# The Effects of Printing Parameters on Mechanical Properties of a Rapidly Manufactures Mechanical Ventilator

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*Abstract*— **With the advent of SARS-COV-2, industry and academy have been mobilizing themselves to find technical solutions to satisfy the high demand for hospital supplies. This work aims to study the manufacturing process by melting and depositing thermoplastic material (three-dimensional printing) to build a mechanical ventilator. We center the methodology of this work on the observation of good practices for the procedure of printing plastic parts for medical and hospital use, aiming to guarantee mechanical resistance and satisfy sanitary restrictions. At first, we studied materials for manufacturing parts for application in the medical-hospital environment. In a second moment, a study of the mechanical resistance of specimens for traction test was developed, based on the ASTM D638 standard, printed with different directions of material deposition and using different types of thermoplastics with potential use in medical systems such as PLA, ABS, and PETG. In a third moment the mechanism of a mechanical ventilator in Solidwork was created, this mechanism automated an AMBU using a rack and gear system, the properties of the PLA material (of the second moment) were applied to the gear (it is the most critical part of the mechanism) and the effects of torsion on the gear were simulated ( stepper motor). Finally, a 3D printing mechanism was created. For the production of these specimens, we employed the Simplify3d software. Optimized settings were suggested for the deposition of the thermoplastic material, considering a reduction in speed to 30 mm/s, a layer height of 0.100 mm, 100% filling, and a line overlap of 60% to avoid voids at the edges of the pieces, within order to increase the mechanical resistance. The observed results are satisfactory and are under the analyzed bibliography, indicating that adjustments in parameters and configurations of material deposition influence the mechanical strength of the parts.**

*Keywords*— **3D printing; SARS-COV-2 Covid-19; Hospital supply; PLA; Mechanical Ventilator.**

## I. Introduction

With the advent of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-COV-2) and Coronavirus Disease 2019 (Covid-19), industry and academy have been pushing to seek new technology solutions to be able to meet the growing demand for inputs every day more urgent worldwide [1][2]. In the race for solutions that will mitigate the consequences of the pandemic, the 3D Fused Deposition Modeling (FDM) printer emerges as an ally for the prototyping and manufacturing of hospital supplies [3][4].

3D FDM printers or rapid prototyping, is an additive manufacturing technology, in which the production of three-dimensional parts is formed through the sequential deposition of molten material in layers, based on a Computer-Aided Design (CAD) [5][6]. Rapid prototyping differs from traditional manufacturing technologies, as it is a tool capable of producing parts with complex geometry and unique characteristics in just one manufacturing process [5]. Besides, material waste is much less when compared to production techniques such as subtractive manufacturing, in which components are constructed by subtracting material [7].

One can divide the manufacturing process through three-dimensional printing into three stages; it would be the design of parts through computational modeling, the processing of CAD using 3D slicing software and finally, the manufacturing and finishing process part [8][9].

The slicing process is one of the most significant for additive manufacturing since at this stage the printing parameters are defined. Parameters such as layer height, nozzle temperature, deposition speed, filling, layer overlap, extrusion speed of the thermoplastic, number of layers of finishes of the piece, among others, are analyzed [10][11]. We can evidence this fact in the works of [9] and [10], in which, they demonstrate that parameters such as extrusion speed, layer height, and orientation layers, are essential, as they directly influence the mechanical characteristics of the material. According to [10] the effects of this negligence are not noticed because some of the parameters, when isolated, have little influence on their properties. However, together, they considerably influence the final properties of the produced parts [12][13].

According to [12], the finish of the piece, and its structural resistance is directly related to the parameter of internal filling. This parameter can cause severe deformation in the parts, affecting the external finish and its mechanical strength. In addition, the slicing software is also of significant importance for production, as they are imprecise in the printing time and the amount of material used, such parameters directly influence the final quality of the product [14][15].

In this way, the main contribution of the paper is to study how the parameters of 3D printing influence the quality and properties of parts produced to meet the growing demand for hospital supplies caused by the SARS-COV-2 pandemic. A case study was conducted for producing the main parts that have not direct contact with patients of a mechanical ventilator equipment. We utilized tensile tests for collecting data on the mechanical properties of materials, simulations of maximum motor torque for the validation of mechanical parts, and, finally, a bibliographic study to generate a set of patterns in the printing parameters.

## II. Materials and Methods

For the development of this research, an open source Graber i3 FDM printer of simple extrusion was used in the production of the structures and samples. For slicing and processing the CAD, we used the Simplify3D software. The materials used were 3DLAB filaments, 1.75mm in diameter, made from the following thermoplastics Lactic Polyacid (PLA), Acrylonitrile Butadiene Styrene (ABS), Poly (Ethylene Glycol Terephthalate) (PETG), all of them in natural color. The parts were designed and simulated using SolidWorks computer modeling software.

The research was divided into three main stages. Firstly, the slicing parameters and good prototyping practices were analyzed. Consecutively, the production of several samples intended for mechanical characterization of the materials. Finally, we performed simulations of critical parts and manufactured components of a mechanical ventilator prototype.

### A. Slicing parameter

In rapid prototyping, it is necessary to have a 3D printing software treatment, to determine the parameters, such as the layer orientation, extruder nozzle temperature, deposition speed, layer height, and the coordinates of the three-dimensional object.

This situation reflects the same found by [16], in which it was confirmed that the orientation of the part and that the height of layers has direct and accentuated influences on the mechanical properties of the parts produced. In addition, the height of the layer along with the deposition speed, has a lot of influence on the existence of voids in the piece. Geng et al. [10], managed to demonstrate that extreme speeds, slow and fast, are detrimental to mechanical properties. Therefore, in this work the study of 3D printing pieces employed deposition speeds similar to that reported in [9], and the tracking angle that generated satisfactory mechanical properties as in [17][16][18].

The main parameter addressed in this work was the effect of the printing orientation on the mechanical properties. Three sets of 5 units were manufactured, each set produced taking into account a print orientation: horizontal, vertical, and flat. Parameters such as edge overlap, printing angle, and bed height, and types of supports, were studied in this research as well, but only their finishing effects were studied in the production of pieces for the mechanical respirator. Primarily, we produced the pieces by using traditional parameters, layer height of 0.200 mm, printing speed of 60 mm/s, tracking angle of -45 / +45 degrees and 100% filling, and 0.4 mm diameter nozzle. Subsequently, we employed optimized parameters, in which the layer height was 0.100mm, print speed from 20 mm/s to 30 mm/s, tracking angle of 0/90 degrees, 100% filling, and overlapping edge of 60%.

### B. Mechanical tests

In this research, several tensile tests were conducted to characterize the properties of the materials, and thus analyze the influences of the printing parameters. For this, the technical standard ASTM D638 was used, which is responsible for the standardization of mechanical tests for tensile properties of plastic materials and applies to reinforced and non-reinforced plastics [18].

The tensile test was applied to printed samples under specific conditions of room temperature, humidity, and speed, using an Instron® 8801 equipment. This machine is a compact servo-hydraulic fatigue testing device that meets the requirements of static and dynamic tests.

### C. Development of an Ambu-based mechanical ventilator

In this work, we adopted the specifications of the minimally clinically acceptable ventilator used during the Covid-19 pandemic. Table 1 summarizes the set of clinical requirements based on the consensus of what is minimally acceptable in the opinion of anesthesia and intensive care medical professionals and the regulatory agencies, taking into consideration the emergency context. Details regarding monitoring and alarms, gas and electricity supply, biological and software safety can be found in [19] [20].

Table 1: Minimal requirements of a mechanical ventilator. CMV (Continuous Mandatory Ventilation), VCV (Volume Controlled Ventilation), PCV (Pressure Controlled Ventilation), Plateau Pressure (PAP), Peak Pressure (PEP), Inspiratory Airway Pressure Limit (IAPL), Positive End Expiratory Pressure (Peep), Inspiratory:Expiratory ratio (I:E), Respiratory Rate (RR), Tidal Volume ($V_t$)

| Requirement | Mandatory | Optional | Observation |
|---|---|---|---|
| CMV | VCV | PCV | – |
| PAP | 35 cm$H_2$O | 70 cm$H_2$O | – |
| PEP | 37 cm$H_2$O | – | – |
| IAPL | 15-40 cm$H_2$O | – | steps 5 cm$H_2$O |
| PEEP | 5-20 cm$H_2$O | – | steps 5 cm$H_2$O |
| I:E | 1:2 | 1:1 and 1:3 | – |
| RR | 10–30 breaths per minute | – | steps of 2 |
| $V_t$ | 400 ml | 350 and 450 ml | – |

Figure 1 shows the CADs of the proposed Ambu-based ventilator, which aims to be an open source and low cost rapidly manufactured equipment that provides basic functions, reserving most sophisticated ventilators for critical patients.

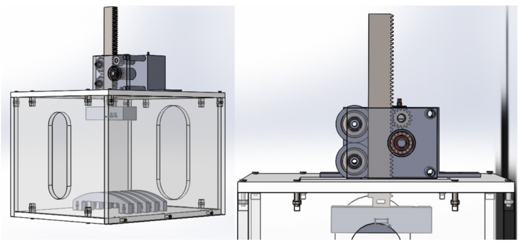

Fig. 1: Schematic of the mechanical respirator

A static analysis of the system was performed allowing the motor to be selected. For the analysis it was assumed normal and tangential forces produced by the Ambu (ideally at 30 degrees) as shown in Fig 2).

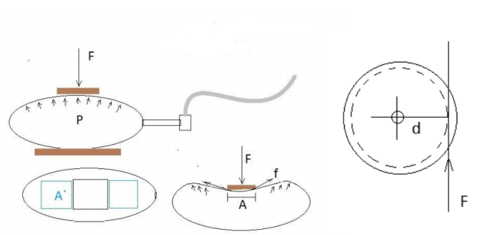


Fig. 2: Pressure analysis: Peak Pressure $PEP = 37cmH_2O$ ($0.037Kgf/cm^2$), Gear radius $Gr = 0.85cm$, contact area with the Ambu $A = 24cm^2$, Safety Factor $S_F = 1.2$

$$F_a = PEP \times A \tag{1}$$

$$f = \sin(30) \times PEP \times A' = \sin(30) \times PEP \times A/2 \tag{2}$$

$$F = (F_a + 2f) \times S_F \tag{3}$$

The force $F_a$ is $0.888Kgf$, $f$ is $0.2222Kgf$, and $F$ is $1.5984Kgf$, being the necessary force in the rack with a safety factor of $S_F = 1.2$; however, it's not necessary torque in the gear. The torque in the gear is expressed by 4.

$$Tg = F \times Gr \times S_F \tag{4}$$

The estimated minimum motor torque is about $1.6313Kgfcm$ with a safety factor $S_F = 1.2$. Based on the estimated torque, it was selected a Nema23 step motor with a maximum torque of $5.61Kgfcm$ at 3600 PPS (pulse per second) ($0.55Nm$).

### D. *Simulation and production of parts for the prototype of the mechanical ventilator.*

The results obtained in the mechanical characterization of the materials manufactured through rapid prototyping were the basis for the numerical simulations in SolidWorks. In particular, it is important to analyse the torsion effect on the gear responsible for transferring the torque of the Nema 23 motor to the rack of the mechanical ventilator.

The simulation procedure was separated into two parts. Initially, it was used an isotropic model of the gear, using the lowest properties found in the tensile test for PLA. Subsequently, we employed an orthotopic model, by using the property values obtained in the horizontal direction applied in the $X$ and $Y$ directions and the vertical direction applied in the $Z$ direction of the simulation. For both models, the Von Mises criteria was applied.

For the simulation it was necessary to conduct convergence analysis of the finite elements mesh. Since the results at 12 thousand knots, there was a very small difference of 0.45% compared to the 25 thousand knots, one can conclude that it would not be necessary to use a mesh more refined than 13 thousand knots, in a tetrahedral mesh.

We manufactured gears for Nema 23 motor, supports, spacers, fastener assembly, rack, and fittings for hoses for the prototype of the ventilator. Those parts were produced with 1.75 mm diameter filament of the 3DLab brand made of and natural PLA. Different values for deposition speed, contour overlap and first layer nozzle temperature were used, allowing qualitative comparison to be performed.

# III. Results

## A. Mechanical tests and simulations

Table 2 shows the main mechanical properties for ABS, PLA, and PETG, achieved in the tensile tests. It was possible to notice the effect of the printing orientation on the mechanical properties. The samples printed using the horizontal orientation ($H$) had their properties maximized, while the samples produced using the vertical orientation ($V$) had the worst results. Only PETG presents the worst results for the flat orientation ($F$).

Table 2: Mechanical properties of materials

| Material Guidance | Shear Modulus(Gpa) | Poisson's Ratio ($\upsilon$) | Young Modulus(Gpa) | Yield Strength (Mpa) |
|---|---|---|---|---|
| ABS H | 0.68 ± 0.039 | 0.31 ± 0.082 | 2.20 ± 0.097 | 34.12 ± 0.203 |
| ABS V | 0.56 ± 0.042 | 0.27 ± 0.083 | 2.09 ± 0.102 | 27.40 ± 0.203 |
| ABS F | 0.58 ± 0.042 | 0.22 ± 0.083 | 2.19 ± 0.102 | 32.43 ± 0.203 |
| PLA H | 1.21 ± 0.075 | 0.34 ± 0.094 | 3.58 ± 0.161 | 59.88 ± 0.101 |
| PLA V | 1.18 ± 0.064 | 0.25 ± 0.090 | 3.34 ± 0.143 | 53.23 ± 0.101 |
| PLA F | 1.13 ± 0.064 | 0.23 ± 0.087 | 3.39 ± 0.148 | 46.58 ± 0.101 |
| PETG H | 0.64 ± 0.040 | 0.36 ± 0.080 | 1.80 ± 0.105 | 40.32 ± 0.100 |
| PETG V | 0.65 ± 0.040 | 0.29 ± 0.077 | 1.67 ± 0.105 | 34.16 ± 0.100 |
| PETG F | 0.63 ± 0.040 | 0.26 ± 0.080 | 1.61 ± 0.105 | 36.18 ± 0.100 |

$H$ is horizontal printing (axis X), $V$ is vertical printing (axis Z), $F$ is flat printing (axis Y)

In the mechanical ventilator, the applied torque was 0.55Nm. Table 3 shows the simulation results for isotropic and orthotropic models of the gear made of PLA. Notice that for the isotropic model (horizontal orientation) the safety coefficient was 9.284, whereas, for the orthotropic model, the safety coefficient was 9.266. One can conclude that the prototyped gear can whithstand the mechanical efforts previewed in the design of the mechanical ventilator (maximum motor torque of 0.55Nm).

Table 3: Simulation of mechanical properties of the gear made of PLA

| Material Guidance | Simulation type | Safety factor | Von Mise Tension (Mpa) | knot quantity |
|---|---|---|---|---|
| PLA H | Isotropic | 9.284 | 6.439 | 12837 |
| PLA V | Isotropic | 8.254 | 6.436 | 12837 |
| PLA | Orthotropic | 9.266 | 6.452 | 12837 |

## B. Printing parameters and their influences.

Using the standard printing parameters such as 0.200 mm layer height, 60 mm/s printing speed, and 100% fill, a qualitative analysis of the prototyped parts was performed. It was possible to notice that, in parts of greater complexity, such as mechanical respirator connections, there was a lamination of some layers and distortions in the geometry. Additionally, in the parts with small details, such as the gear, it was observed voids of filling so that the teeth became brittle (see Fig. 3).

Fig. 3: Defective parts: The left upper quadrant shows the layer lamination in the center of the part; the right upper quadrant shows local voids and detachment from the table; the left lower quadrant shows the loss of details of the gear teeth; and the right lower quadrant shows the voids at the gear edges, caused by the lack of complete filling of the image generated by the Simplify3D slicing tool

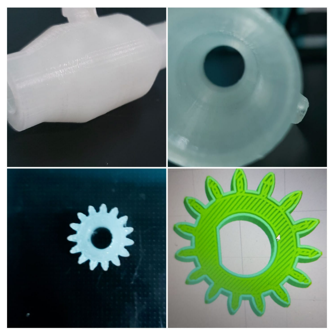

Fig. 4: Enhancement of the same parts after using the new parameters

After analyzing the results obtained using the traditional printing parameters, it was decided to search through the bibliographic search, which parameters best apply to the various parts necessary for the production of the prototype of the proposed mechanical ventilator. With that, it arrived at the following parameters: (a) deposition speed of 20 to 30 mm/s depending on the geometry complexity. It was noticeable that a speed less than 20 mm/s caused the PLA parts to have a displacement between the layers and a speed higher than 30 mm/s produced voids in its construction; (b) tracking angle of 0/90 degrees; (c) layer height of 0.100 mm; (d) contour overlap of 60%. On the one hand, values higher than 60% of the contour overlap generated defects in the part finishing and depth loss of the gear teeth enclaves. In more significant pieces, we observed burrs, which would be extremely harmful for tubes and connectors that need a smoothed interior. On the other hand, values less than 55% generated the appearance of voids at the edges; (e) the nozzle temperature in the first layer was set to be 5 degrees Celsius higher than the rest of the layers. In this case, variations higher than 5 degrees in nozzle or bed of print generate thermal stresses in the parts, thus causing it to warp and detach from the printing table [10][12][9][17].

The above mentioned parameters were used to produce all parts of the ventilator, from those with extremely complex geometries, to those that had very little detail, without problems of bed displacement, deformation of the parts or presence of voids, as can be seen in Fig. 4. In Fig. 5, it is possible to see the effects of the printing orientation of the rack. Figure 6 shows details of the produced parts assembled on a prototype of the mechanical ventilator.


Fig. 5: Print orientation, (a) vertical (V), (b) is horizontal (H) and (c) is flat (F)

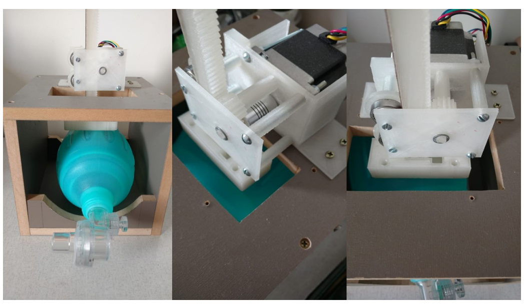

Fig. 6: Prototype of the mechanical ventilator. A video of the mechanical ventilator can be seen at the following link: https://youtu.be/uHftWasdNIs

## IV. Discussion

In the study on the effect of printing parameters on the production of parts for a mechanical ventilator, it was observed the importance of creating a set of printing parameters, which maximizes mechanical properties and facilitates the prototyping of these structures. Besides, there was a need to create a standard in the production of structures made by rapid prototyping, which makes validation feasible in health agencies.

The main results obtained with this study were the definition of a set of printing parameters that managed to be efficient for the structures of geometries of different complexities and specificities, allowing the prototyping of all the parts necessary for the construction of a mechanical ventilator prototype. This set of parameters proved to be efficient not only qualitatively but also quantitatively through the results obtained in the mechanical tests. Furthermore, the strength of prototyped parts was demonstrated through simulations, so that the safety coefficient shows that PLA can be used for the production of the structures.

The results obtained corroborate the of works of [4], [12],[9],[10], in which they demonstrated how the parameters directly influence the structures produced, both qualitatively and quantitatively. Besides, they demonstrated the effects of the horizontal print orientation ($X$), maximization of the parts' mechanical properties. It is possible to see this clearly when analyzing the figures 3 presented in the results, where the use of inadequate parameters can generate parts with severe defects, as in the case of the gear that has lost its shape completely, or in the case of the connection that suffers damage in the middle of the parts that make its use unfeasible. In figure 4 presented in the results, it is possible to see the beneficial effects of using a set of correct parameters.

PETG's elasticity modulus was inferior to those found in the bibliographies, but this difference is due to the anisotropy of the material, and in the literature, its elasticity modulus should be around 2.1 Gpa. It is visible that there is a similarity of behavior in the results of the mechanical tests of both PETG and ABS, this is because both materials are amorphous, whereas PLA is a semicrystalline material as seen in[8].

Despite the positive and corroborative results with several authors, it is necessary to create more profound studies on the topic, so that one can make a complete analysis of the effects of each parameter on the mechanical and chemical properties of the parts, and how their influence in hospital environment applications. Interestingly, an analysis of the effects of heat treatments on parts produced by rapid prototyping, considering that studies such as Avila et al. (2019), suggest that the heat treatment carried out at 90% of the glass transition temperature, on parts produced by rapid prototyping, has its mechanical properties maximized in some cases up to 10%. Eventually, a study is needed if one puts together these results to those obtained through the improvement of printing parameters and if this would not generate any harmful effect for use in hospital environments.

## IV. Conclusion

The maximization of the mechanical properties of the prototyped structures through three-dimensional printing taking into account the horizontal printing orientation (X), together with the best finishes on the parts that we produced with the improved printing parameters, demonstrate the importance of always considering the influence of these parameters when producing parts through rapid prototyping.

In summary, the results obtained were significant, as they open the possibility of using three-dimensional printing, inside hospitals, by technicians responsible for the maintenance of hospital equipment, in which, in a matter of hours, it can produce parts for the replacement of defective structures, speeding up the maintenance of hospital supplies and independence. However, one must always consider that the pieces cannot be in direct contact with the person, as they would need a more in-depth study on the subject. Furthermore, it would be necessary to create a manual of good practices for the production of hospital supplies through rapid prototyping, so that one could easily apply to different production sites without losing the standards of production excellence.

Despite the possibilities that arise through these studies and the possible applications of 3D printing in biomedical engineering projects, it is necessary to carry out more in-depth research on the effects of printing parameters on the production of hospital supplies through rapid prototyping, requiring an analysis regarding which thermoplastics are most suitable for such applications. It is also necessary to carry out several other mechanical tests, whether destructive or non-destructive, so that the effects that these sets of parameters have on the properties of the structures produced through three-dimensional printing become more evident and conclusive.

## Conflict of Interest

The authors declare that they have no conflict of interest.

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