Structural and Dimensional Analysis by Computed Tomography of Multi Geometric Template Manufactured by Fused Deposition Modeling

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Structural and Dimensional Analysis by Computed Tomography of Multi-Geometric Template Manufactured by Fused Deposition Modeling

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Abstract
During the last decade of the 20th century, there has been significant growth in the applications and development of manufacturing processes associated with Additive Manufacturing (AM). The evolution of production systems has made it possible that today there are more than 20 technologies associated with this production system. As a consequence of the development of AM, strategies have been developed to optimize the printing process focused on reducing manufacturing time, such as using Genetic Algorithms (GA). The effect caused by the modification of the path patterns is an effect of interest in two aspects; on the one hand, the dimensional assurance focused on the compliance of the dimensions of the components in comparison with the digital design of the same, and on the other hand, the structural composition and resistance that the printing process itself can generate. This paper aims to present the effect of optimizing the path of Fused Filament Fabrication (FFF) equipment on the dimensional finish and structural quality of a multi-geometric component. For this purpose, a template
composed of 23 geometric elements, printed by FFF technology, using PLA as base material, is used. The dimensional analysis is performed using Geomagic software, and the porosity analysis is performed using VG Studio software concerning the 134 attributes of interest. The results show, on the one hand, a 12% reduction in the total process time required to print the component. On the other hand, using Computed Tomography (CT), it was identified the effect on the dimensional precision of printing three elements with characteristics associated with the angular precision or definition of external angles and the roundness demanded by an unsupported cantilevered arch. In addition, it was possible to ensure that the structural quality of the multi-geometric component was not affected by the modification of the path required by the printing process.

Keywords
Fused Filament Fabrication, Computed Tomography, Dimensional Analysis.

Introduction
Manufacturing
New production technologies, recent marketing strategies, and compliance with customer demands based on quality standards are the guidelines that govern the development of the manufacturing and service industry [1, 2]. Faced with such business development guidelines and with the concern to subsist in a dynamic production system, the development of analyses focused on comparative indexes between market growth and development of countries involved in manufacturing and service activities has been triggered [3] that with the wide range of existing competitors, the pressure on the economy and inflation, it is possible to forecast that the growth of the manufacturing and services industry by 2025 will be 3.7% [4-6].

Considering the growth forecast for the manufacturing and services industry, Subtractive Manufacturing (SM) and Additive Manufacturing (AM) have defined their market niches based on the production capacity of their technologies. On the one hand, MS focuses on mass production systems, with smooth finishes on components, higher dimensional tolerance, and medium to large volume production runs [7]. On the other hand, MA focuses on small production runs, with the manufacture of complex designs and mechanisms or components that re-
quire a not very high mechanical requirement [8, 9]. However, despite the clear market definition that MS and MA have determined, both compete to satisfy, according to their capabilities, the most developed productive sectors shown in Table 1.

Table 1. Production sectors with the greatest development within the manufacturing industry [10].

<table>
<thead>
<tr>
<th>Industry</th>
<th>Developed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automotive</td>
<td>644</td>
</tr>
<tr>
<td>Chemicals</td>
<td>520</td>
</tr>
<tr>
<td>Building materials</td>
<td>180</td>
</tr>
<tr>
<td>Textiles &amp; Clothing</td>
<td>112</td>
</tr>
<tr>
<td>Pharmaceuticals</td>
<td>317</td>
</tr>
<tr>
<td>Precision Instruments</td>
<td>185</td>
</tr>
<tr>
<td>Machine Tools</td>
<td>175</td>
</tr>
<tr>
<td>Aerospace</td>
<td>50</td>
</tr>
</tbody>
</table>

**Additive Manufacturing**

Defined as the process of layer-by-layer fabrication from a digital design[11], Additive Manufacturing (AM) has made inroads into the component manufacturing industry through design freedom, product customization, reduced tooling cost, and in some cases, reduced costs associated with logistics activities [12-14].

Starting in 1980 with the filing of the first AM technology patent, AM has evolved to 22 technologies by 2022, which are; Fused Deposition Modeling or Fused Filament Fabrication (FDM or FFF), Vat Photopolymerization, Stereolithography (SLA), Digital Light Processing (DLP), Continuous Digital Light Processing (CDLP), Programmable PhotoPolymerization (P3), Material Jetting, Polyjet, NanoParticle Jetting (NPJ), Drop on Demand (DOD), Binder Jetting, Powder Bed Fusion, Multi Jet Fusion (MJF), Selective Absorption Fusion (SAF), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electro Beam Melting (EBM), Direct Energy Deposition, Laser Engineering Bet Shape (LENS), Electro Beam Additive Manufacturing (EBAM), Laminated Object Manufacturing (LOM)[15-18]. This rapid technological growth is evidence that AM is advancing, seeking to strengthen the range of production possibilities in the face of existing manufacturing systems.
According to Businesswire [10], Economics [13], and Nikitakos et al. [19], the significant development of AM technologies has changed the perspective regarding the future of manufacturing processes; one of these changes is generated by the feasibility in the development of complex design elements, which are manufactured in a single process, compared to the set of processes and sub-processes that the same design would demand in an SM process. Another change is associated with the projected growth of 16% in the industrial and professional printer sector and 40% in desktop and personal computers. Finally, it is worth mentioning that the use of AM has reduced waste generally produced in SM processes, and the nature of these processes generates that.

Despite the advantages of AM versus SM mentioned above, AM has been characterized as a low-volume production system unable to date to compete against SM, with quality defects associated with component repeatability, dimensional variations, and depending on the process, lack resistance to extreme operating conditions, such as temperature, compressive, tensile, torsional and bending stresses[20-22].

**Fused Filament Manufacturing**

Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF) is one of the AM technologies that bases its process on the extrusion of thermoplastics. The production system starts with the component's design, is coded by the printing equipment, and then proceeds to the printing process layer by layer[23].

According to Market Data Forecast [24], the ease of operation of FFF equipment and the low cost it represents for users, FFF technology has become the AM technology with the most economic gains generated during the last decade, achieving a total revenue of $550 billion, distributed in prototyping, production, proof-of-concept, market samples, art, education, and hobby applications.

Despite the growth of FFF, the technology exhibits quality defects associated with structural deformation [25-27], dimensional deformation[28, 29], low quality [30-32] and processing time [33, 34], which represent an obstacle for the use of this technology in the fabrication of functional prototypes and direct digital fabrication of objects intended for liquids and gases.
Optimization Algorithm

One of the strategies employed by software developers of printing equipment focused on reducing dimensional defects and surface finish generated by the FFF process has been implementing and developing different programming algorithms. These algorithms have been based on the findings obtained from their implementation in operating computer numerical control (CNC) equipment. Some practical algorithms for FFF have been the robot path optimization for machining [35], the Genetic Algorithm (GA) for the reduction of tool travel time without adding value to the component (tool air time) [36], the GA for optimization of the operating parameters and reduction of operating times [37, 38], recently Yodo & Dey [39] presented their proposal for multi-objective optimization based on evolutionary algorithms.

As mentioned, the use of GAs has evolved considerably in the optimization of CNC or extrusion tool paths. It is worth mentioning that use has also been made of hybrid methods focused on the reduction of operation times, for example; in the combination of the neural network algorithm in combination with the response surface algorithm focused on the optimization of parameters [40], or the combination of hybrid particle swarming with bacterial foraging optimization to optimize operating parameters [41], as well as those for Artificial Immune Systems (AIS) and Artificial Neural Networks (ANN) [42], GA with Particle Swarm Optimization (PSO) [43] or that of Ülker et al. [44] which report the combination of GA with AIS.

Specifically in the FFF, GAs have been executed to improve the performance of this technology based on the operating parameters and the determination of their optimal operating values, as demonstrated by [45] with the parameter optimization model, or [12], [34].

There is no doubt that the FFF process represents an alternative for the development of 3D printed components; however, the time necessary for the manufacturing of components and the dimensional finishing of the printed features represents an opportunity for progress from several research aspects. Considering the principles of transport methods, it is possible to make use of routing models, in which the path of the tool (extruder) depends on two questions, the first one directed to the curve to be traced and the second one the direction in which the curve will be printed. The mathematical expression
of this principle is shown as a function of two variables for decision-making:

\[ X_i = \begin{cases} 1 & \text{if the initial vertex of arc } i \text{ is } v_{i1} \\ 0 & \text{if the initial vertex of arc } i \text{ is } v_{i2} \end{cases} \]

\[ Y_{ij} = \begin{cases} 1 & \text{if the } i \text{-th traced arc is } \text{arc } j \\ 0 & \text{any other case} \end{cases} \]

With the variables described above, the model's objective function focuses on minimizing the total time required to perform the run, precisely the time that does not add value to the component print (air time). The time required is proportional to the distance traveled between subsequent arcs described by the following function:

\[
\min Z = \sum_{j=1}^{n} Y_{1j}[X_ja_{0j} + (1 - X_j)a_{1j}] + \sum_{j=1}^{n} Y_{nj}[X_ja_{1j} + (1 - X_j)a_{0j}] + \sum_{i=1}^{n-1} \sum_{j=1}^{n} Y_{ij} \left( \sum_{l=1}^{n} Y_{i+1,l}Z_{jl} \right)
\]

Where

\[ Z_{jl} = X_jX_l a_{jl} + X_j(1 - X_j)b_{jl} + (1 - X_j)X_l c_{jl} + (1 - X_j)(1 - X_l)d_{jl} \]

\( n \) is the total number of curves to be printed.

\( a_{ij} = \text{distance } (v_{i2}, v_{j1}) \)
\( b_{ij} = \text{distance } (v_{i2}, v_{j2}) \)
\( c_{ij} = \text{distance } (v_{i1}, v_{j1}) \)
\( d_{ij} = \text{distance } (v_{i1}, v_{j2}) \)
\( a_{0j} = \text{distance } (\text{origin}, v_{j1}) \)
\( a_{1j} = \text{distance } (\text{origin}, v_{j2}) \)

The use of constraints that avoid loops allows Tuker's formulation to obtain a transport model with the following objective function:

\[
\min Z = \sum_{i=1}^{n} \sum_{j=1}^{n} Y_{ij}D_{ij}
\]

Subject to:

\[
\sum_{j=1}^{n} Y_{ij} = 1 \text{ for } i = 1 \text{ until } n,
\]
\[
\sum_{i=1}^{n} Y_{ij} = 1 \text{ for } j = 1 \text{ until } n,
\]
\[
Y_{ij} = [0,1]
\]
\[
u_i - u_j + py_{ij} \leq p - 1 \text{ para } i = 1, \ldots, n; j = 1, \ldots, n; i \neq j
\]
With the objective function of the previous model, \( u \), are variables, and \( p \) is the maximum number of nodes that the extruder must cover from its initial position until it finishes printing the layer. Subject to the principle of integer programming models, a sequence in which the arcs are optimally visited is determined.

**Computed Tomography**

It is no secret that Computed Tomography (CT) has become an essential option for the analysis and development of manufacturing systems, the main reason being its ability to perform multiple analyses as well as the ability to observe inside the part in a relatively short time compared to traditional measurement techniques[46, 47]. With a single scanner, it is possible to obtain a 3D model of the workpiece and perform analysis inside the part (even in areas that are not accessible to the eye), a dimensional analysis, and analysis of multi-material parts without the need to separate the workpiece to perform reverse engineering, the 3D model of the workpiece can also be used to perform simulations, all this without the need to destroy or intervene the part[48].

CT is increasingly used to analyze complex geometries and in additive manufacturing processes. Part interior analysis and dimensional accuracy are these parts' most critical quality control analyses. Khosravany & Reinicke [49] presented a summary of industrial and academic applications, models created with different additive manufacturing processes or techniques in different materials and shapes to analyze porosity and material density mainly, all with regular geometries or with repetitive manufacturing patterns. On the other hand, Cho & Lee [50] presented the use of CT for porosity and material density analysis of a dog-bone-shaped specimen printed in Carbon fiber reinforced plastic.

In the report presented by Tkac [51], CT is used to analyze the porosity of a part based on the 3D-printed model of the lattice structure. This same part is used in[52] to perform a mechanical structure analysis.

The common feature of the parts mentioned in previous paragraphs is that they are parts with basic geometries or with repeated geometry patterns. The objective of the present research is to determine the dimensional finish and structural quality of a component composed of multi-geometric elements.
Methodology

The present research was developed in the following stages:

1. **Multi-geometric component.** The template presented by Aguilar-Duque et al.[53]. The modifications consisted of the redistribution of the geometric elements and the integration of two threaded cylindrical elements.

2. **Preprocessing of the multi-geometric component.** The parameters described in Table 2 are used to obtain the processing time required for printing the multi-geometric component.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Magnitude</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle diameter</td>
<td>0.3 mm</td>
<td>Solomon, I.J., Sevel, P. &amp; Gunasekaran. [54]</td>
</tr>
<tr>
<td>Quality</td>
<td>Layer height Magnitude 0.15 mm</td>
<td>[55, 56]</td>
</tr>
<tr>
<td>Perimeter</td>
<td>Wall thickness Magnitude 0.8 mm</td>
<td>[56, 57]</td>
</tr>
<tr>
<td>Filling</td>
<td>Filling density Magnitude 100%</td>
<td>[15, 58]</td>
</tr>
<tr>
<td>Filling pattern</td>
<td>Lines</td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Diameter 60°C</td>
<td>[59, 60]</td>
</tr>
<tr>
<td>Printing bed temperature</td>
<td>1.75 mm</td>
<td></td>
</tr>
<tr>
<td>Flow</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Retraction</td>
<td>Enabled</td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>Printing speed Magnitude 60 mm/s</td>
<td>[15, 56]</td>
</tr>
<tr>
<td>Travel speed</td>
<td>120 mm/s</td>
<td></td>
</tr>
<tr>
<td>Cooling</td>
<td>Print cooling Activate</td>
<td>[61]</td>
</tr>
<tr>
<td>Support</td>
<td>Generate support Active for -Z</td>
<td>[62-65]</td>
</tr>
<tr>
<td>Support placement</td>
<td>Support placement Everywhere</td>
<td></td>
</tr>
<tr>
<td>Adhesion of the printing plate Type of adhesion Border</td>
<td>[54, 62, 63, 66]</td>
<td></td>
</tr>
<tr>
<td>Edge width</td>
<td>8.00 mm</td>
<td></td>
</tr>
</tbody>
</table>

3. **Printing of the multi-geometric component.** The printing process of the control template and the template with the modified path process was carried out using an Ultimaker S5 printer. Considering the recommenda-
tions of the parameters identified in the literature review, the printing equipment was prepared according to the parameters shown in Table 3.

Table 3. Printing equipment characteristics

<table>
<thead>
<tr>
<th>Feature</th>
<th>Technical data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Print size</td>
<td>330 x 240 x 300 mm</td>
</tr>
<tr>
<td>Feeding</td>
<td>100 – 240 VAC, 50 – 60 Hz</td>
</tr>
<tr>
<td>Software</td>
<td>Ultimaker Cura</td>
</tr>
<tr>
<td>XYZ Resolution</td>
<td>6.9, 6.9, 2.5 micras</td>
</tr>
<tr>
<td>Nozzle diameter</td>
<td>0.25</td>
</tr>
<tr>
<td>Nozzle temperature</td>
<td>180 – 260 ºC</td>
</tr>
<tr>
<td>Bed temperature</td>
<td>20 – 110 ºC</td>
</tr>
<tr>
<td>Printing speed</td>
<td>&lt;24 mm3/s</td>
</tr>
</tbody>
</table>

Polylactic acid filament (PLA) is used for the printing process. The characteristics of the material according to the manufacturer's data sheet are presented in Table 4.

Table 4 PLA characteristics

<table>
<thead>
<tr>
<th>Característica</th>
<th>Dato técnico</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance</td>
<td>Filament</td>
</tr>
<tr>
<td>Color</td>
<td>White</td>
</tr>
<tr>
<td>Ignition temperature</td>
<td>388 ºC</td>
</tr>
<tr>
<td>Thermal decomposition</td>
<td>250 ºC</td>
</tr>
<tr>
<td>Melting point/melting range</td>
<td>145 – 160 ºC</td>
</tr>
<tr>
<td>Density</td>
<td>1.24 g/cm3</td>
</tr>
</tbody>
</table>

Before the printing process, the materials were stored in an air conditioning cabin, complying with the minimum period of 40 hours at a temperature between 23 and 25 °C until the preparation of the printing equipment.

After the printing process and to ensure that the dimensions of the components were not altered, vacuum packaging with insulation was used to prevent temperature changes and protect them from shocks. For the digitization process, the components were stored and subjected to an air-conditioning process inside a room with temperature and humidity control for a minimum period of 40 hours at a temperature of 20±2°C and relative humidity without condensation of 50±10%. The part was scanned using the ZEISS Metrotom 800 CT system for the measurement of plastic parts with high accuracy.

The components were measured using VG Studio software for porosity analysis and Geomagic for dimensional analysis. Using a point cloud of the workpiece, the geometric shapes were created, always avoiding the edges of the elements to avoid influences of possible imperfections.

Each of the components was measured according to the reference coordinates. The comparative analysis considers the characteristics of interest presented in Table 5.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat base</td>
<td>Quadrangular base, set of blocks, pyramid overhang</td>
</tr>
<tr>
<td>Prisms</td>
<td>Base quadrangular groove, base quadrangular groove, perforated cube, ladder, grooves.</td>
</tr>
<tr>
<td>Cylindrical drilling</td>
<td>Coaxial cylinders, base pass-through drilling, base drilling, cube-drills</td>
</tr>
<tr>
<td>Sphere</td>
<td>Set of spheres</td>
</tr>
<tr>
<td>Solid cylinder</td>
<td>Concave semi-cylinders</td>
</tr>
<tr>
<td>Hollow cylinder</td>
<td>Convex semi-cylinders, cantilevered arch.</td>
</tr>
<tr>
<td>Cone</td>
<td>Truncated cones</td>
</tr>
<tr>
<td>Angled surfaces</td>
<td>Truncated cones, triangular perforation, stair-case, inclined planes, pyramid of blocks</td>
</tr>
</tbody>
</table>

The component has 23 geometric elements in the upper part for dimensional analysis and three geometric elements in the lateral face of the component. For each element, at least one specific attribute is described in Table 5, from which 134 attributes of interest are obtained. Figure 2 shows a component describing one attribute, which is presented in Table 6.

**Figure 2. Spherical component.**

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>Feature</th>
<th>Description</th>
<th>Reference value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long</td>
<td>Plane A to Plane B</td>
<td>Distance from Plane A to Plane B (Plane A is parallel and opposite to Plane B)</td>
<td>13 ± 0.5 mm</td>
</tr>
</tbody>
</table>

5. Comparison of nominal versus actual CAD.
From the dimensions specified in the design, the error generated by the fused filament printing process is determined by tomographic analysis.
Comparison with the image.
Error calculation.
Classification of geometry deviations in ranges of units.
Classify the issue of nominal and real volumes considering the internal characteristics.

Results

Reduction of manufacturing time through GA

Using the software proposed by the manufacturer, the component requires 25 hours and two minutes to complete the printing process, consuming 14.34 meters of material. Using the Genetic Algorithm to reduce the total process time required, Table 7 shows the synthesis of 10 layers of the component associated with the number of iterations required by the optimization process. The selection of the layers was performed randomly.

Tabla 7. Time required per layer number

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Time (seconds) required per layer number</th>
<th>Total time required for printing the component (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0  1810  731.8  619.5  443.9  334.2  235.1  184.9  157.2  91.15  63.41  51.52</td>
<td>90120</td>
</tr>
<tr>
<td>10</td>
<td>1.0  1707  704.1  590.5  418.8  321  221.9  175.7  150.6  87.19  60.77  50.2</td>
<td>85930</td>
</tr>
<tr>
<td>50</td>
<td>5.0  1676  684.3  568  406.9  309.1  219.3  169.1  144  84.54  59.45  47.56</td>
<td>83424</td>
</tr>
<tr>
<td>100</td>
<td>10.0  1645  659.2  558.8  406.9  301.2  211.4  166.4  142.7  83.22  56.8  46.24</td>
<td>81951</td>
</tr>
<tr>
<td>500</td>
<td>50.0  1601  653.9  553.5  396.3  295.9  210  163.8  140  81.9  56.8  46.24</td>
<td>80093</td>
</tr>
</tbody>
</table>

With the modification of the tool path, a reduction of 11% is obtained, considering the printing time proposed by the manufacturer’s software versus the modification of the path generated by the GA.

Computed Tomography

Figure 3 shows the 3D volume of the workpiece obtained by CT. This volume is used to perform the dimensional analysis.

Figure 3. CT image of the workpiece

Dimensional analysis
In order to obtain information to initiate a CAD comparison of the workpiece, it is possible to observe two points of maximum deviation. The points of maximum deviation are +5.573 and -5.774 mm, presented in two punctual sites shown in a circle and a red circle in figure 4. Therefore, the average deviation of the workpiece is +0.147 and -0.124 mm.

**Figure 4. CAD comparison**

Figure 5 compares the point of maximum positive deviation; it is possible to observe that the 3D printing finishes on the edges are deficient and the planes are irregular.

**Figure 5. Comparison of maximum positive deviation point (left CT image, right CAD image).**

Figure 6 shows the point of maximum negative deviation and its comparison against CAD; it can be seen that there are significant quality defects and extra elements to the original geometry, which is the main reason for the deviation against CAD.

**Figure 5. Comparison of maximum negative deviation point (left CT image, right CAD image).**

In order to make a quick comparison by type of geometry, the attributes have been associated in three groups: Lengths, Angles, and Diameters. In Figure 7 it is possible to observe the absolute lengths deviations of the 3D volume measurement obtained with computed tomography from the original CAD design. The average deviation is 0.16 mm, the maximum is 0.90 mm, and the minimum is 0.01 mm. In this particular case, only two attributes are out of tolerance.

**Figure 6. Measurement deviation (absolute values) lengths.**

In Figure 8, it is possible to observe the absolute angle measurement deviation. In this case, we can observe that 9 out of 22 evaluated attributes are out of tolerance, the average deviation is 1°53', and the maximum value is 8°12'.

**Figure 7. Measurement deviation (absolute values) angles.**
Figure 9 shows the absolute deviation of the measurement of the group of diameters. The average deviation is 0.28 mm, the maximum value is 0.87 mm, and the minimum is 0.01 mm. In this case, 6 of 47 attributes are out of tolerance, 5 are spherical geometries, and one is a half cylinder.

**Figure 8. Measurement deviation (absolute values) diameters.**

**Structural Analysis**

A critical parameter in additive manufacturing processes is the filling parameter established at the time of printing, so the porosity analysis is essential to know the capacity of the manufacturing system. In this case, the total volume of the part is 194 717.30 mm³, and the percentage of porosity is 3921.25 or 2% of the total volume; most of the porosity is at the base of the template (Figure 10).

**Figure 9. Bottom view and side view of the workpiece.**

Although the porosity of the geometries is lower than that of the base, two elements have porosity defects in the interior, the perforated cube and the quadrangular base (Figure 11).

**Figure 10. Porosity in perforated cube and quadrangular base.**

Another vital aspect of 3D printing is the surface finish and print resolution. We can appreciate some findings in the workpiece in the following figures. Figure 12 shows a quality problem in the planes of the cantilevered arch.

**Figure 11. Comparison of defect of the cantilevered arc attribute (left CT image, right CAD image).**

Figure 13 shows that the CT image on the left does not have the threaded element, e.g., the printer cannot print this type of geometry.

**Figure 12. Comparison of threaded element defects (left CT image, right CAD image).**
Figure 14 shows an isometric view of the workpiece. Some printing defects on the external faces of the geometries are shown in red circles.

**Figure 13. Elements with quality defects**

**Conclusions**

GA in reducing tool path time is one of many strategies employed by technologies based on the principle of Computer Numerical Control (CNC), such as Fused Filament Manufacturing. By modifying the path, it is possible to reduce the time required for manufacturing by 12%. The time required to define the optimal route was 36 hours, a resource that should be considered for manufacturing single parts or small batches of parts. Therefore, executing the GA to manufacture the same component in small volumes is advisable.

It is essential to highlight that CT is the only technology capable of performing all the analyses presented from a 3D volume in a relatively short time, which is impossible with any other technology. Concerning the dimensional finish, it stands out that three of the 23 components considered in the template suffered effects on the dimensional finish associated with the phenomenon related to the modification of the extruder path, as well as deviations in the diameter of the material. The components affected are the inclined planes, the cantilevered arch, and the stepped pyramid, which, due to their characteristics, presented variation in the vertices generated by the planes.

Finally, it should be noted that the characteristics identified with CT made the analysis of the cylindrical elements, the inclined planes for angle measurement, and the cantilevered arch in the dimensional finishing and shape definition possible. In them, maximum deviations were identified as +5.573 and -5.774 mm caused by foreign bodies. Furthermore, in the analysis of the images and follow-up of the printing process, it is possible to define the phenomenon of bulging and seams...
caused by the closing of the geometry and finishing of the extrusion process. The abrupt change of direction of the extruder generates these two.

Referring to the step pyramid in Figure 6, as an element for the impression of dental orthoses, it is concluded that this type of geometry is not helpful for the development of implant bodies or for the implant abutment, which are elements of fastening and fixation of the dental crown. Despite being a fast and economical manufacturing process, the finish identified in the interior angles does not guarantee the fixation of the orthosis (dental crown).

The uses of this technology in the automotive industry favor aesthetic elements that require specialized molds and that will not be exposed to mechanical stresses. In the case of inclined planes, it is possible to identify that this technology is not useful for the determination of gears that require precision in the circular pitch, tooth thickness, ridge, face, shoulder and valley of the toothed element. However, structurally the printing process of angled elements is acceptable due to its low porosity, so the technology is recommended under the restriction of the magnitude of the angle.

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Figure 1

Analysis Methodology.
Figure 2

Spherical component.
Figure 3

CT image of the workpiece
Figure 4

CAD comparison

Figure 5
Comparison of maximum positive deviation point (left CT image, right CAD image).

Figure 6

Comparison of maximum negative deviation point (left CT image, right CAD image).
Figure 7

Measurement deviation (absolute values) lengths.

Figure 8

Measurement deviation (absolute values) angles.
Figure 9
Measurement deviation (absolute values) diameters.

Figure 10
Bottom view and side view of the workpiece.
Figure 11

Porosity in perforated cube and quadrangular base.

Figure 12

Comparison of defect of the cantilevered arc attribute (left CT image, right CAD image.)
Figure 13

Comparison of threaded element defects (left CT image, right CAD image).
Figure 14

Elements with quality defects