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ANTICIPATION AND CORRECTION OF ADDITIVE MANUFACTURING GEOMETRIC DEFECTS AT THE DESIGN STAGE

Mastering additive manufacturing processes is crucial to ensure the production of elements with high geometric quality while avoiding discrepancies between the CAD model and the final component after manufacturing. Therefore, focusing on error compensation and deviation correction from the design phase is essential. By adopting this approach, the CAD model will align perfectly with the manufactured product, reducing undesirable deviations and enhancing the overall precision of the manufacturing process.

1. INTRODUCTION

Additive manufacturing has revolutionized the manufacturing industry, producing complex-shaped products that were previously difficult or impossible to manufacture using traditional methods [1]. Faced with a globalized and increasingly competitive economy, innovation has become an essential lever for companies to develop or survive. Technological innovation enabled by Additive Manufacturing (AM) is revolutionizing the way we produce. By allowing material to be added layer by layer only where it is needed, AM transforms the design and manufacturing processes [2]. Additive manufacturing (AM), once mainly used for rapidly producing polymer prototypes, is expanding remarkably. The release of certain patents has considerably popularized this technology, thanks to its evolution and use of various materials, attracting the attention of many manufacturers. Sectors producing small series, such as aeronautics, aerospace, and medical, are particularly interested in these advances. Additive manufacturing today allows the production of functional parts and is therefore emerging as one of the means of implementing personalized production that

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addresses current issues. Without the need for dedicated tooling or raw material, additive processes provide new perspectives on the Product-Process-Material triptych [3].

AM covers processes that enable the element to be manufactured from raw materials, transformed layer by layer according to a digital model, without tooling. This technology differs radically from machining, which consists not of creating material but of progressively removing it from a block of material to make the object. In contrast, machining is a subtractive method. AM will not supplant other traditional manufacturing techniques. It is a complementary technique dedicated to the production of small series. It enables the production of monolithic elements, eliminating the need for assemblies and welds with complex geometries that are not feasible with traditional techniques. For example, honeycomb structures, known as "lattices", can be used to reduce the weight of elements through topological optimization or to facilitate the integration of implants into the human body. Another major advantage of AM is its ability to mass-produce customized elements [4].

There are many AM processes. Standards bodies at the international level (ISO/TC 261, ASTM F42) and in France (UNM 920) have classified them into seven categories according to the form of the raw material and the energy source used to transform it, layer by layer. These categories are as follows:

1. BJT (Binder Jetting)
2. DED (Directed Energy Deposition)
3. MEX (Material Extrusion)
4. MJT (Material Jetting)
5. PBF (Powder Bed fusion)
6. SHL (Sheet Lamination)
7. VPP (Vat Photopolymerization).

The manufacturing technology enables the assembly of materials to create objects from 3D models without requiring tooling, typically layer by layer, in contrast to subtractive manufacturing methods [5]. However, it lacks the benefit of a century of research into component production, as precision subtractive manufacturing techniques do. This means that certain aspects of the manufacturing value chain, such as metrology and inspection, are better understood by experts in subtractive techniques and still require many improvements in additive manufacturing [4]. The nominal shape of a layer is obtained by slicing the STL file at the desired layer height and connecting the points to form a nominal contour. Similarly, the actual printed shape is derived by gathering points from measurements to form an actual contour [6].

2. LITERATURE REVIEW

Additive manufacturing stands out from traditional methods due to its layer-by-layer construction, which presents design challenges related to knowledge, tools, rules, and processes. Due to various factors, the dimensional and geometric accuracy of the final product remains a major challenge for additive manufacturing in terms of quality assurance. In most cases, components produced by additive manufacturing do not achieve the required geometric accuracy or surface quality to meet functional and assembly requirements [7].

A displacement between the nominal and actual surfaces identifies the geometric deviations of elements produced by additive manufacturing. An ideal substitute surface models the actual surface with a geometric deviation resulting from a combination of defect modes. Effective modelling of geometric deviations is a crucial issue in Design for Additive Manufacturing (DfAM) as it enables the evaluation of geometric consistency and the optimization of geometric design [8]. Additively manufactured components often exhibit insufficient quality due to the formation of various defects [9].

Managing imperfections during the design phase of additive manufacturing is essential. Assessing the geometrical quality of an assembly is crucial for improving its functionality. Accurate mathematical models are needed to represent the imperfections and behaviour of assemblies. Dimensional tolerances and form defects must be considered to optimize product quality from the design phase.

The primary sources of error affecting the positioning accuracy of drop deposition in rapid prototyping systems, such as FDM, include mathematical errors related to the approximation of element surfaces in the standard input file. Additionally, process-related errors can occur, such as positioning inaccuracies in the *XY* plane due to the printer head's movement and in the *Z*-axis due to the alignment of different layers. Material-related errors, such as shrinkage, distortion, and binder infiltration during production, also play a significant role [10].

The Study [11] states in their thesis titled “Quality Control in Additive Manufacturing” that the manufacturing process impacts quality in two different ways. First, the process parameters are accessible to the user. They can influence the quality of the elements, such as the powder size, the manufactured geometry, layer thickness, and so on. Then, there are all the characteristics specific to each manufacturing process that the user does not have control over.

The study in [12] focuses on analysing defects arising from additive manufacturing using electron beam melting (EBM). To this end, they selected a specific geometry featuring an overhanging volume. The major geometric defects primarily concentrate on the front face (material loss at the edge) and the lower element of the piece (thickness variations). To characterize these defects, they applied Principal Component Analysis (PCA) to identify the most significant modes per batch of produced elements. Their analyses reveal that the defects are closely related to the manufacturing strategy and that elements positioned at the periphery of the build platform exhibit significant defects.

In his thesis titled "Contribution to the Design of Mechanisms: Tolerance Analysis with the Influence of Form Defects", [13] explores the analysis of geometric tolerances by considering the impact of form defects through two analytical approaches: the worst-case approach and the statistical approach. The application of these methods was demonstrated through assembly examples, and to illustrate the differences between the two approaches, a calculation of the non-conformity rate was performed.

Additive manufacturing by extruding filled polymers allows for rapidly prototyping complex metallic elements. However, eliminating rhomboid voids remains a challenge, influenced by the deposition method. A study shows that a 20% overlap strategy eliminates these voids and minimizes dimensional deviations, thus improving the quality of the produced elements [14].

Dental CAD/CAM (Computer-Aided Design/Computer-Aided Manufacturing) software developers optimize filtering parameters, such as chord error, to manage points in high-density areas. A small chord error enhances details but extends post-processing time. Geometric and dimensional deviations are present, but other CAD formats, though more precise, take longer to process. The STL model is preferred for its speed despite some approximations [15].

3. CHALLENGES OF 3D PRINTING

Parts manufactured using FDM (Fused Deposition Modelling) exhibit a limitation in the achievable accuracy [16]. To print our object, it must be saved as a printable file (a format that can be understood by 3D printers), as a file extension. Stl (Standard Triangle Language) (Fig. 1). STL allows the 3D printer to interpret CAD model data and then create a physical object. It represents the surface of the digital model as a mesh of triangles, with each triangle consisting of three elements: vertices, edges, and faces. This file type divides the surface of an object into triangles to form the shape. Simpler shapes require fewer triangles, while more complex shapes need more. Today, other formats are used for 3D printing, such as the *.3MF format developed by Microsoft, but STL remains the most common.

```
solid CATIA STL
  facet normal  0.000000e+000  0.000000e+000  1.000000e+000
    outer loop
      vertex -5.176381e+000  1.931852e+001  3.000000e+001
      vertex  5.176381e+000  1.931852e+001  3.000000e+001
      vertex  1.224606e-015  2.000000e+001  3.000000e+001
    endloop
  endfacet
  facet normal  -0.000000e+000  0.000000e+000  1.000000e+000
    outer loop
      vertex  5.176381e+000  1.931852e+001  3.000000e+001
      vertex -5.176381e+000  1.931852e+001  3.000000e+001
      vertex  1.000000e+001  1.732051e+001  3.000000e+001
    endloop
  endfacet
```

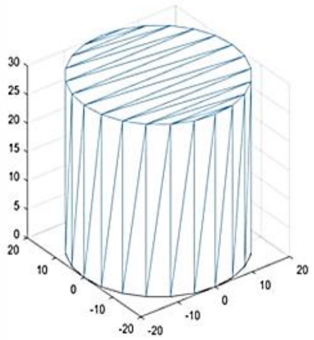

Fig. 1. Excerpt from STL file for a cylindrical element

However, print quality can be improved by adjusting a few parameters when saving in STL format, the first of which is conversion tolerance. Tolerance, also known as "chord height," is the maximum distance between the surface of the original design and the STL mesh (Fig. 2a). It is recommended to set the tolerance between 10 µm and 100 µm. There is no need to reduce this factor further, as 3D printers cannot print beyond this level of detail [8]. The second parameter is the plane angle. The plane angle, or angular tolerance, defines the maximum angle between the normal adjacent triangles when modelling flat surfaces (or surfaces with no angular variation). By default, this angle is typically set to 15 degrees (Fig. 2(b)). Reducing the tolerance (0° to 90°) improves print resolution. A tolerance of 0° offers the finest detail possible but may lead to the creation of very small triangles. The lower and better the conversion factor, the smoother your print will be.

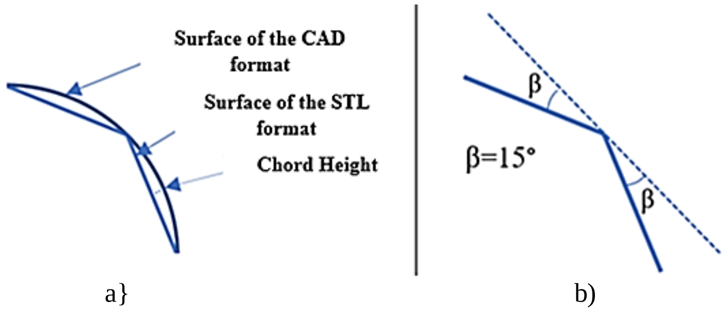

Fig. 2. a) 2D illustration of chord height, b) angular deviation

A slicing engine will take the STL file and slice it. This layer slicing allows the 3D printer to understand how to build the object incrementally, layer by layer, by depositing or solidifying the material according to the instructions provided by the model file. By dividing the model into slices, the 3D printing software ensures the accuracy and fidelity of the final object's reproduction by the initial CAD model (Fig. 3).

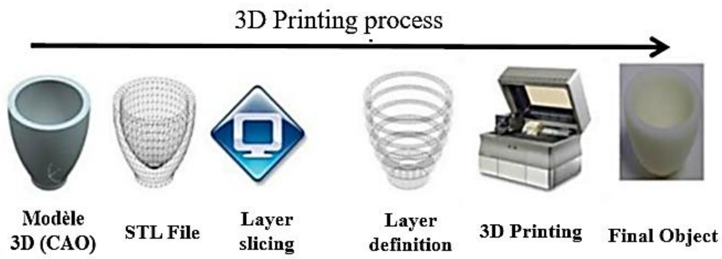

Fig. 3. The 3D printing process in a few easy steps [17]

3.1. CONVERSION ERROR FROM CAD FORMAT TO STL FORMAT

As expressed, current machines do not rely on the computer-designed digital model CAD (Computer Aided Design) to manufacture 3D objects but on a file format called STL (Standard Triangle Language), which describes the object's shape through a set of triangles. This format simplifies the manufacturing process but also introduces errors between the ideal surface of the object (nominal surface) and the surface approximated by the triangles (triangular mesh representation). These are called geometric approximation errors, illustrated in Figure 4A [18].

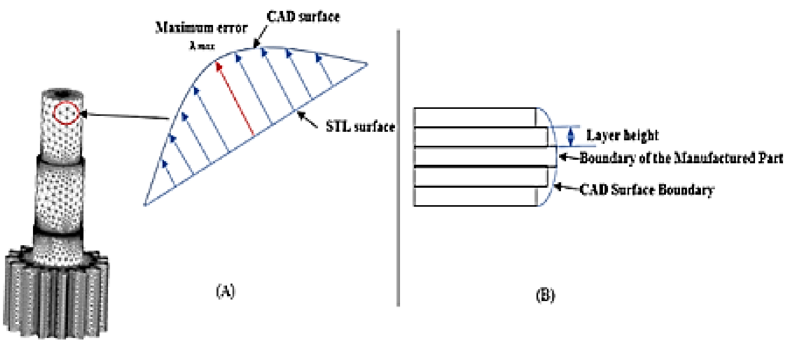

Fig. 4. 2D illustration of CAD to STL conversion errors

In addition to the previously mentioned mesh defect, other types of defects can affect the geometry of the final element. Among these are material shrinkage due to cooling, which varies depending on the material used, and elliptical deviations, also known as ellipse modes. Elliptical deviations, denoted by eccentricity (e), measure the distortion between the final shape and a perfect circle with zero eccentricity. These deviations can also apply to other geometric shapes. For example, a square with dimension (a) may transform into a rectangle with differing lengths and widths. These defects generally result from a combination of process parameters, material choices, design errors, thermal factors, and environmental conditions.

3.2. SURFACE INTERPRETATION ERROR BY CMM

To ensure the compliance of manufactured elements, a coordinate measuring machine (CMM) is utilized to identify discrepancies and decode tolerances. This process relies on the data collected while probing the measured surface. Given the uncertainty regarding the precise location where the probe contacts the surface, an approximate contact point, or measured point, is used instead. The calculation of this contact point depends on the coordinates of the probe's center, the approach direction, and the probe's radius. However, this method introduces uncertainty about the exact position of the measured point. This uncertainty affects the parameters of the associated surfaces and the geometric construction necessary for verifying technical specifications, as the point cloud obtained is fundamental for creating the surface and geometry of the element.

When an element is inspected on a coordinate measuring machine (CMM) (Fig. 5), measuring the surfaces with more points than the strict minimum required to define the geometric element mathematically is crucial. This allows for matching the theoretical component to the measured points by understanding the parameters that connect them to the point cloud, thereby minimizing defects.

Additionally, a “staircase error” arises due to the layer-by-layer slicing of the STL file during the part-building process, as illustrated in Fig. 4B.

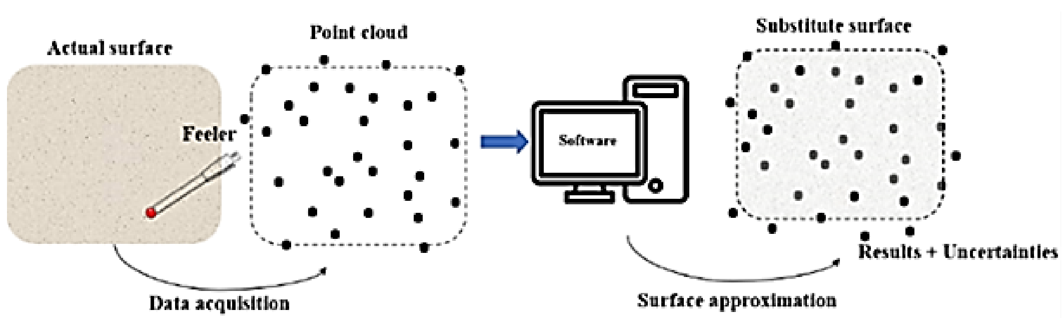

Fig. 5. Principle of surface interpretation by CMM

There is always a difference between the real surface and the approximated one, as the latter is obtained from a point cloud using either the least squares method or the min-max method. These two methods, while powerful, rely on points that are themselves subject to errors. Each measured point corresponds to the center of the probe's ball, rather than the direct contact point with the surface. This subtle deviation introduces an approximation that, although close, fails to accurately reproduce the reality of the measured surface (Fig. 6).

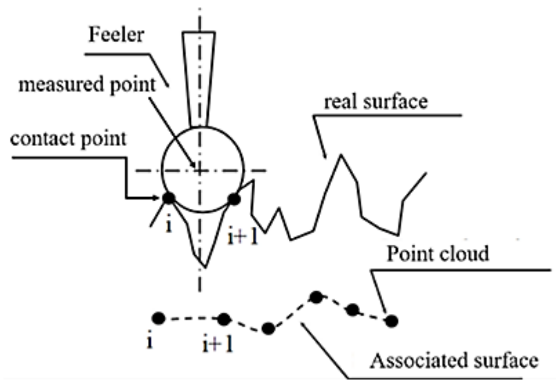

Fig. 6. Elaboration of point clouds using the CMM [19]

As shown in Figure 6, since the actual contact point between the probe and the measured surface is unknown, an estimated contact point called the measured point, is used. This point is calculated based on the probe center coordinates, the probing direction, and the probe's radius, assuming contact occurs at the intersection of the stylus sphere and the surface normal. This approximation introduces uncertainty regarding the exact position of the probed point, which may alter the geometry of the inspected element and compromise the reliability of the results [19].

4. CORRECTION OF GEOMETRIC ERROR FOR A CYLINDRICAL ELEMENT

The objective is to determine the correction factor for the global surface of the mesh. This adjustment will align the geometry of the element with the designed surface accurately. The correction coefficient is defined by the following formula:

$$C_{\text{correction}} = \frac{S_{\text{Nominal}}}{S_{\text{Calculated}}} \tag{1}$$

Where $C_{correction}$: Correction coefficient; $S_{Nominal}$: Nominal area, and $S_{Calculated}$: Calculated area

4.1. DETERMINING THE NOMINAL AREA

Initially, the element under study was modelled in CATIA V5, with a radius of 20 mm and a length of 30 mm, as depicted in Fig. 7. This step provided the essential base geometry for the analysis. Subsequently, the nominal surface area of the element was calculated, assuming flawless geometry without considering any potential errors or deformations.

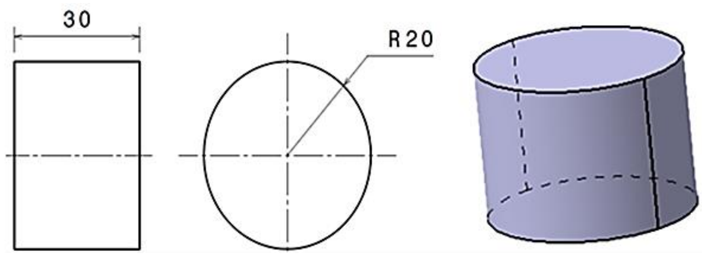

Fig .7. Studied element

The surface area of our cylinder can be calculated using the following formula:

$$S_{\mathrm{N}} = S_{\mathrm{L}} + S_{\mathrm{B}} \tag{2}$$

With: S_{N}: Nominal Surface, S_{L} : Lateral Surface, where:

$$S_{\mathrm{L}} = 2\pi \mathrm{Rh} \tag{3}$$

S_{B} : Base surface, where:

$$S_{\mathrm{B}} = 2\pi \mathrm{R}^2 \tag{4}$$

Based on the initial dimensions, with a radius of 20 mm and a height of 30 mm, our calculations reveal a nominal area, S_N= 6283,18 mm².

4.2. DETERMINING THE CORRECTED AREA

To study defects caused by different factors in a targeted manner, it is necessary to develop defect modes that directly reflect the nature of defects caused by model errors, process-induced errors, and machine errors, respectively. Additionally, the feasibility and accuracy of the proposed modes applied to the method of geometric deviation identification and prediction should be verified before being applied to real AM elements.

Generally, three types of errors impact the geometry of elements produced through additive manufacturing. These errors are outlined below.

1. Mesh error ($\lambda 1$): This error arises from interpreting the geometry of an element through Delaunay triangulation, specifically during the conversion phase from the CAD model to an STL model. The following formula can quantify it:

$$\lambda_{1\max} = R - \sqrt{R^2 - \left[R \cdot \sin\left(\frac{\pi}{ne}\right)\right]^2} \tag{5}$$

Where; n: represents the number of polygon vertices in the mesh and *R*: is the radius of the element to be printed (mm).

The contour is discretized into 32 points, with these data giving $\lambda 1$max=0.38 mm

2. Radius change mode error ($\lambda 2$): This error stems from the contraction of the material used. For instance, the shrinkage rate of PLA (polylactic acid) can range from 0.3% to 0.5%. This phenomenon is represented by a radius contraction mode, identified by the following parameter:

$$\lambda_2 = R - R' \tag{6}$$

Such as R: Nominal diameter (mm); and R': Shrunk radius (mm).

According to the literature, taking the example of the plastic material PLA, which has a 0.5% shrinkage rate, we obtain $\lambda 2$ = 0.1 on a 20 mm radius.

3. Elliptical error ($\lambda 3$): arises from machine displacement. For some low-precision AM machines, the toolpath designed for a cylinder often results in an elliptical cross-section. Due to irregular movement along the *X* and *Y* axes during manufacturing, the key parameter is the semi-axis of the ellipse along the *Y*-axis. In contrast, the semi-axis along the *X*-axis is assumed to remain constant (R):

$$\lambda_{3\max} = R - \frac{R.R\prime}{\sqrt{R^2 sin^2(\theta) + R\prime^2 \cos^2(\theta)}} \tag{7}$$

$\lambda 3$: A maximum difference of 0.2 mm is assumed between the nominal and minor radius of the ellipse.

The various stages and processes of additive manufacturing (AM) introduce multiple and complex sources of errors that pose significant challenges to the geometric quality of the manufactured product. Therefore, effective modelling of geometric deviations is essential for additive manufacturing [20]. To facilitate the quantitative study of the impact of process parameters on the geometric deviation of elements obtained by additive manufacturing, this research proposes geometric defect modes based on defect shapes caused by various process factors. The method for identifying and predicting geometric deviations in additive manufacturing is also presented, where the overall error of these modes is represented by the following formula:

$$\lambda_G = \Sigma \lambda_i \tag{8}$$

Such as i = 1 ,2 and 3, And since λ_1 = *0.38 mm*; λ_2 = *0.1 mm* and λ_3 = *0.2 mm*
Where; λ_G: Overall error; So λ_G= 0.68 mm

In this study, a cylinder with a radius (r) of 20 mm and a length (h) of 30 mm was analysed, presenting a geometric deviation (E) of 0.68 mm. Considering this error, the radius adjusts to:

R' = R initial – 0.68 mm. Therefore, the actual radius is 19.32 mm

The surface area of our cylinder can be calculated using the following formula:

$$S_{\mathrm{C}} = S_{\mathrm{L}} + S_{\mathrm{B}} \tag{9}$$

With: S_{C}: Calculated Surface, S_{L} : Lateral Surface, where:

$$S_{\mathrm{L}} = 2\pi \mathrm{R}'\mathrm{h} \tag{10}$$

S_{B} : Base surface, where:

$$S_{\mathrm{B}} = 2\pi \mathrm{R}'^2 \tag{11}$$

Therefore, the calculated surface area is $\boldsymbol{S_C}$=5987 mm².

Since the correction coefficient is equal to the ratio between the nominal surface and the calculated surface (including the deviation generated by the three modes) (Equation 1), the correction coefficient is therefore: $\boldsymbol{C_{correction}}$ = 1.05

4.3. INTERPRETATION

A correction coefficient of 1.05 indicates that the calculated surface area (actual surface) is slightly larger than the theoretical (meshed) surface, with a 5% difference. This means a geometric increase is needed to adjust the element's dimensions. For a circular element, the surface area is proportional to the square of its radius ($S=\pi r^2$). Therefore, a 5% decrease in the surface area (indicated by a correction coefficient of 1.05) requires an adjustment to the radius. The correction coefficient's square root should be applied to obtain this corrected radius. Thus, with a correction coefficient of 1.05, the adjustment factor for the radius will be $\sqrt{1,05}$. The following formula provides the corrected radius:

$$R_{Corrected} = R_{initial} * \sqrt{C_{correction}} \tag{12}$$

Where: $\boldsymbol{R_{corrected}}$: Corrected radius, $\boldsymbol{R_{initial}}$: Nominal radius (20 mm), $\boldsymbol{C_{correction}}$: Correction coefficient, with a value of 1.05. Therefore, the corrected radius is 20.49 mm. This results in a corrected diameter of: Corrected diameter = corrected radius × 2 = 40.98 mm

4.4. DISCUSSION

The study highlights the main sources of geometric errors that affect the accuracy of elements produced by additive manufacturing, including mesh errors, material shrinkage, and deviations caused by machine movements. These combined factors result in a total deviation of 0.68 mm, necessitating adjusting the cylinder's radius. A correction coefficient of 1.05 indicates that the actual surface area is 5% smaller than the theoretical surface area, thus requiring a geometric increase. Since the surface area of a circular element is proportional to the square of its radius, the radius adjustment is made by applying the square root of the correction coefficient. Consequently, the initial radius of 20 mm is adjusted to 20.49 mm to compensate for this difference. This correction ensures that the final element meets dimensional tolerances, reducing errors and optimizing the overall precision of the manufacturing process.

4.5. TEST PIECES

To ensure the reliability of the study and verify that the applied correction is optimal for the element, five samples were fabricated with an adjusted diameter of 40.98 mm (see Fig. 8 (Right)). This was done using the Ultimaker S5 3D printer (see Fig. 8 (Left)) and a 0.4 mm white PLA filament, following the detailed manufacturing parameters outlined below:

- Layer thickness: 0.15 mm
- Movement speed: 100 mm/s
- Fill density: 40%
- Infill type: Zigzag
- Wall thickness: 0.8 mm.

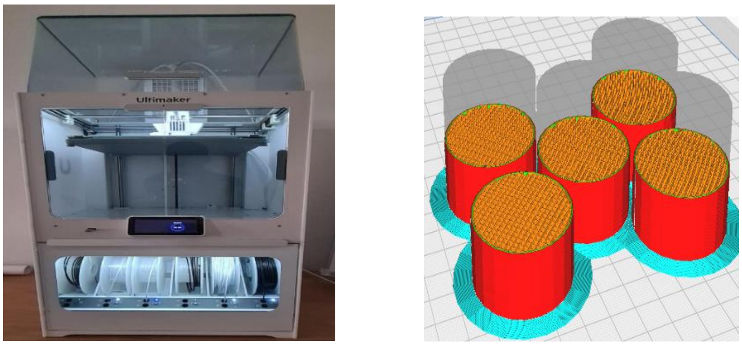

Fig. 8. (Left) Ultimaker S5 machine used; (Right) 3D view of the element arranged on the printer bed

For each element shown in Fig. 9, ten precise measurements were randomly performed along the entire height of the studied part using a calibrated calliper. This approach ensured dimensional consistency and allowed verification of compliance with the theoretical diameter. The detailed results of these measurements are presented in Table 1.

Fig. 9. The actual manufactured elements

Table 1. Measurement Results for the 5 Manufactured Parts

Parts	M1 [mm]	M2 [mm]	M3 [mm]	M4 [mm]	M5 [mm]	M6 [mm]	M7 [mm]	M8 [mm]	M9 [mm]	M10 [mm]
1	40.11	40.09	40.13	40.05	39.98	40.13	40.07	40.1	40.14	40.12
2	40.12	39.99	40.11	40.11	40.1	40.16	40.02	40.12	40.12	40.05
3	40.1	40.14	40.08	40.09	40.11	40.2	40.16	40.1	40.09	40.13
4	40.12	40.1	40.11	40.15	40.08	40.12	40.12	40.07	40.11	40.12
5	40.09	40.15	40.1	40.14	40.11	40.13	40.1	40.13	40.08	40.11

4.6. INTERPRETATION

The above results show that the average diameter remains 40.11 mm after correction. This indicates a persistent deviation due to random error. ε. caused by various factors affecting the printing process. Unlike systematic error. random error is unpredictable and can vary randomly from element to element depending on factors such as machine variability.

environment. material. etc. To remedy this. a study will be conducted on a sample of 100 randomly generated values based on a normal distribution. This analysis will allow the quantification of random errors and deepen the understanding of their distribution. Although these errors are generally less significant than systematic errors. 20% of the systematic errors will be considered as a tolerance interval. This will allow the determination of the maximum error using the following formula:

$$\varepsilon_{max} = 0.2 * \lambda_G \tag{13}$$

where λ_G = 0.68. This gives. ε_{max}= 0.14.

This procedure enabled the calculation of the standard deviation using Equation 14 and the generation of 100 random values according to the normal distribution. This exploration of the distribution of random errors (Fig. 10) helped assess their impact on the printing process and geometric and dimensional accuracy:

$$\sigma = \frac{\mathrm{IT_{max}}}{6} \tag{14}$$

were ε_{max}= $\mathrm{IT_{max}}$. So. σ=0.02.

The graph in Fig. 10 reveals a symmetrical distribution of errors around the mean. indicating a stable process with no significant bias. Most errors are near zero and follow a normal distribution. suggesting well-controlled random variability in the manufacturing process. The deviations between the measured diameters and the nominal 40 mm circle (Fig. 11) show slight variations. with values generally very close to the target. These small fluctuations around the nominal diameter can be attributed to manufacturing tolerances. random errors. or inherent variations in the process. Nevertheless. the overall alignment of the measured circles with the nominal circle demonstrates great stability and precision in the process. with errors falling within an acceptable range. After correction. the five pieces manufactured were found to be very close to the desired values. ensuring that the manufactured pieces accurately reflect the designed pieces.

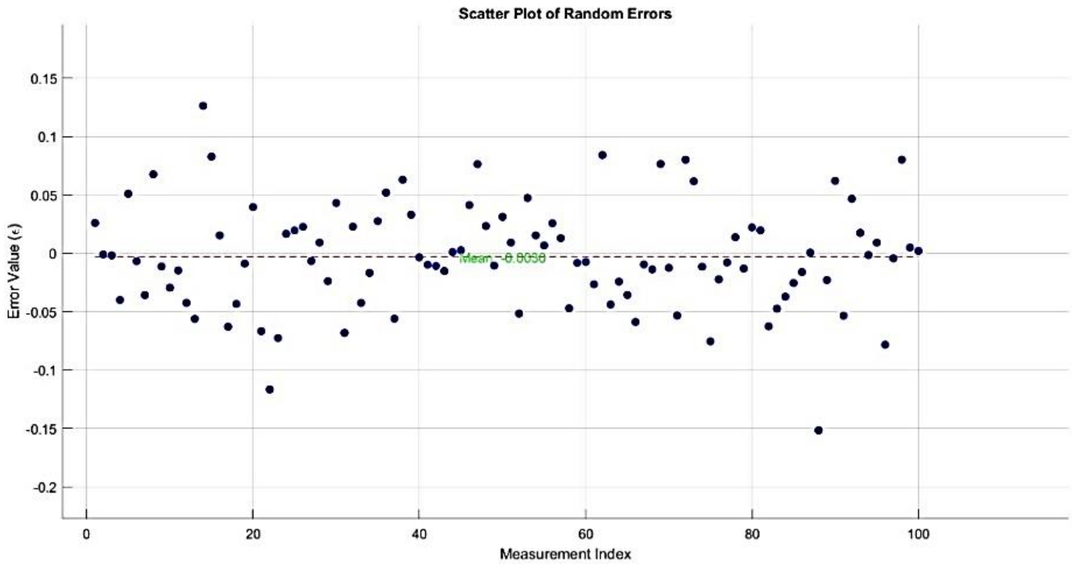

Fig. 10. Error distribution and deviation from the mean

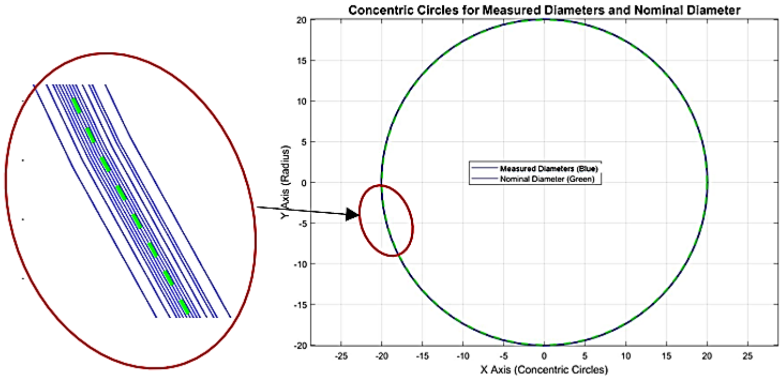

Fig. 11. Variability of measured diameters relative to the nominal diameter

4.7. DISCUSSION

The desired nominal diameter for the part is 40 mm. However. several challenges and impacts prevent obtaining this part with the nominal diameter. The design stage uses the CAD product model. while the fabrication relies on the STL file. a tessellated representation of the design model. By predicting the deviations caused by the AM process. this method provides valuable feedback to optimize the product design. Shape shrinkage during printing. mesh errors. and machine displacement deviations in elliptical mode result in systematic errors. while random errors arise from material fluctuations and environmental conditions. Modelling these deviations helps predict and correct repeatable and unforeseen variations in the final product's shape. For this reason. it was decided to work on the 2D plane to identify the deviation and determine the compensation value. Thus. to achieve a final diameter of 40 mm. an adjustment of 0.98 mm must be made during the design phase.

This compensation was carried out during the design phase of a cylindrical part with a diameter of 40.98 mm (Fig. 12). The fabrication of this part was performed by an Ultimaker S5 machine (Fig. 8 (left)) at the Laboratory of Technology and Industrial Services of the Higher School of Technology of Fès. To verify that the fabricated part met the identified compensation value. five parts with a diameter of 40.98 mm were manufactured. and ten measurements were taken on each of them. The average value of the 50 measurements taken was 40.11 mm. which shows that the deviation was minimized from 0.68 mm to 0.11 mm (Table 2). without considering the random errors related to different factors and environmental conditions. The results indicate a persistent deviation due to random error. ε. caused by various factors affecting the printing process. Unlike systematic error. random error is unpredictable and can vary from one element to another depending on machine variability. environment. and materials. To address this. a study will be conducted on a sample of 100 randomly generated values. based on a normal distribution. This analysis will allow for the quantification of random errors and deepen the understanding of their distribution.

Table 2. Assessment of Diameter Deviations and Corrective Adjustments

Nominal Diameter	Diameter with Deviation	Diameter after Correction	Corrected Deviation (Systematic Error)	Remaining Deviation (Random error)
40 mm	40.68 mm	40.11 mm	0.57 mm	0.11 mm

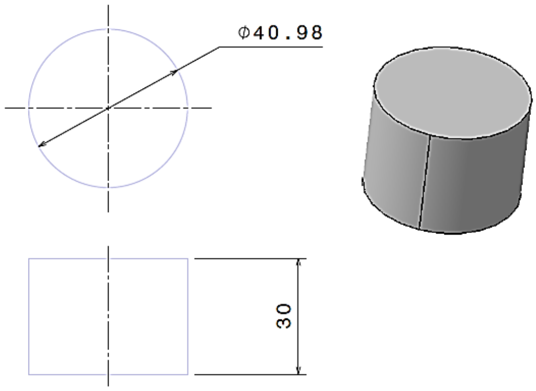

Fig. 12. Desired part with adjusted diameter

Although these errors are generally less significant than systematic errors. 20% of those will be considered as a tolerance interval. This will allow the determination of the maximum error using the formula. A value of 0.14 has been identified as the random error. With process control. the diameter will be minimized to 39.97 mm. which will compensate for both systematic and random errors. ensuring greater precision in the quality of the fabricated part while disregarding various factors that impact the desired piece. As a continuation of this work. the integration of modes in the (*x*. *y*. *z*) plane will be pursued to identify the impact of these modes on a cylinder. This will allow for the correction of this deviation in a 3D context.

5. CONCLUSION

This analysis highlights the main sources of geometric errors affecting the accuracy of elements in additive manufacturing: mesh imperfections. material shrinkage. and deviations due to machine movements. These factors create a total deviation of 0.68 mm. requiring an adjustment of the cylinder radius to 20.49 mm with a correction factor of 1.05. indicating an actual surface area 5% larger than expected. This correction ensures that the final element meets dimensional tolerances. Although the measurement distribution is cantered around the mean. slight random variability can impact the element's functionality. especially if the nominal diameter is critical for assembly. By rigorously adjusting the process to minimize these deviations. this approach enhances the precision and reliability of the elements. thereby improving the quality and durability of additive manufacturing products. What we can conclude from our study and testing is that there are still challenges in additive manufacturing. from the design phase through to the final element. Errors appear as soon as the CAD model is converted into an STL file. followed by the conversion of the latter into G-code. which enables the desired element to be sliced. Errors were also identified due to 3D printing parameters. such as layer thickness. nozzle diameter. and density. as well as machine errors caused by the movement of the nozzle support. Additionally. random errors arising from environmental factors. temperature. etc. were observed. It is therefore advisable to always consider the deviation caused by these conditions to anticipate and minimize errors at the design stage.

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