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Preliminary Technological and Environmental Considerations for Generating Mechanical Components using Plant-based UV Resin

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Abstract: *The scope of this paper is to determine the evolution of the dimensional value of the part and to study if there is gas and particle emission produced by the plant-based resin in the 3D printing process with mask stereolithography. For dimensional measurement, a solution with digital calliper is used. For the measurement of emission, two devices are used for indoor air quality. In the vertical direction of part body printed, it is possible to observe a descending linear type of direction with a minimum value at the highest element 3D printed. The data taken into account in this study are mathematically studied using the EXCEL regression equation for dimension. The gases emitted are measured with the booth devices in parallel for formaldehyde and volatile organic compound gases. For* CO_2 *and particles, one of these devices is used. The air quality index was determined in relation to* CO_2 *and, respectively, particle emitted. In the printing process, an increase in* CO_2 *emission of 500 ppm can be observed in the initial phase of the process and a lower value in the body area. It is possible to consider that the quality air in 3D printing with plant-based clear resin is in the good to medium level from all types of emission. These data were put in ac-cordance with the level value offered by the manufacturer of the measuring devices. In this study the dimensional aspects are evaluated in parallel for two types of part bodies and the dimensional equations are the same after three mount times.*

Keywords*: biomaterials; sensors for gas or particle, 3D printing, polymer processingword 3*

1. Introduction

The main purpose of the present study is to establish how the geometric position of mechanical components can affect the dimension of the printed body. The study under-taken is considered preliminary both from the point of view of dimensional slopes, but also from the point of view of determining the level of emissions because it is desired to extend the activity from the laboratory area to the university learning spaces. At the same time, the use of dimensional results as a database is considered for the realization of 3D printed mechanical components for the endowment of laboratory stands, but also of the installations developed by students within the bachelor, master, or doctoral programs.

For this study, 3D printing with masked stereolithography (MSLA) was considered. At the same time, for printing, a clear plant-based UV resin is used.

In the 3D printing process, it is possible to see that there exists emission of gases and/or particles at a different level, considering the investigation conducted by other authors [1-4]. The author of this article studies the technological and ecological aspects in some articles using basic resin as a material to determine the technological condition of MSLA 3D printing.

Some type of emission can produce various changes in the proper functioning of the human respiratory system. The level of gas and particle emission generated in the 3D printing process requires an apparatus or sensors dedicated to each class or family of gases and particles [5,6]. In the study conducted by Goletto et al. [5] they used low-cost instruments to find the emission of gases and particles in building construction. In the study conducted by Lifsetb et al. [6] are studied the life care assessment (LCA) factors of the 3D printing process and the instrument with which it is possible to determine the level of emission from different types of 3D printing solution. The minimum value of standard emission

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for particulate matter (PM)2.5 is $12*10^{-6}$ g/m^3 and $0.4*10^{-6}$ g/m^3 for total volatile organic compounds (TVOC) and 600 ppm for carbon dioxide (CO2). These data are taken from the RESETTM Air Standard for Commercial Interiors [7]. From the Seeed Gas Sensor Selection Guide [8] it is essential to see that some gases, such as CO_2, are normal with an outdoor level of 400 ppm.

Some of the sensors used individual or in the structure of the apparatus are sensitive to humidity and temperature. The 3D printing process imposes an excellent printing condition for resin at a level between 25°C and 35°C and between 45°C and 60°C for the post-cure resin structure. This information is taken from Zguris [9] or from the printer and/or the UV resin producer used in the study. In 3D printing with resin and low-cost printer, domestic safety air condition is important to find the level of CO_2, humidity, and VOC emission. In the study conducted by Kotsev et al. [10] some of the sensors used in the measurement of emissions are presented in the outdoor medium in which an ARDUINO microcontroller is used for the measurement. In the study conducted by Johnston et al. [11] the solution is used to monitor air quality and particle emission on the city scale using an IoT apparatus.

Some studies analyze the emission from the manufacturing of part bodies with the thermoplastic material using fuse deposits solution. Polylactic acid (PLA) type materials [12-14] are used in this study, and others are made with acrylonitrile butadiene styrene (ABS) [13]. The emission is studied and evaluated with a commercial apparatus.

Arnold et al. in their study [15] the objective is to analyze the quality of the surface as a function of the printing parameter. Valentincic et al. [16] investigated the issues related to the use of low-cost printers in the stereolithography process. In addition, some aspects of the dimensionality and precision of surfaces and volumes are the subject of a studio made by Tulcan et al. [17]. Zhang et al. [18] and Koehler et al. [19] used apparatus or sensors to determine the level of particle emission in indoor air quality. Cavaliere et al. [20] study the next generation station to monitor particle emission. Aspects related to the characterization and classification of ultrafine particles in the 3D printing process were studied by Bernatikova et al. [21].

The good level of emission for formaldehyde (HCHO) is 0.100 ppm, for TVOC 0.6 ppm, and for CO_2 it is 1000 ppm (AQI CO_2 maximum 2) consider the data from the reference table [22].

2. Materials and methods

2.1. Resin and Printer

In the research, plant-based resin was used for the 3D printing process. This resin is produced by the ANYCUBIC material supplier (Anycubic, Shenzhen, China) [23] and in Figure 1a it is possible to observe some of the printed parts. The materials used in this re-search are clear plant-based resins. For the polymerization process, a digital light processing (DLP) solution is used. From the resin data sheet, it is possible to observe that it has a composed chemical structure. The base plant structures are obtained from soy material that is processed from soybean oil.

An ANYCUBIC PHOTON printer [24] is used for printing. In Figure 1b, it is possible to observe the printer with the screen part, the CO2 device near the printer (100 mm distance from the printer). This sensor measures the temperature at the bottom of the vat photopolymerization inside the printer. This printer used a system-type MSLA with a light solution based on an LCD system with UV light of 405 nm [24]. Plant-based UV resins are sensitive from 355 to 410 nm according to data taken from [23, 25].

2.2. Part body

The printed parts bodies with support structure can be seen in Figure 2a. The triangular part is arranged in the horizontal position and is placed in the central zone of the plate. The other parts bodies are placed vertically and are oriented in the X or Y direction. As can be seen in other studies conducted by the author [16], the positioning and generation of supporting elements are very important for both the dimensional accuracy and the success of the printing step. It is important to note that the evolution of the temperature and level of emissions differ depending on the illuminated layer position.

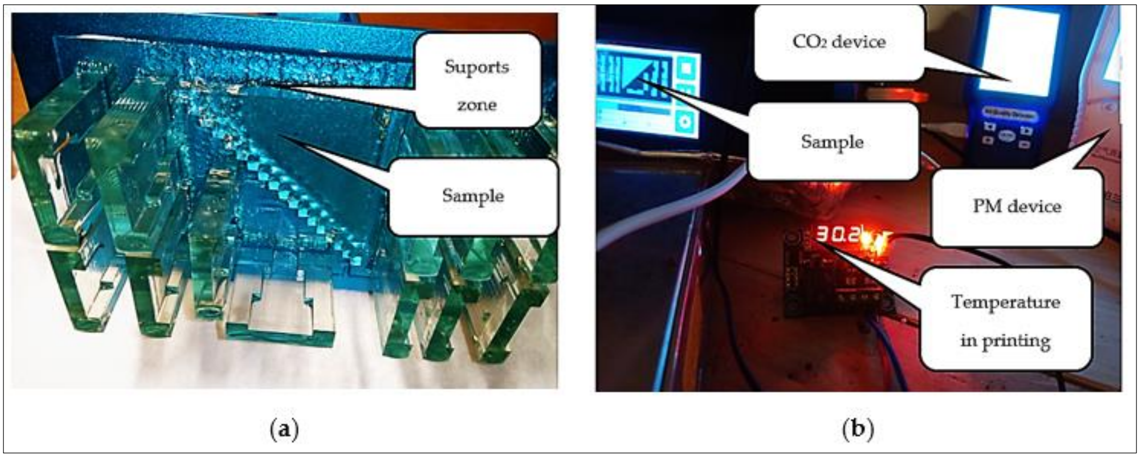


Figure 1. The part body and the printer used (**a**) 3D printed part body made with clear plant-based resin; (**b**) printer and CO2 device used

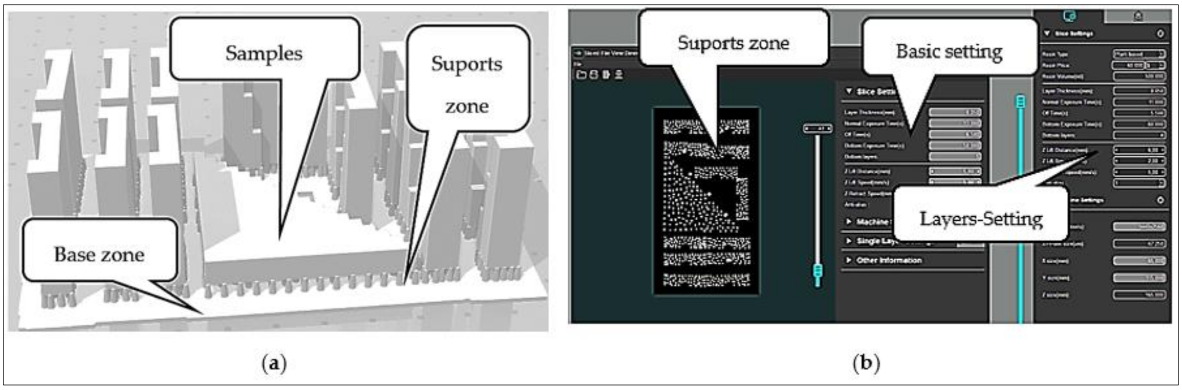


Figure 2. Plan part body 3D printed with clear ecological resin: (**a**) 3D printed part bodies with supports in standard triangle language (STL); (**b**) 47-layer structure of cylindrical support zone

In Figure 2b, one can observe the 47-layer generated with the data from the generation setting and the basic setting. Considering not only the print settings, but also the dimensions of the elements to be printed (base layer, supports layers, parts layer), it is possible to visually calculate the time durations. Its importance is given by the fact that the level of emissions differs depending on the surface that is illuminated.

The first zone is the base structure, which is made up of nine layers with a 50s time of the photopolymerization process. After that, from 10 layer to 69 layers are the supports zone that are generated with an expose time of 13 s and a layer height of 0.05mm. The last is the structure of the part with different Z dimensions from 70 layer to 670 layer.

The time in minutes is the physical element used for making a correlation between printing layer and measuring of emission. Considering these last aspects, the study is divided into three zones. Fist from zero to seven minutes. The second from eight to twenty minutes and the last from twenty-one to 152 min.

In this study, the dimension of the generated part bodies is measured with 0.01mm precision using a digital caliper. This solution is taken because the data obtained by [16] agree with the average precision of the linear dimension.

2.3. Devices

To measure air quality and emission level, two devices are used. The first is for emission of TVOC, CO_2 or HCHO is placed Figure 3 in left position. The air quality index (AQI) is determined separately in relation to the CO2 value of gas emission [22]. From the producer's data sheet, the fluctuation error of the measured value is 3% to 30%. The second device used can measure particle emission and is of type JBL-B600, and at the same time it is possible to determine the emission of TVOC, HCHO. For AQI particles, the value can be determined separately. At the same time, with them, it is possible to measure the value of temperature and humidity [24].

In Figure 3 the two instruments used to measure the emission value and the ambient conditions under which the printing is carried out are presented. It is possible to observe in the bottom and back space of the printed zone the structure thermic isolated in which the apparatus and the 3D printer are placed. The volumes of this space are 500 mm in all directions. The measured emission data loaded from the two devices are transferred to a spreadsheet.

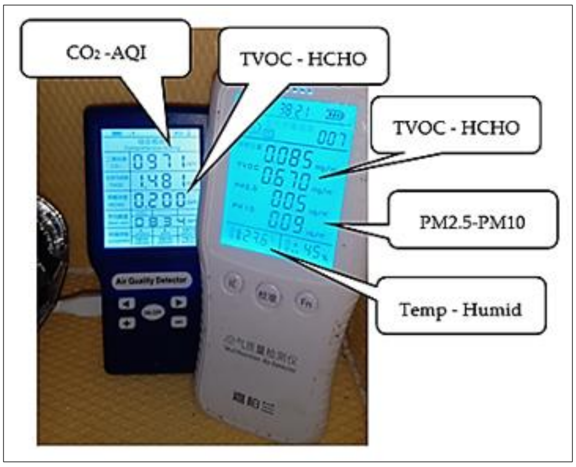


Figure 3. Devices used to measure emission

2.3. Method used

The first step is to generate the computer-aided design (CAD) part bodies used in the study with a Fusion 360 program from Autodesk Educational Solution. After that, these elements are placed in the virtual space of the surface used for 3D printing. With ANYCUBIC 64 software, the base and supports used for the printing of parts bodies are generated. This structure is divided into layers and the speed of the lifting element generates the zone in which the optical polymerizations are placed Figure 2b. With the video solution in Figure 2b, it is possible to see the generated layer and determine the number and time for each of the generated zones.

3. Results and discussions

The experimental study was carried out in two directions. First, we consider the dimensional aspects after the printing process, no post-processing UV after the printing step. Second, the emission is considered in the printing process, and the evolution in time with the considered devices.

3.1. Evolution of the linear-dimensional extension result

The first step in the dimensional study is to observe the mode in which the printing process influences the dimension of the printed parts. It should be shown that mechanical compression phenomena that result in the printing process in the phase of transition from the liquid to the solid phases could affect the dimensional value of the parts. In addition, shock waves are also produced because the vacuum phenomenon created between the lower surface of the vat photopolymerization, and the base surface can generate a modification.

In Figure 4a, it is possible to observe the geometrically generated part body with numerical dimension in the CAD solution (Fusion 360 Educational solution). At the same time, in Figure 4b, the two positions chosen for the printing of the part body are presented with the measured solution used.

For the horizontally oriented part, the dimensions measured in the X are presented in Figure 5a and for Y directions in Figure 6a. The value in terms of both the size and the evolution of the deviation has a linear evolution. For each of the two-dimensional elements, both the mathematical regression equation and the optimal quadratic mean deviation R^2 were determined. It is important to note that the printed samples measured after three months dimensionally showed no significant changes in Figure 5b and Figure 6b.

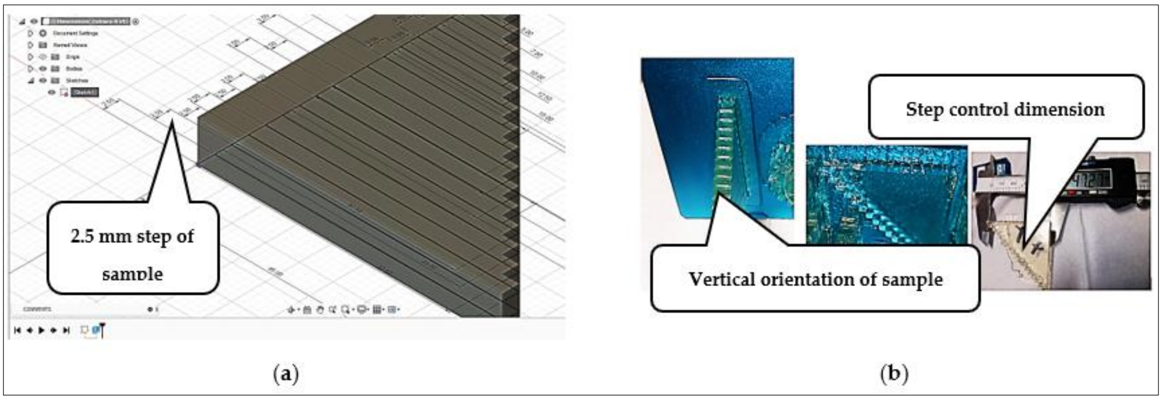


Figure 4. The dimension and orientation of the part, (**a**) the CAD dimension, and (**b**) the orientation

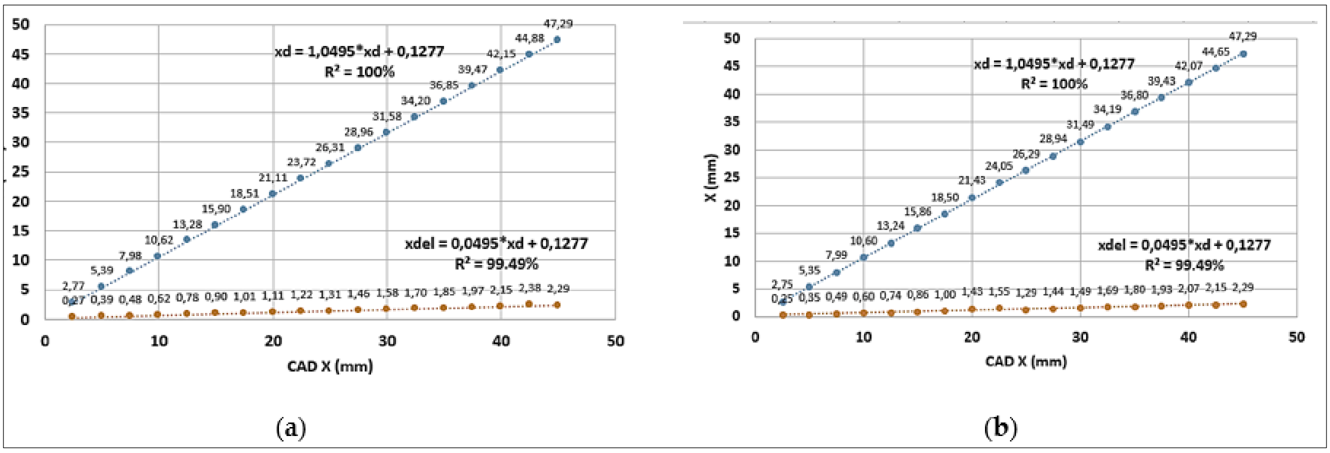


Figure 5. Evolution of the X dimension and deviation in the horizontal position, (**a**) after printing step, and (**b**) three months after printing process

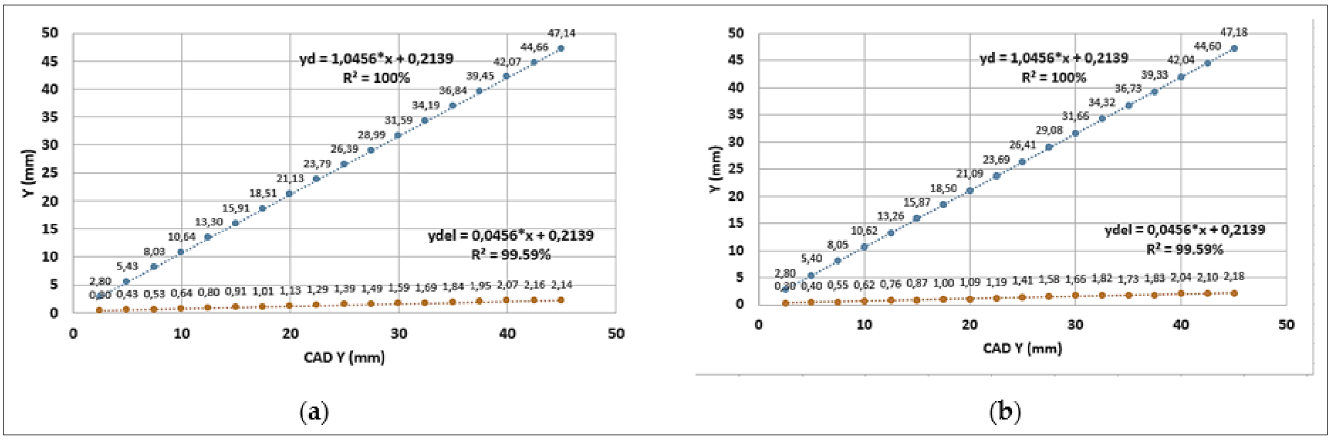


Figure 6. Evolution of the Y dimension and deviation in the horizontal position, (**a**) after printing step, and (**b**) three months after printing process

In Figure 7 are presented the evolution in horizontal plane for Y direction and in Figure 8 the evolution of dimension end deviation in vertical position of the printed part. At the same time, if is made a comparison between the equation obtained in the same horizontal plane for the variable y, the value of the free constant is double for the case of printing in the horizontal plane compared to the one resulting for printing in the vertical plane. This observation leads us to state that the size of the printed surface has an influence on the dimensions in the horizontal plane after the two directions.

Considering the identified aspect, but also the fact that from a dimensional point of view, as can be seen, the triangular sample was printed in two positions, the dimensional investigation was extended to parallelepiped part body oriented in a vertical direction Figure 1a. The positioning of the parallelepipedal element in steps was made by printing according to the direction X and oriented with the long side after Y Figure 9.

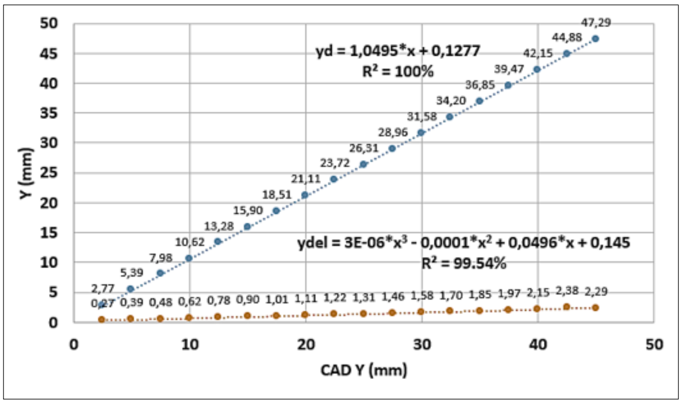


Figure 7. Evolution of the Y dimension and deviation in the vertical printing position

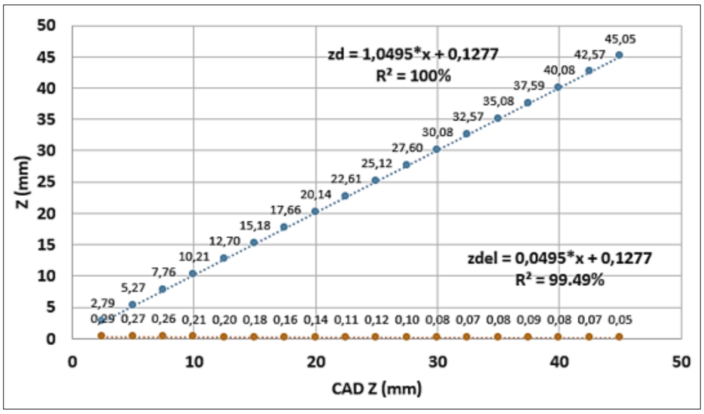


Figure 8. Evolution of the Z dimension and deviation in the vertical printing position

3.2. Evolution of the temperature and humidity in the printing process

From the point of view of the evolution of these two physical elements, a DHT11 sensor was used to measure these data, which is incorporated at the base of the apparatus to measure the particulate emissions. It must be shown that only the particle emission device is equipped with such a system for identifying temperature and humidity variations.

In Figure 10a, it is possible to observe the evolution of the temperature in the first studies of the printed structure. In the first step, which is affected by the generated base of the printing elements, it is possible to observe a decree of the temperature with 0.80°C. From a physical point of view, it is possible to have a major influence on the temperature in printing system, which can transfer part of the temperature in this step outside the printing chamber.

In the step of printing supports the temperature, has a small variation between a minimum value of 22.78°C and a maximum value of 22.90°C at the final position of these phases. From the analysis of only this phase of printing, a slightly increasing trend of temperatures can be observed.

Given that the distribution of the measured points has a random variation, and the mathematical regression equations, whatever their type, generally do not reach the desired optimum value, in the further analysis of the measured physical or chemical quantities only a linear analysis of the tendency is used.

In Figure 10b, it is possible to observe the evolution of temperature in the body structure of elements. In the first part, a slight increase in temperature by 1.71°C can be observed, followed by a tendency to decrease the slope of increasing the analyzed physical parameter. Subsequently, the general trend is to maintain temperatures between normal limits between 23.5°C and 24.00°C with small deviations that may be due to disturbances external to the printing process from the space where the 3D printer was positioned. To be put in evidence in the figure is generated a line with which it is possible to observe the tendency of the evolution of temperature in the printing process.

No	Poz.	Y CAD	Y1	Y2	Med Y	Δ Y	Y calc	ΔY calc
1	Top	5,00	5,35	5,37	5,36	7,20%	5,44	8,84%
2	Midle	7,00	7,49	7,47	7,48	6,86%	7,53	7,62%
3	Down	9,00	9,71	9,54	9,63	6,94%	9,62	6,94%
4	Top	25,00	26,24	26,24	26,24	4,96%	26,35	5,42%
5	Midle	25,00	26,23	26,23	26,23	4,92%	26,35	5,42%
6	Down	25,00	26,27	26,27	26,27	5,08%	26,35	5,42%

No	Poz.	X CAD	X1	X2	Med X	Δ X	X calc	ΔX calc
1	Top	6,00	6,34	6,38	6,36	6,00%	6,42	7,08%
2	Midle	6,00	6,37	6,38	6,38	6,25%	6,42	7,08%
3	Down	6,00	6,46	6,43	6,45	7,42%	6,42	7,08%
4	Top	2,00	2,13	2,12	2,13	6,25%	2,23	11,34%
5	Midle	2,00	2,20	2,16	2,18	9,00%	2,23	11,34%
6	Down	2,00	2,45	2,43	2,44	22,00%	2,23	11,34%

No	Poz.	Z CAD	Z1	Z2	Med Z	Δ Z	Z calc	ΔZ calc		
1	Left	30	30,78	30,78	30,78	2,60%	31,61	5,38%		
2	Midle	30	30,85	30,80	30,83	2,75%	31,61	5,38%		
3	Rigth	30	30,78	30,78	30,78	2,60%	31,61	5,38%		
4	Top	30	30,78	30,78	30,78	2,60%	31,61	5,38%	3,96	2,49
5	Midle	20	20,83	20,81	20,82	4,10%	21,12	5,59%	1,47	
6	Down	10	10,91	10,89	10,90	9,00%	10,62	6,23%		

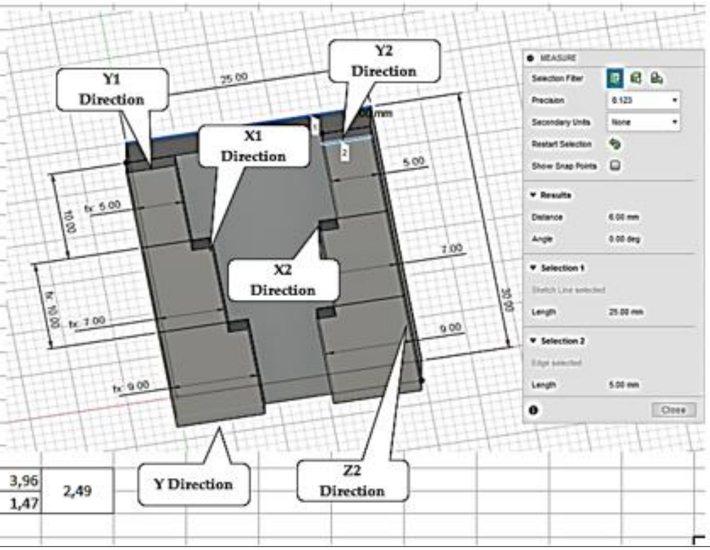
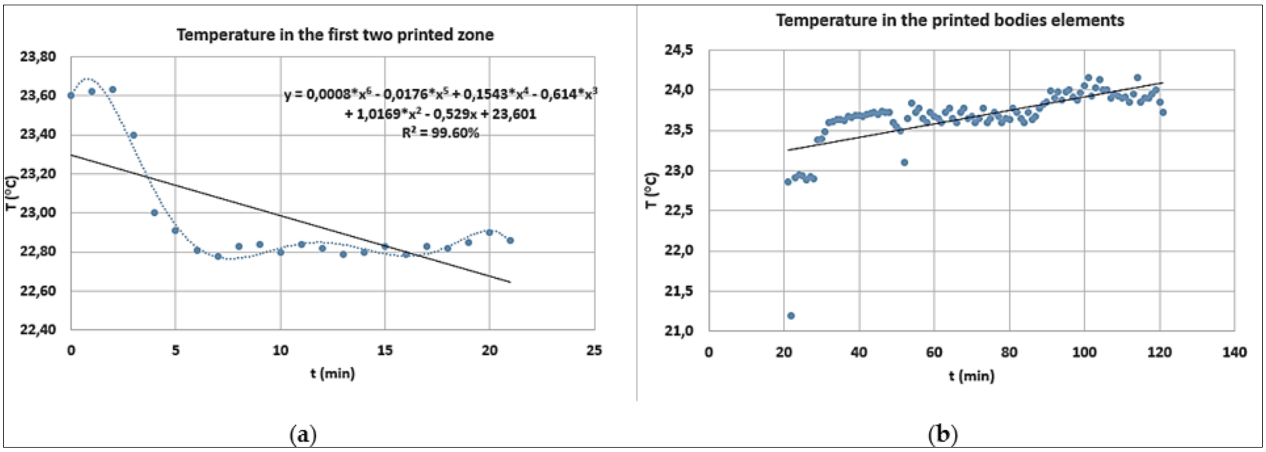


Figure 9. Evolution of the Y-Z dimension and deviation of the part body in vertical printing position



(a) (b)

Figure 10. Evolution of temperature (**a**) for first two step of printing and (**b**) for the bodies printing

3.3. Evolution of the CO_2 emission

The evolution of CO_2 emission which are produced in the printing process with transparent plant-based resin was split in two zones. The first are bottom and supports structure Figure 11a. For this area, the optimal mathematical regression equation is power type with a R^2 96.11% value. The second are the bodies elements in which the concentration of CO_2 in printing space has a smaller growing trend Figure 11b.

3.4. Evolution of the HCHO emission

In the case of the measuring the value of concentration of HCHO in printing space it is possible to observe that are two phases. In Figure 12a, it is presented the data determination from the first two steps of printing process (bottom and supports structure). All of two devices used in study present a growing trend. The device of the CO_2 emission measuring instrument has a more pronounced slope of growth than that of the particle measuring device. In Figure 12b, the analysis for the two devices was made for the last steps of printing process. It is possible to observe that that the value measured by the particle's device has a high growing trend in rapport with the devices for measuring emission for CO_2.

3.5. Evolution of the TVOC emission

The determination of TVOC emissions was possible with the two devices used in this study. In Figure 13a, the evolution of TVOC emission is presented in the first two steps of the printing process determined with a CO_2 measuring type apparatus. From the evolution of emissions, it is possible to observe an increase from a lower value of 0.025ppm to 0.425ppm at the end of the supports printing phase. In Figure 13b, the analysis for the same steps was performed with the particle emission apparatus. From the evolution of emissions, it is possible to observe an increase from a lower value of 0.180mg/m^3 to 1.400mg/m^3 at the end of the supports printing phase. It can be seen from the two graphs that there is the same upward trend, although the units of measurement are different. The rising slope measured with the particulate emission meter is lower than that determined by the first apparatus used in the study.

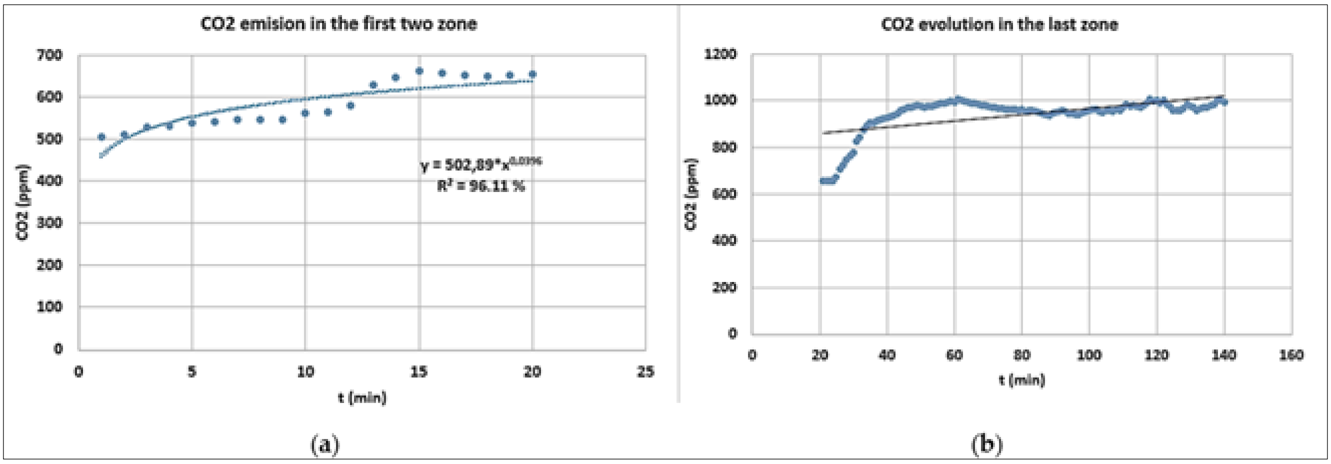


Figure 11. Evolution of CO_2 (**a**) for the first two steps and (**b**) for the bodies

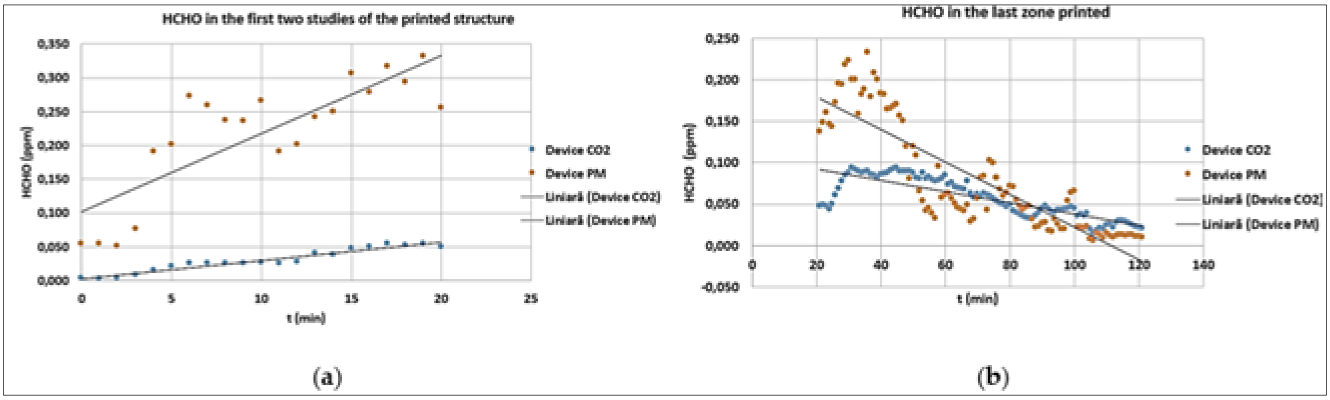


Figure 12. Evolution of HCHO gas emission for the printing process
(**a**) for the first two steps and (**b**) for the bodies

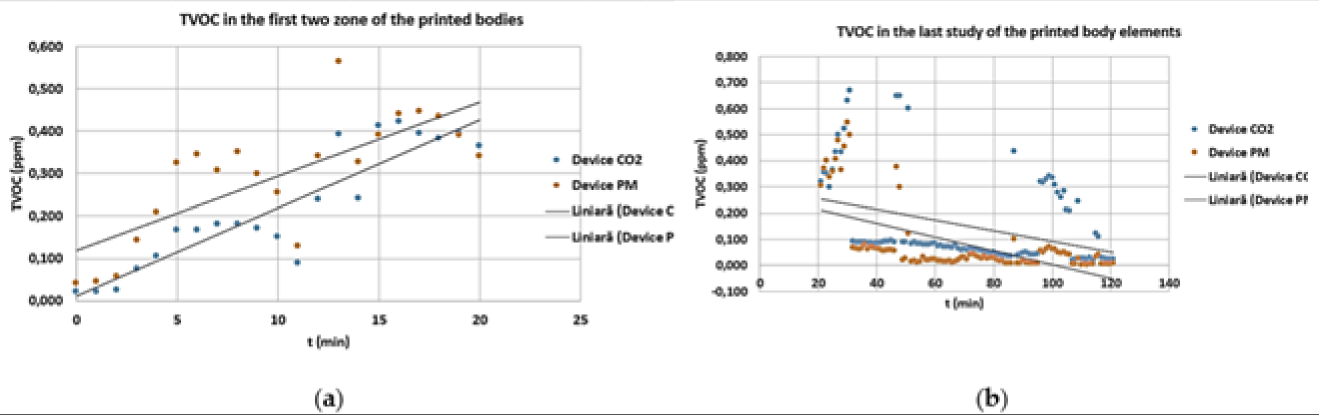


Figure 13. Evolution of TVOC gas emission (**a**) for the first two steps of printing and (**b**) for the bodies printing

From the two evolutions, it is possible to observe a similarity in the arrangement of the measured values and a quadratic regression equation with a close power coefficient. As in the case under consideration for CO_2, it is recommended for the same reasons to extend the analysis to the level of the printing space in the upper area of the printing parts.

3.6. Evolution of the PM emission

The analysis of the first two areas of the folding area of the supporting structure of the parts subjected to the printing process shows a decreasing variation for the first area for the PM2.5 emission Figure 14a and an increasing variation for the PM10 emission Figure 14b. In the second area (supports), the evolution of the emitted particles has a linear tendency with alternating variations in the average of the emissions compared to their aver-age zone. The scattering of values is lower for the average values measured for PM10 than for PM2.5.

For the printing area of the parts bodies, it can be found that for the emission of particles with a diameter of 2.5µm the tendency in Figure 15a is slightly decreasing, while for those of 10µm medium diameter in Figure 15b the tendency is close to keeping constant.

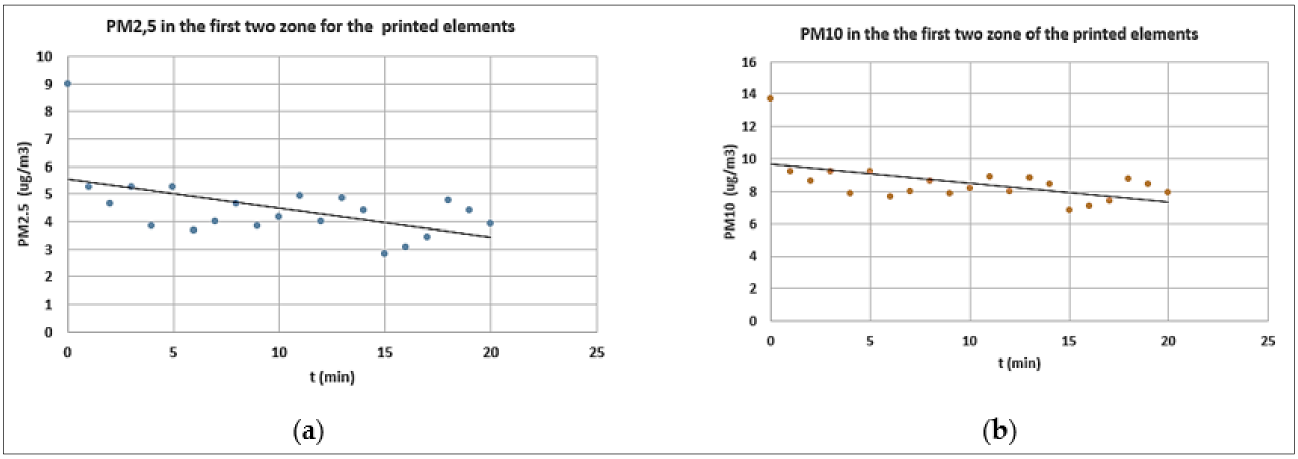


Figure 14. Evolution of particle emission, which is determined in the first two zones (**a**) for PM2.5 and (**b**) for PM10

3.7. Evolution of the AQI

From the point of view of the evolution of the air quality on the carbon emission side, it could be found that they are in zone two type good working conditions in the area. Slight exceedances of this level are presented in completion of the printings, and the air quality passing in the 3rd zone with less recommended working conditions in that environment.

From the point of view of the quality of the particulate emissions in the printing process, as can be seen in Figure 16, it is situated in the area between 8 and 3.5 for the air quality determined for particles with a diameter of 2.5mm.

3.8. Discussions

From the evolution of the dimensions according to the graphically analyzed directions for the horizontal orientation the evolution is increasing and the mathematical equation for each of the two directions is of the linear type with R2=1. The same development can be observed for the coefficient of increase in size. From the point of view of the quadratic coefficient, it has a value of less than one, but it falls within the accepted trust field for the mathematical analysis of the 5% confidence coefficient. For vertical orientation, changes in the dimensions and coefficient of expansion may be observed, especially in the vertical direction. A reason for this is given by the decrease in the contact surface in the horizontal plane. It should also be noted that if for the effective dimensional value their graphic distribution is of the linear type, for the expansion coefficient the distribution after the horizontal direction is of the polynomial type of the minimum three degrees. After the vertical direction it is of descending linear type with the minimum value at the highest cubic element printed 3D.

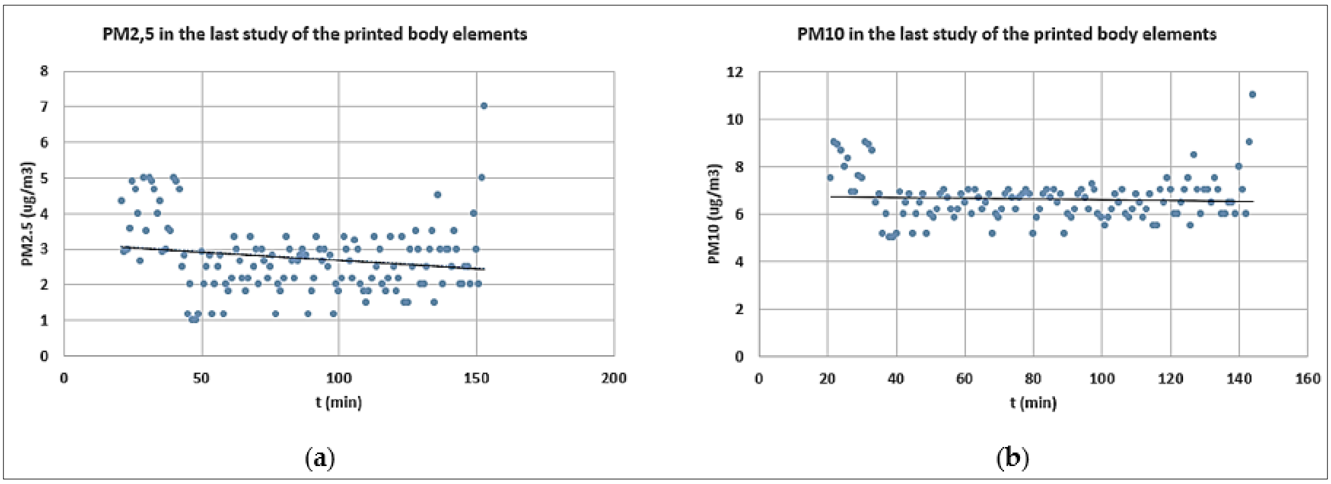


Figure 15. Evolution of particle emission, in the final zones (a) for PM2.5 and (b) for PM10

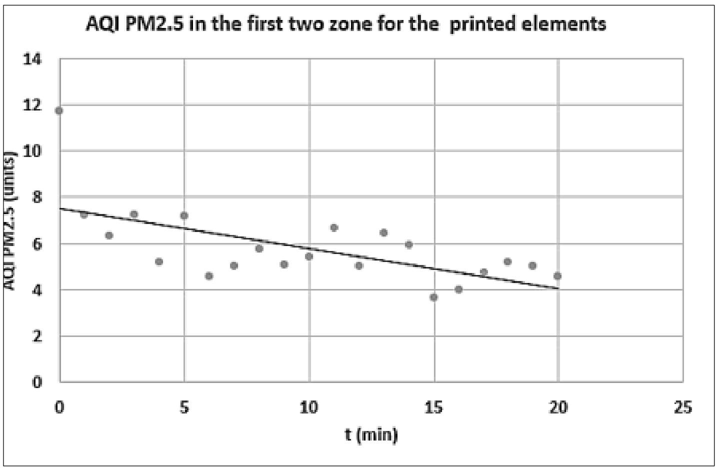


Figure 16. The AQI evolution determinate with particles sensor in the printing process

If we analyze the evolution of temperature and humidity at the level of the measuring instruments, they show small variations compared to the initial conditions for their determination before the experimental process.

From the analysis of the CO_2 emission values, an increasing trend can be observed in printing the basic structure. The percentage of growth is 10%. In the printing area of the supports, an increase of 11% is observed on the cylindrical part of their structure, followed by a relatively constant area with a 2% variation in the emission. In the printing area of the part body at the beginning, there is an increase in emissions of 400 ppm, followed by a maintenance and, respectively, a slightly oscillatory trend in the generation part of the elements with higher height.

From the analysis of the comparatively measured data for HCHO in relation to the experimental values, the proportional correlation between the measured ppm value and the value in mg/m^3 is not respected. The deviations are both on the calculation side where the percentage determined by the relationship of the molar mass of 30.02598 g/mole is only randomly reached, but also during the measurement process where the deviations are large at the beginning of the measurement process and decrease to the final part of the process. From the analysis of the distribution of the experimental points, it can be stated that the arrangement of the determined values is closer to an optimal mathematical evolution for the measuring apparatus in ppm for the first two parts of the generated structure and is preserved for the third part as well.

From the analysis of the comparatively measured data for TVOC in relation to the experimental values, the proportional correlation between the measured ppm value and the value in mg/m^3 is not respected. The deviations are both on the calculation side where the percentage determined by the relationship of the molar mass of 78.9516 g/mole is only randomly reached, but also during the measurement process where the deviations are large at the beginning of the measurement process and decrease to the final part of the process. From the analysis of the distribution of the experimental points, it can be stated that the arrangement of the determined values is closer to an optimal mathematical evolution for the measuring apparatus in ppm for the first two parts of the generated structure and is not preserved for the third part.

Given the decreasing trend of particle emissions, but also the very high degree of scattering of emission values in the third zone, it is necessary to extend the study with a sensor dedicated to measuring such emissions to achieve a better determination of these types of emissions. If possible, constructively, for the determinate real emission of the particle part, the study can be extended with the placement of a dedicated sensor in the print space.

4. Conclusions

Based on the analysis of the results obtained, on the one hand, the conclusion of extending the study resulted in the use of dedicated sensors with a measurement accuracy higher than those that enter the construction of the emission measurement devices used in the study.

We must not forget the extension of the study of the thermal process at the level of the printing surface, but also at the level of the control of the heat and humidity transfer from the inside of the lower printing area to the outer space. The importance of studying this process is determined not only by the printing temperature limit of 20°C to 35°C for the analyzed resin, but also by the deformation that may occur after the printing process is carried out as a result of the temperature difference between the printed layers.

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