multicriterială a procesului de fabricație aditivă FDM pentru componente cu geometrie cilindrică

Prezenta lucrare a fost realizată ca o continuare a unor studii anterioare legate de influența poziționării reperelor de tip roată dințată sau tubulare. Autorii au avut în vedere extinderea procesului investigațiunile abordând în paralel analiza experimentală psihologică modificată, dar și ținând cont de aspectele economice, de mediu și respectiv dimensionale și de calitatea suprafeței pentru repere cilindrice în trepte. Pentru realizarea reperelor a fost utilizat un material care are ca structură de bază acidul poli lactic care este modificat pentru a putea lucra cu viteză mare de imprimare. Pentru stabilirea orientării constructive optime care poate influența procesul de fabricație aditivă a reperelor s-a avut în vedere suprafața de imprimare. Pe baza prezentului studiu s-a putut observa că realizarea reperelor în poziție verticală satisface cel mai bine criteriile de mediu și constructive și a fost poziționată pe același loc la mică distanță din punctul de vedere economic de imprimarea în poziție orizontală.

Cuvinte cheie: *Fabricație aditivă, PLA, Modelare 3D, Imprimare 3D, Măsurători dimensionale.*

Mircea Dorin VASILESCU, PhD, Professor, Politehnica University Timisoara, Mechanical Machinery, Equipment and Transportation, mircea.vasilescu@upt.ro, Bd. Mihai Viteazu, nr. 1, 300222, Timisoara, Romania.

Doru-Alexandru LUCA, PhD student, Politehnica University Timisoara, Mechanical Machinery, Equipment and Transportation, doru.luca@student.upt.ro, Bd. Mihai Viteazu nr. 1, 300222 Timisoara, Romania