

## Article

# Analysis of the Dimensional and Shape Accuracy and Repeatability of Models Produced in the Process of Additive Extrusion of Thermoplastic Polymers Using Fused Filament Fabrication Technology

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**Abstract:** To achieve high precision and repeatability of prototyped models, work is carried out to improve existing solutions and thus expand the areas of application of 3D printers. Ways to increase the efficiency of 3D printing are being sought. The subject of the work concerns the analysis of dimensional and shape accuracy and repeatability of samples produced by a technology based on layered extrusion of thermoplastic polymers using FFF—fused filament fabrication technology. The key parameter for assessing the quality of parts is the property most expected by 3D printer users regarding the accuracy of dimensions of manufactured prototypes. As part of the research, conclusions were drawn regarding the precision of the samples as original patterns. The dimensional accuracy in the x, y, and z axes of the 3D printer was determined in terms of the design of the 3D printer's actuator system. Three-dimensional maps of deviations of the pattern surface were used in relation to the nominal 3D CAD model to test the accuracy. The analytical results obtained during the research work, together with the graphs of the normal distribution probability function, indicate a high repeatability for each of the axes, and the highest repeatability was for the z-axis. The dimensions in the remaining axes were within the assumed tolerance of 0.1 mm, except for the two extreme dimensions, which were caused by a different method of heat dissipation, proving the influence of the arrangement of samples on the working platform.

**Keywords:** polymer materials; additive technologies; 3D printing; repeatability



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## 1. Introduction

In engineering applications, additive manufacturing (AM) methods are characterized by a number of advantages that determine the suitability of their use in unit production and prototype production [1–5]. First of all, they ensure ease of production preparation—it is not necessary to construct special equipment, molds, dies, or fixtures. There is also no need to develop the sequence of operations and settings because the entire process takes place in one operation and setting [1,4]. The FFF (fused filament fabrication) method is universal, and a thermoplastic polymer is used as the model material [5,6]. The construction of a semi-finished product is also unnecessary, because, in the vast majority of cases, the item is ready-made, without the need for subsequent processing [7].

In the available works, there is a lot of research on process parameter optimization, which potentially allows for obtaining increased dimensional accuracy [8–12]; however, such works are strictly related to the process parameters but do not take into account all factors that are connected to the topology of the produced part. Some other approach has been suggested by Nath et al. [13], who developed a tool that allowed for a kind of calibration of

the part that is going to be manufactured, based on experimental data. Such a tool could be used to minimize geometric inaccuracies, such as thickness errors and printing time. Minetola et al. [14], in their work, proved that using small layers during AM production leads to a better definition of the geometry of the features, but in some cases using higher layer values (0.21 mm versus 0.10 mm) allowed for obtaining better ISO IT grades. To overcome such technological obstacles, Moroni et al. [15] developed a tool for obtaining better dimensional quality based on the voxel volumetric representation. The main limitation of this proposed method is related to the vastness of the information associated with this representation scheme. A new approach is becoming more available with the development of artificial intelligence and statistically-based software (AI) [16,17]. Such tools make it possible to predict the geometrical dimensions with their deviations, including process parameters and other factors that are not directly related to the AM process.

The purpose of the accuracy and repeatability of the research was to analyze the dimensionality and shape of the FFF technology, carried out on the example of the developed pattern. Analyses allowed a more complete understanding of the limitations of additive technologies and also helped to determine the probability that a defective detail does not meet the conditions of geometric accuracy [18–25], which leads to a justification of the use of statistically based and AI-supported tools to predict part dimensions and deviations. Unlike previous studies that often focus solely on process parameters, this research considers the complete topology of the produced part and incorporates a broader range of factors, thus providing a more holistic understanding of the limitations and capabilities of additive technologies.

## 2. Materials and Methods

For the purposes of this research, a pattern model was designed to reflect the basic features used in the structure. The 3D CAD model was designed in the Autodesk Inventor Professional 2021 (Autodesk Inc., San Francisco, CA, USA, Version: 2021), environment. An OriginalPrusa i3 Mk3 (Prusa Research a.s., Prague, Czechia) printer was used to create research models using the fused filament fabrication technology. The research models were measured using an automated and robotic ZEISS Scan Box (Carl Zeiss Industrielle Messtechnik GmbH, Oberkochen, Germany). Dimensional and shape analyses were performed using the ZEISS Inspect software (Carl Zeiss Industrielle Messtechnik GmbH, Oberkochen, Germany, Version: 2023.2.0.71).

### 2.1. Research Model

The research model, along with the features important for the study, was modeled in Autodesk Inventor Professional 2021 (Autodesk Inc., USA, CA, Version: 2021), (Figure 1). The pattern model was built based on a cuboid with overall dimensions of  $40 \times 40 \times 5$  mm. The dimensions of the pattern were optimized to enable sequential printing, i.e., the creation of models during one print, on one printing platform. This was an important factor in the study to limit the impact of external conditions on the study. The research methodology was developed based on the PN-EN ISO 10360 standard [26]. Various geometric parts were defined in the designed model, e.g., cylindrical and spherical surfaces and cuboids with graduated heights. The last geometric part is flat surfaces spaced angularly every  $15^\circ$ . These parts were used to analyze the angular accuracy of the designed part.

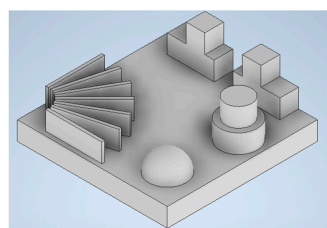


**Figure 1.** Designed template file.

## 2.2. Production of 3D Models, Materials, Process Monitoring

In order to test the repeatability of the manufacturing process, a series of 12 samples were developed. The polymers used in the study and their symbols are listed in Table 1. The most commonly used material is PLA (polylactide acid). The research defined, among others, the following parameters: sequential printing option, layer height of 0.2 mm, quality, and generic PLA option. Based on the STL template file, a machine code was created, the so-called gcode (Figure 2).

**Table 1.** Technical specification and physical properties of the Noctuo Ultra PLA filament (Noctuo, Gliwice, Poland).

|                                    |                     |
|------------------------------------|---------------------|
| Filament diameter Ø                | 1.75 mm             |
| Density ρ                          | 1.30 g/cm           |
| Print speed v                      | <120 mm/s           |
| Vicat softening point              | 60 °C               |
| Melting temperature                | Od 150 °C do 170 °C |
| Charpy notched impact strength KV  | 7 kJ/m <sup>2</sup> |
| Modulus of elasticity in bending   | 2650 MPa            |
| Elongation at break                | 19%                 |
| Bending stress σ                   | 64 MPa              |
| Modulus of elasticity in tension E | 2600 MPa            |
| Yield point                        | 47 MPa              |
| Product weight m                   | 250 g netto         |

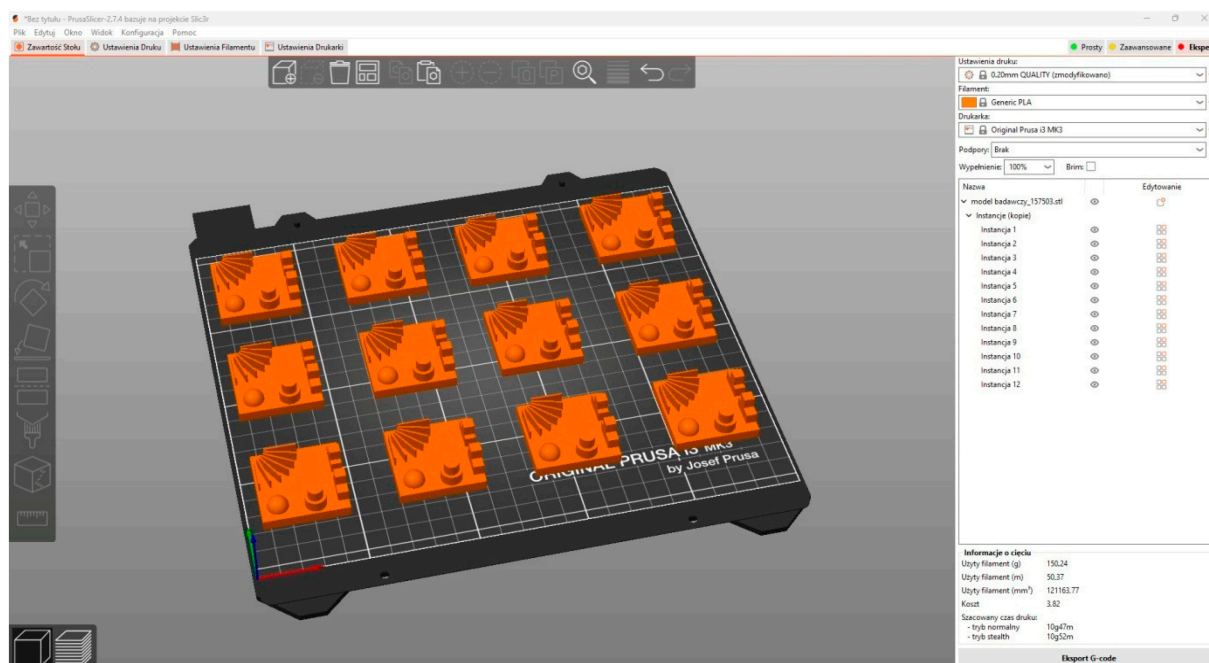


**Figure 2.** Template files in the PrusaSlicer Software (Prusa Research a.s., Prague, Czechia, Version: 2.7.2).

The printer was equipped with a nozzle with a diameter of 0.4 mm, the printing speed of the first layer was 20 mm/s, the printing speed was 60 mm/s, the head temperature was 215 °C, the layer height was 0.2 mm, the thickness of the lower and upper layers (all layers have the same thickness, but their speeds are different; the first one is 20 mm/s

and the last one is 40 mm/s). Additionally, a heated table with a temperature setting of 60 °C was used. A 100% infill was used during printing. Cooling was turned on from the second layer to 100%. The research defined, among others, the following parameters: sequential printing option, layer height (0.2 mm), QUALITY" and dedicated option for PLA in PrusaSlicer, generic PLA". Sequential printing, which means that the printer creates each model separately and not layer by layer, all models at once. The next step was to prepare the device and the material. The station is equipped with an electronic thermometer for temperature measurement and a TROTEC TTK 166 ECO moisture absorber. Before starting the actual printing process, the device automatically calibrated the table leveling to properly compensate for curvatures. The purpose of calibrating the first layer is to set the appropriate distance between the nozzle tip and the worktable surface, i.e., one that ensures good adhesion of the filament path and slightly flattens its cross-section. This is about compensating for any unevenness of the table in the Z direction. The Prusa i3 mk3 printer has a built-in "PINDA" sensor that creates a current map of the table with each printout—in our case, it was 16 points. The position in the X and Y directions (zeroing the axis) is performed by reaching the limit switches on each axis and obtaining the zero position. Original Prusa FFF printers have a sensor that detects the distance from the printing surface. During calibration, and before each print, the sensor measures the distance from the plate at a specific number of points arranged on the table surface in the form of a grid (it does not matter whether the plate is textured or smooth). These points are interpolated and used to create a virtual table mesh. If the bed has slight unevenness, the sensor will continue to accurately follow the surface consistently with the measured mesh while printing. To avoid air movement resulting from the movement of people, which could cause different cooling processes of individual layers and could also affect the shrinkage of the material, the room was closed during the entire printing process. All readings and progress of model creation were monitored using a camera that displayed the image on a mobile device. During the process, the ambient temperature and humidity were read every hour. The temperature was 19.4 °C–19.8 °C and the humidity was 42%.

### 2.3. Measurements Using the ATOS ScanBox Series 4 Scanner

The measurement process was performed on the automated and robotic ATOS ScanBox Series 4 device (Figure 3). The adopted measurement strategy aimed to increase the repeatability of the measurement process.



**Figure 3.** ATOS ScanBox Series 4 measurement station.

#### 2.4. Accuracy Testing Methodology Using ZEISS Inspect Optical 3D

The ZEISS Inspect Optical 3D program was used to test the precision of the patterns produced. Three-dimensional maps of the surface deviations of the actual template in relation to the designed model were made. Two files in STL format were used to create the maps: a model design exported from CAD software (Autodesk Inc., USA, CA, Version: 2021) and three-dimensional meshes reflecting the actual geometry of individual patterns. These meshes were obtained by mapping the models using a 3D optical scanner. The maps were created on the surface of real models, because of which the deviation values are also supported by the illustration of structure inaccuracies. To facilitate comparison of the accuracy of the generated model features, a uniform deviation scale was used for all maps. The numbering of the models corresponds to the location on the printer's working platform, which allowed for verification of whether dimensional deviations depend on the arrangement, i.e., on the method of dissipating heat to the environment. Figure 4 shows the arrangement of models on the platform.

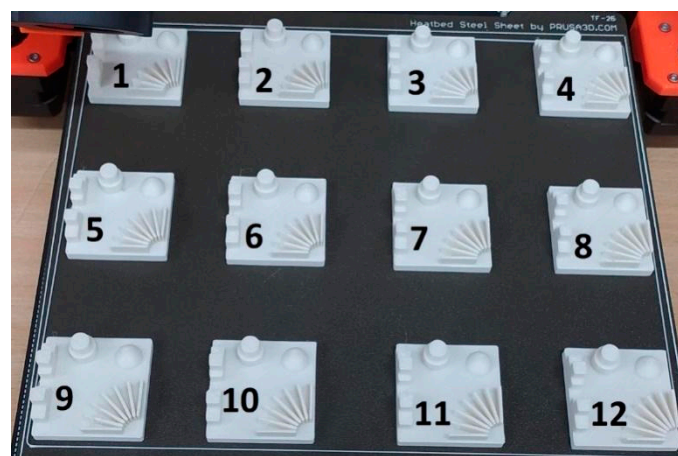


**Figure 4.** Arrangement of PLA samples on the platform.

### 3. Results

Figure 5 shows the dimensional and shape accuracy analyses of patterns made of PLA material. After the initial analysis, most research models had equally located areas with similar deviations from the nominal dimensions. The research cube was no exception. The base, which is in the central place, has a dimension corresponding to the nominal value of 12 or is smaller than this value, unlike other models, where in this area the value is higher than the nominal dimension.

The general inspection procedure in GOM software (Carl Zeiss Industrielle Messtechnik GmbH, Oberkochen, Germany, Version: 2023.2.0.71). begins with the import and basing of CAD and live data.

CAD data contains information about all possible nominal geometric elements. Individual elements must be defined. The live data contains information about all extracted geometric elements, and individual elements must be created.

Once a nominal item and an actual item have been created, they can be compared using one or more checks. An inspection creates an inspection element as its result. Tolerances can be applied during the control definition process. The tolerance information is used to interpret the inspection result.

In a standard workflow, inspected items are constructed on CAD data. Current equivalents are not created manually but are generated from nominal elements by applying measurement rules. This procedure combines live elements with their nominal original, enabling parametric inspection.

The inspection results in inspection items that are distinct from the nominal and actual items on which they are based.

Geometric and dimensional analyses that can be performed include:

- Comparing surface deviations
- Comparing dimensional deviations
- Geometric Dimensioning and Tolerancing (GD&T)

Surface comparison compares each CAD point to the mesh or vice versa.

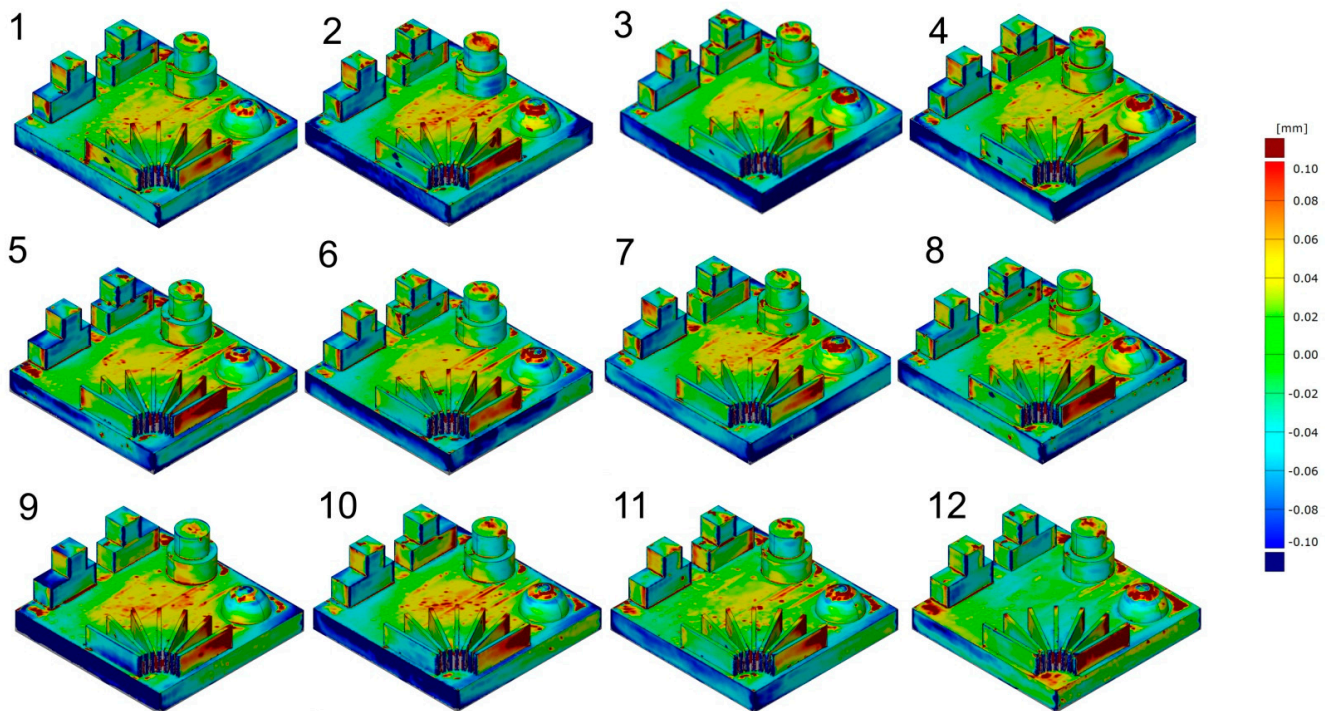


**Figure 5.** Analysis of the deviation values of patterns made of PLA material.

The results are displayed in the form of a color map of deviations. Green areas indicate no deviations. Red areas indicate positive deviations. Blue areas indicate negative deviations. The color is applied to the CAD or mesh copy, depending on the option selected.

Figure 6 shows the area selected for analysis of linear dimension deviations. The results obtained for these dimensions are shown in Figure 7.

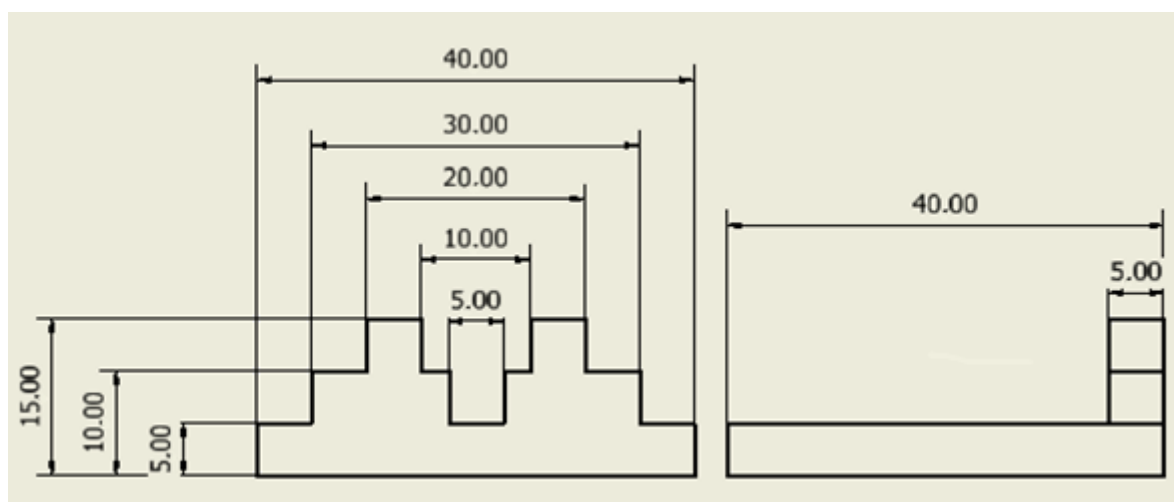


**Figure 6.** Nominal dimensions of the template for analyzing deviations of linear dimensions.

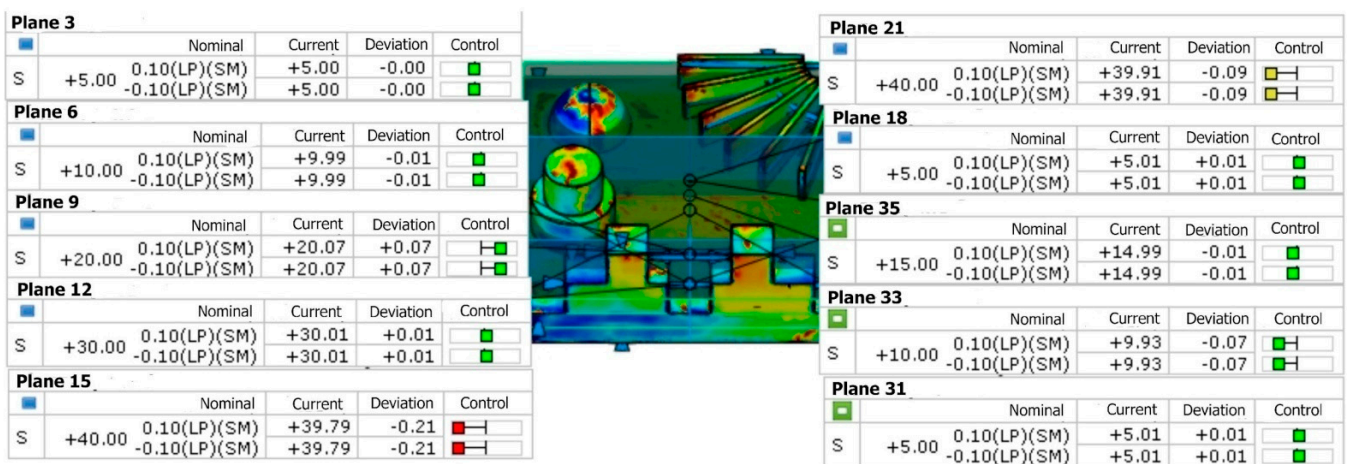


Figure 7. Analysis of deviations in linear dimensions for pattern no. 1.

The dimensions marked with the name plane from 3 to 15 correspond to the dimensions in the direction of the x-axis, planes 18 and 21 correspond to the dimensions in the direction of the y-axis, while planes numbered 31–35 correspond to the dimensions in the direction of the z-axis. This analysis shows that there are slight roundings at the corners in the xy plane, even though the design assumes sharp corners (Figure 8).

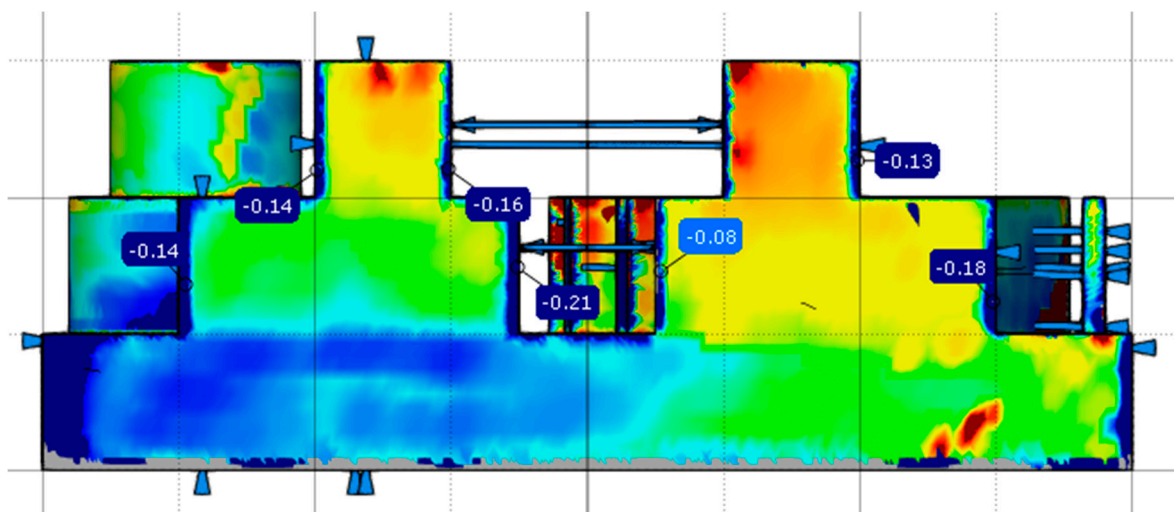


Figure 8. Detailed analysis of the deviations at the corners of the model.

These deviations are caused by the manufacturing method used. In this method, when a corner is cornered, one of the axes slows down and the other accelerates, making a small rounding. Appropriate calibration of the device allows you to minimize this problem, but it is not possible to eliminate it completely. For this reason, each subsequent scan of the part will have a rounding at the same place and of a similar size. The remaining dimension deviations from the nominal part were analyzed for each of the patterns. It was observed that the dimensions in the direction of the z-axis have values closest to the nominal values for each of the 12 formers. This was caused by the difference in the way the movement was transferred from the engine to each axis. The z-axis is driven by a stepper motor via a trapezoidal screw. The range of motion in this axis is small, one layer in the tested model is 0.2 mm high, which results in low speeds and low acceleration values for this axis. The x and y axes are also driven by a stepper motor, but toothed belts are used to transmit the drive. Such straps must be sufficiently tensioned to transmit movement properly. Looseness in the belts could cause deviations from the nominal values and also

cause the device to vibrate, causing deterioration of the printer's properties. The highest dimensional deviation values occurred on the external dimensions of the cube. These values reach up to 0.25 mm of deviation from the assumed value. This may be due to the fact that the external dimensions were more exposed to the influence of external factors, which caused these edges to cool faster and in turn could cause material shrinkage, which despite the low value for PLA material still occurs. After repeatability analysis, Gaussian plots (See Appendix A) were made for each dimension, which determines the frequency of x-values among the results. In the central place at the extreme of the graph, there is the average value of the measurement results. The place with the nominal value is marked with a vertical blue line (See Appendix A). The first dimension analyzed was the internal linear dimension defined in the x-axis direction with a nominal value of 5 mm. The distribution of measurement values was presented on a graph by reducing the area of the graph on the y-axis to the values appearing in the data (Figure 9). It can be observed that the difference between the extreme measurement values of 4.95 and 5.01 mm is 0.06 mm. However, the average value of the measurement results is 4.99 mm and the median of the measurements is also 4.99 mm. You will also notice that the graph changes depending on the location of the sample on the build platform. Samples 2, 6, and 10, which are second from the left in each row, have a nominal size or larger. The first templates on the left sides, 1 and 9, also have a nominal size or larger, while the middle template has a smaller size than the nominal one. Apart from the last 12th sample, all models on the right have dimensions smaller than the nominal ones.

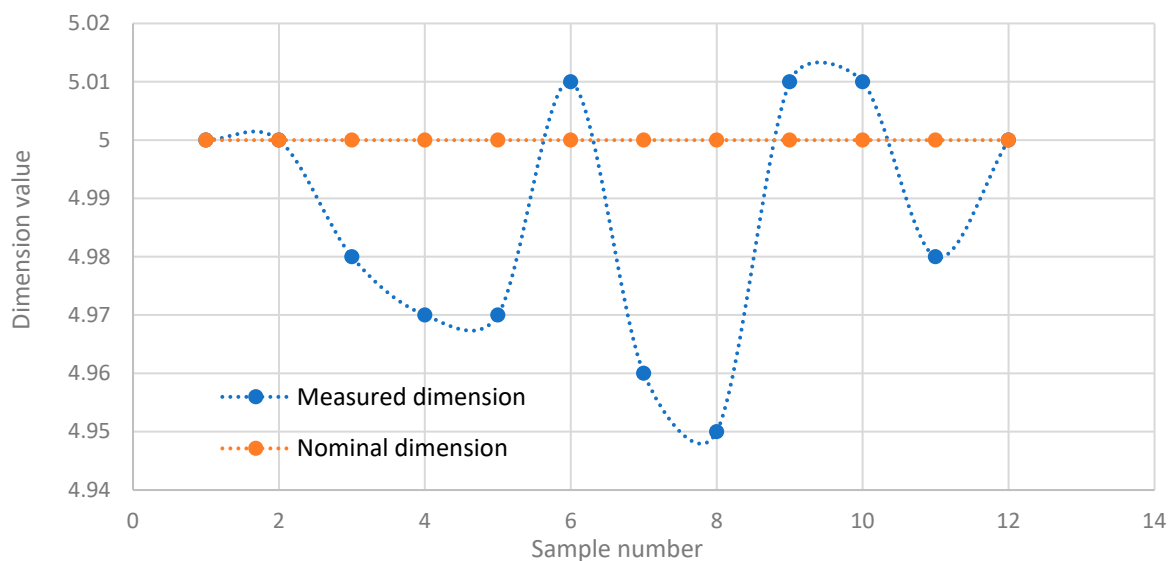


**Figure 9.** Comparison of the results with the nominal value.

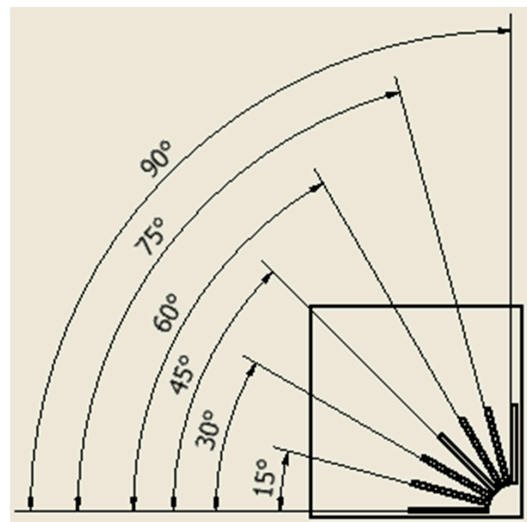
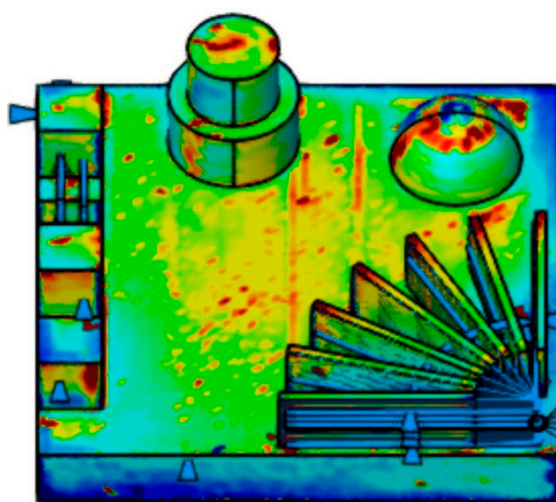
Subsequent analyses included detailed examinations of cylindricity deviations, shape deviations, and positional deviations for the 12 developed templates. Figures 10–13 present selected analyses. The angular dimensions of the templates produced were analyzed based on the nominal 3D CAD model (Figure 10). Dimensions were extracted from the scanned data using ZEISS Inspect software (Carl Zeiss Industrielle Messtechnik GmbH, Oberkochen, Germany, Version: 2023.2.0.71). The dimensions were obtained using the median function, which determines the distance between the surfaces by calculating the median.

Table 2 provides a detailed analysis of the angular dimensions.

From the data presented, it can be inferred that most of the measured angular dimension values are less than the nominal value. The exception is the 60° dimension, where most measurements exceed the nominal value. In particular, the last of these dimensions shows a significant difference of 0.70°, which stands out compared to previous results, where the differences ranged from 0.1° to 0.2°.

**Table 2.** Analysis of angular dimensions of test patterns.

| Test Pattern No. | 15 (°) | 30 (°) | 45 (°) | 60 (°) | 75 (°) | 90 (°) |
|------------------|--------|--------|--------|--------|--------|--------|
| 1                | 14.83  | 29.75  | 44.87  | 59.96  | 74.93  | 89.77  |
| 2                | 14.85  | 29.87  | 44.95  | 60.02  | 75.04  | 90     |
| 3                | 14.62  | 29.77  | 44.91  | 60.04  | 74.98  | 89.84  |
| 4                | 14.69  | 29.72  | 44.87  | 59.94  | 75.03  | 89.74  |
| 5                | 15     | 30.07  | 45.12  | 60.05  | 74.96  | 89.9   |
| 6                | 14.89  | 29.91  | 44.95  | 59.95  | 74.99  | 89.82  |
| 7                | 14.92  | 29.89  | 45.05  | 60.15  | 75.18  | 89.94  |
| 8                | 14.65  | 29.63  | 44.90  | 59.86  | 74.82  | 89.74  |
| 9                | 14.83  | 29.92  | 45.01  | 60.01  | 74.96  | 89.78  |
| 10               | 14.87  | 29.93  | 44.93  | 60.06  | 75.13  | 89.96  |
| 11               | 14.87  | 29.91  | 45.05  | 60.14  | 75.16  | 89.8   |
| 12               | 14.82  | 29.81  | 44.98  | 60.70  | 74.93  | 89.8   |

**Figure 10.** Nominal dimensions of the 3D CAD model of the analyzed feature.

| Wedge 1  |               |         |           |                                     |
|----------|---------------|---------|-----------|-------------------------------------|
|          | Nominal       | Current | Deviation | Control                             |
| ∠ +15.00 | 1.00(LC)(SM)  | +14.83  | -0.17     | <input checked="" type="checkbox"/> |
|          | -1.00(LC)(SM) | +14.83  | -0.17     | <input checked="" type="checkbox"/> |
| Wedge 2  |               |         |           |                                     |
|          | Nominal       | Current | Deviation | Control                             |
| ∠ +30.00 | 1.00(LC)(SM)  | +29.75  | -0.25     | <input checked="" type="checkbox"/> |
|          | -1.00(LC)(SM) | +29.75  | -0.25     | <input checked="" type="checkbox"/> |
| Wedge 3  |               |         |           |                                     |
|          | Nominal       | Current | Deviation | Control                             |
| ∠ +45.00 | 1.00(LC)(SM)  | +44.87  | -0.13     | <input checked="" type="checkbox"/> |
|          | -1.00(LC)(SM) | +44.87  | -0.13     | <input checked="" type="checkbox"/> |
| Wedge 4  |               |         |           |                                     |
|          | Nominal       | Current | Deviation | Control                             |
| ∠ +60.00 | 1.00(LC)(SM)  | +59.96  | -0.04     | <input checked="" type="checkbox"/> |
|          | -1.00(LC)(SM) | +59.96  | -0.04     | <input checked="" type="checkbox"/> |
| Wedge 5  |               |         |           |                                     |
|          | Nominal       | Current | Deviation | Control                             |
| ∠ +75.00 | 1.00(LC)(SM)  | +74.93  | -0.07     | <input checked="" type="checkbox"/> |
|          | -1.00(LC)(SM) | +74.93  | -0.07     | <input checked="" type="checkbox"/> |
| Wedge 6  |               |         |           |                                     |
|          | Nominal       | Current | Deviation | Control                             |
| ∠ +90.00 | 1.00(LC)(SM)  | +89.77  | -0.23     | <input checked="" type="checkbox"/> |
|          | -1.00(LC)(SM) | +89.77  | -0.23     | <input checked="" type="checkbox"/> |

**Figure 11.** Obtained measurement data.

In the next phase of the investigation, the selected geometric tolerances of the patterns were analyzed (Figure 12).

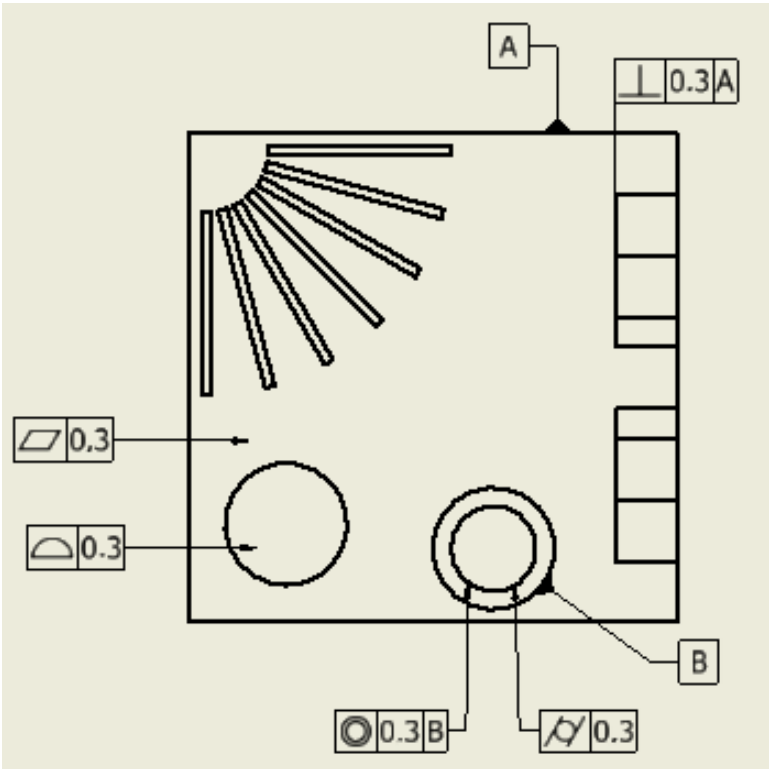


Figure 12. Analyzed geometric tolerances.

Figure 13 shows three-dimensional deviation maps obtained from the measurements.

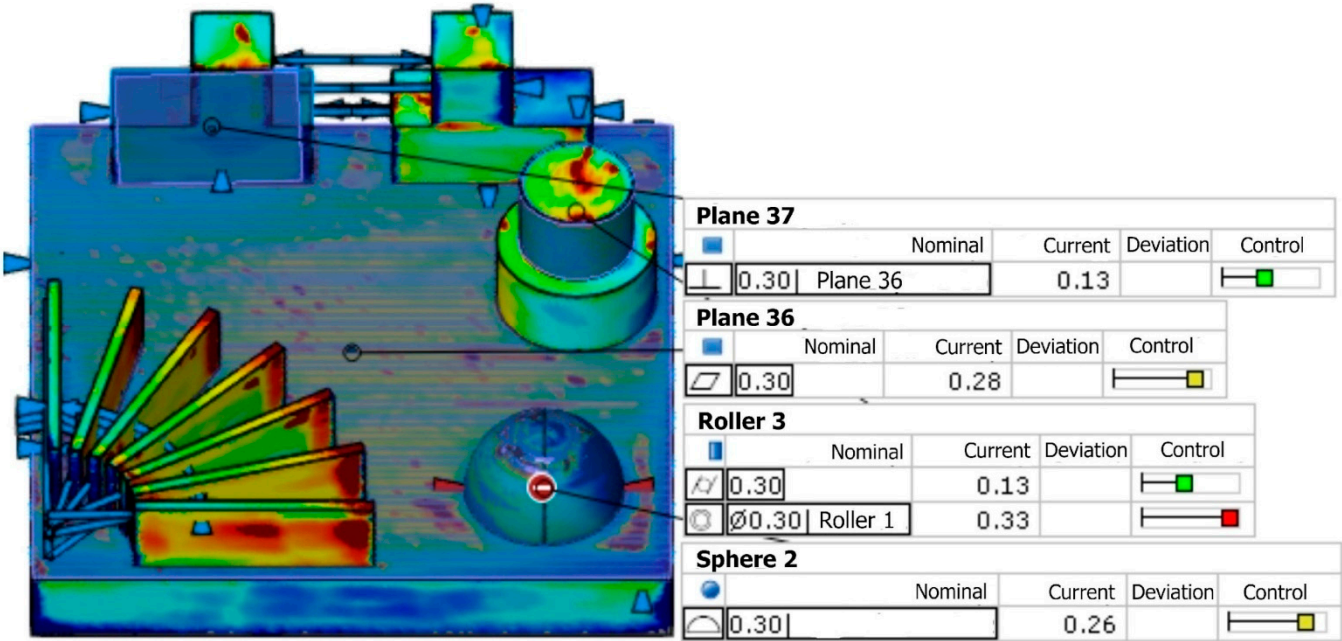


Figure 13. Analysis of shape and positional tolerances.

Table 3 presents selected analyses of the deviations of geometric parts in the templates.

**Table 3.** Analysis of the deviations of selected geometric parts.

| Template | Surface Profile Deviation (mm) | Coaxiality Deviation (mm) | Cylindricity Deviation (mm) | Flatness Deviation (mm) | Perpendicularity Deviation (mm) |
|----------|--------------------------------|---------------------------|-----------------------------|-------------------------|---------------------------------|
| 1        | 0.26                           | 0.33                      | 0.13                        | 0.28                    | 0.13                            |
| 2        | 0.29                           | 0.29                      | 0.14                        | 0.26                    | 0.13                            |
| 3        | 0.34                           | 0.54                      | 0.14                        | 0.25                    | 0.16                            |
| 4        | 0.3                            | 0.41                      | 0.15                        | 0.37                    | 0.12                            |
| 5        | 0.27                           | 0.53                      | 0.17                        | 0.31                    | 0.13                            |
| 6        | 0.31                           | 0.17                      | 0.17                        | 0.22                    | 0.16                            |
| 7        | 0.31                           | 0.7                       | 0.12                        | 0.25                    | 0.11                            |
| 8        | 0.24                           | 0.37                      | 0.15                        | 0.31                    | 0.14                            |
| 9        | 0.23                           | 0.35                      | 0.18                        | 0.29                    | 0.11                            |
| 10       | 0.27                           | 0.44                      | 0.16                        | 0.28                    | 0.17                            |
| 11       | 0.31                           | 0.5                       | 0.15                        | 0.3                     | 0.17                            |
| 12       | 0.23                           | 0.11                      | 0.14                        | 0.33                    | 0.15                            |

Analyzing the data in Table 3, it can be seen that the smallest deviation values were found in the cylindricity measurements, while the largest were found in the coaxial measurements.

#### 4. Summary

The design of plastic parts and their optimization is still a very complex engineering issue that requires detailed knowledge of several scientific fields. Layered extrusion of thermoplastic polymers is based on devices using a frame structure of the executive system. The accuracy of products made of polymer materials depends largely on the design of the 3D printer itself, the drive and actuation systems used, and the stiffness of the device frame. Cartesian 3D printers are the most popular FFF 3D printers available on the market. Based on a Cartesian mathematical coordinate system, this technology uses three axes, X, Y, and Z, to determine the correct position and direction of the print head. The system in which the stage moves in the Y axis, the head is in the X axis, and is lifted in the Z axis corresponds to the 3D printer design used in the research.

The research showed that the direction of the axis along which the model was created influenced the shape and dimensional accuracy, as well as the repeatability of the produced geometric parts. The dimensional accuracy was highest in the direction of the z-axis due to the drive transmission, in this case using a trapezoidal screw. For the other two directions in the x and y axes, the motion was transferred using toothed belts. The level of belt tension has a significant impact on the accuracy of the model, especially when both axes must be used simultaneously to produce a feature, causing the angular dimensions or other features to significantly deviate from the nominal values. Therefore, a new way of transmitting power for the remaining two directions should be considered. A method that will ensure a constant amount of travel and that is sufficiently stiff. Additionally, using a trapezoidal screw for the other two axes may reduce the speeds achieved by the device but would increase its accuracy. The printing process depended on the degree of wear of consumable parts such as the nozzle or linear guides, which depended on the operating time of the printer, which for the tested one was 56 days of printing and 4300 m of extruded filament. The research shows that the accuracies of the models made are influenced by their arrangement on the build platform in sequential prints. The dimensions of each axis were within the assumed tolerance of 0.1 mm. The only dimensions that did not meet this assumption were the external dimensions of the patterns. This could be caused by a

different method of heat dissipation, which, despite the use of PLA material characterized by low shrinkage, resulted in a change in external dimensions. The monitored temperature and humidity in close proximity to the device did not detect any temperature change, so to monitor the phenomenon, the manufacturing process must be performed again while using a thermal imaging camera to monitor the temperature on the work platform. Measurement of the angular dimensions of all values showed that each was within the specified tolerance range of  $0.30^\circ$ .

The accuracy of the research models was influenced by many factors that occurred during the printing itself and during measurement, as well as during the analysis of the dimensional accuracy in the ZEISS Inspect program. During the scanning process, the factor that disturbed the actual value of dimensions was the layer necessary to match the models. When conducting the scans, median values were used, which also introduces some calculation errors, but this solution was optimal in the developed research process.

Analyzing the prepared dimension charts and Gaussian curves (See Appendix A), it can be concluded that the dimensional accuracy and repeatability of all patterns were 0.1 mm. The accuracy of the angular dimensions was within  $0.5^\circ$ . For geometric tolerances, the concentricity value deviated significantly from the set value, while the smallest deviations concerned cylindricity and flatness tolerances. In the case of geometric concentricity tolerance, numerous deviations of the results from the target value were observed. The cylindricity and perpendicularity tolerances had the smallest deviations, and the results did not differ significantly.

## 5. Conclusions

The research suggests the potential to expand its scope by developing a CAD–RP feedback loop aimed at reducing the deformation in the geometry produced. In areas where replication inaccuracies exceed the achievable machine precision, appropriate geometric adjustments can be introduced in the CAD software (Autodesk Inc., USA, CA, Version: 2021) environment. This approach may enhance the accuracy of the obtained models; however, it requires appropriate trials and studies to determine suitable geometry correction algorithms.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

## Appendix A

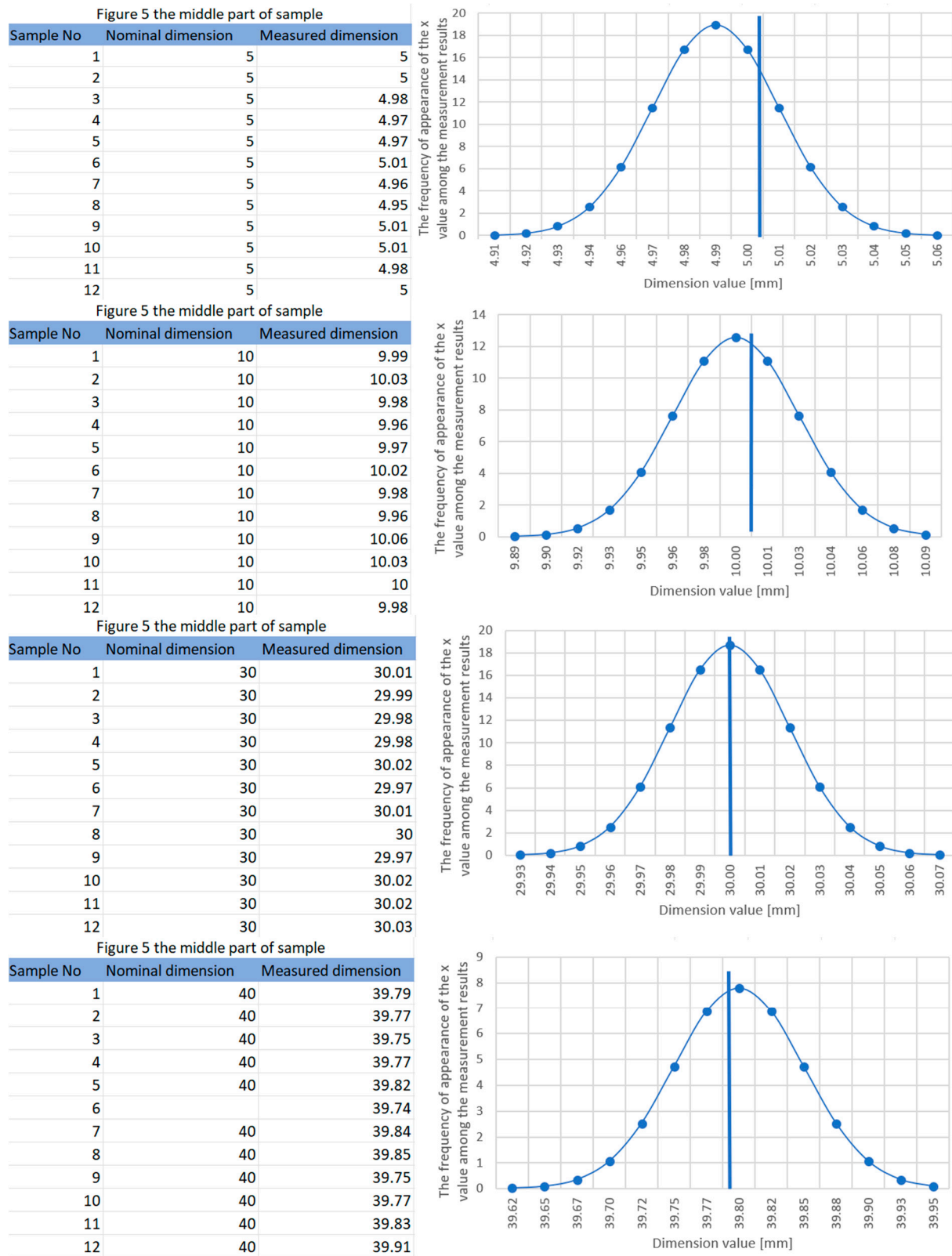


Figure A1. Cont.

Figure 5 the right part of sample

| Sample No | Nominal dimension | Measured dimension |
|-----------|-------------------|--------------------|
| 1         | 5                 | 5.01               |
| 2         | 5                 | 4.96               |
| 3         | 5                 | 4.98               |
| 4         | 5                 | 4.98               |
| 5         | 5                 | 5.02               |
| 6         | 5                 | 4.96               |
| 7         | 5                 | 4.96               |
| 8         | 5                 | 5.02               |
| 9         | 5                 | 5.05               |
| 10        | 5                 | 5.04               |
| 11        | 5                 | 5.01               |
| 12        | 5                 | 5                  |

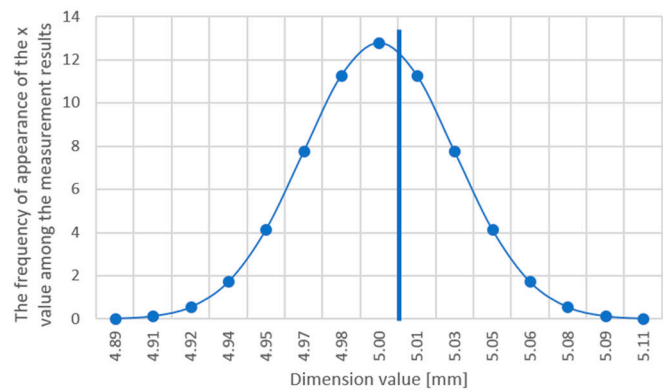


Figure 5 the right part of sample

| Sample No | Nominal dimension | Measured dimension |
|-----------|-------------------|--------------------|
| 1         | 40                | 39.91              |
| 2         | 40                | 39.89              |
| 3         | 40                | 39.84              |
| 4         | 40                | 39.86              |
| 5         | 40                | 39.97              |
| 6         | 40                | 39.87              |
| 7         | 40                | 39.86              |
| 8         | 40                | 39.95              |
| 9         | 40                | 39.99              |
| 10        | 40                | 39.96              |
| 11        | 40                | 39.95              |
| 12        | 40                | 40                 |

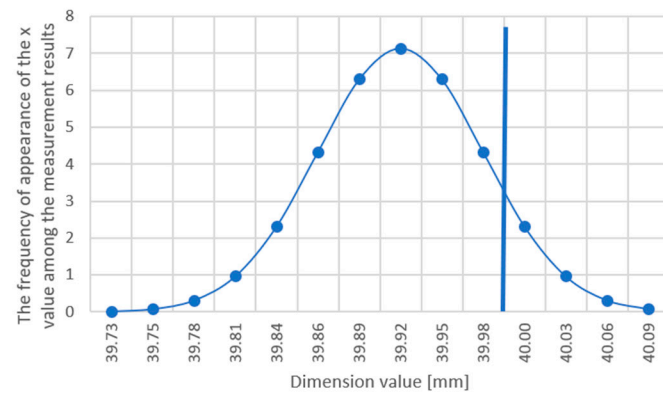


Figure 5 the left part of sample

| Sample No | Nominal dimension | Measured dimension |
|-----------|-------------------|--------------------|
| 1         | 5                 | 5.01               |
| 2         | 5                 | 5.01               |
| 3         | 5                 | 5.01               |
| 4         | 5                 | 5.01               |
| 5         | 5                 | 5.01               |
| 6         | 5                 | 5.01               |
| 7         | 5                 | 5.01               |
| 8         | 5                 | 5.01               |
| 9         | 5                 | 5.01               |
| 10        | 5                 | 5.01               |
| 11        | 5                 | 5                  |
| 12        | 5                 | 4.99               |

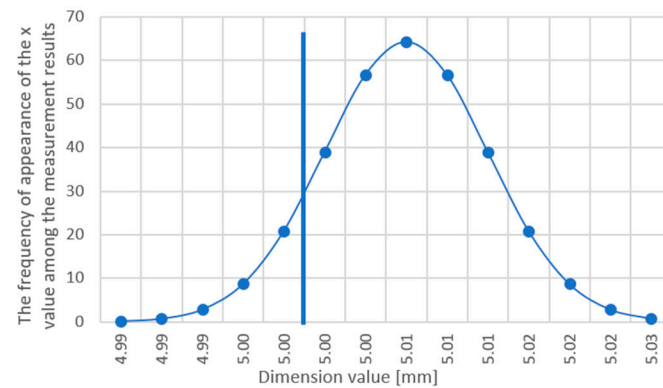


Figure 5 the left part of sample

| Sample No | Nominal dimension | Measured dimension |
|-----------|-------------------|--------------------|
| 1         | 15                | 14.99              |
| 2         | 15                | 15.02              |
| 3         | 15                | 15.02              |
| 4         | 15                | 15                 |
| 5         | 15                | 14.97              |
| 6         | 15                | 15                 |
| 7         | 15                | 14.99              |
| 8         | 15                | 15                 |
| 9         | 15                | 14.97              |
| 10        | 15                | 14.99              |
| 11        | 15                | 14.99              |
| 12        | 15                | 14.99              |

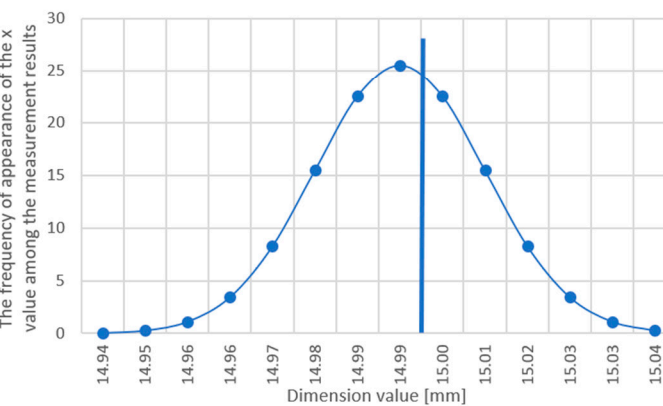


Figure A1. Cont.

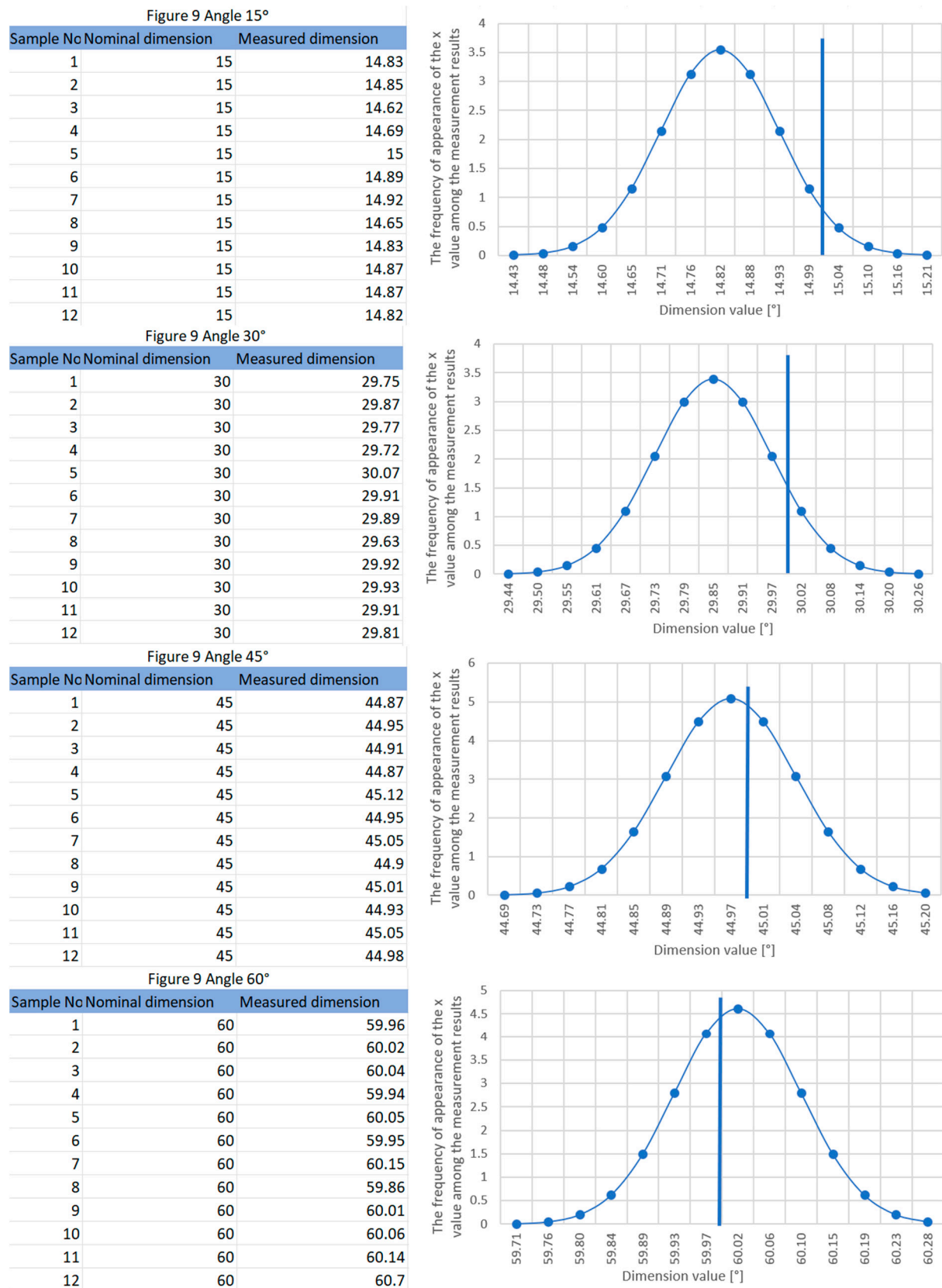


Figure A1. Cont.

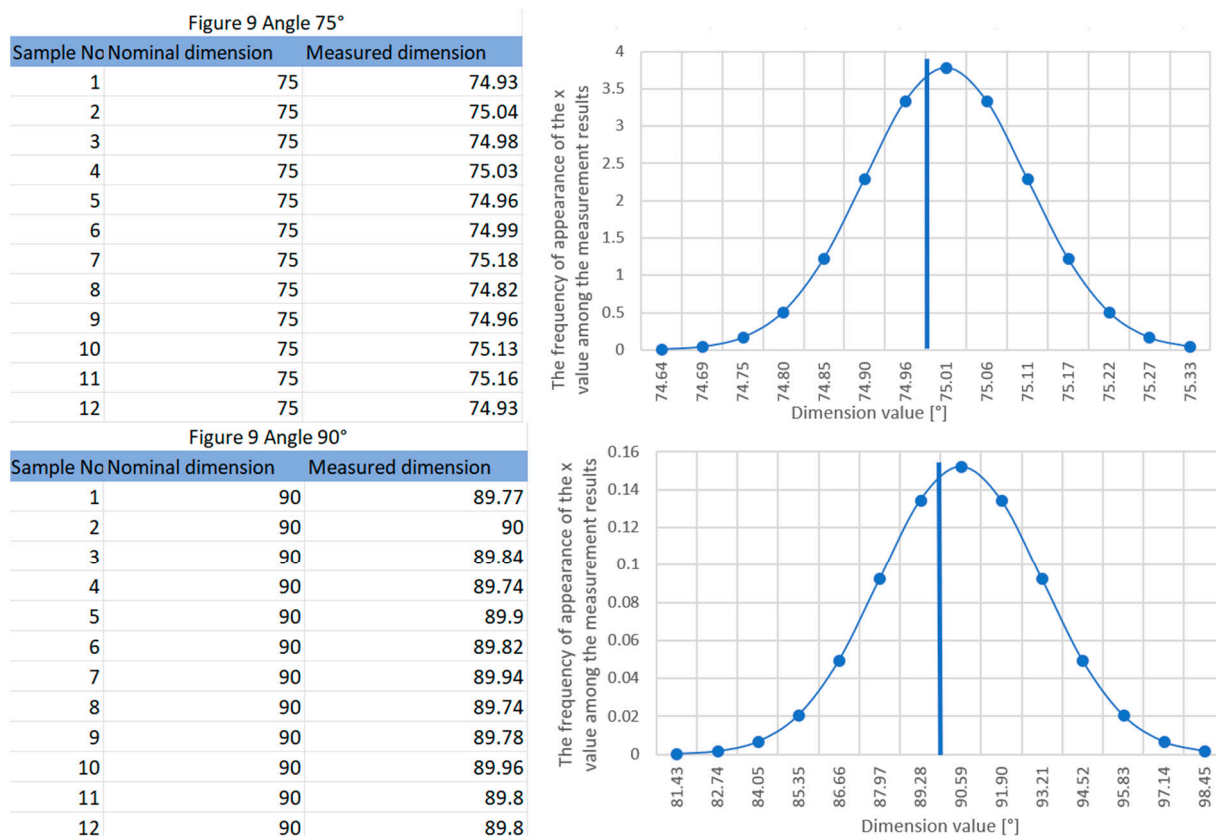


**Figure A1.** Gaussian plots with data from test parts shown in Figures 5 and 9. With a nominal value pointed as blue line.

## References

- Elakkad, A.S.; Shams, A. University 3D Technology in the Automotive Industry. *Int. J. Eng. Res.* **2019**, *8*, 248–251. [\[CrossRef\]](#)
- Budzik, G.; Woźniak, J.; Paszkiewicz, A.; Przesłowski, L.; Dziubek, T.; Dębski, M. Methodology for the Quality Control Process of Additive Manufacturing Products Made of Polymer Materials. *Materials* **2021**, *14*, 2202. [\[CrossRef\]](#) [\[PubMed\]](#)
- Turner, B.N.; Gold, S.A. A review of melt extrusion additive manufacturing processes: II. Materials, dimensional accuracy, and surface roughness. *Rapid Prototyp. J.* **2015**, *21*, 250–261. [\[CrossRef\]](#)
- Siemiński, P.; Budzik, G. *Additive Techniques. 3D Printing. 3D Printers*; Oficyna Wydawnicza PW: Warszawa, Poland, 2015; pp. 18–23.
- Giannatsisa, J.; Vassilakosa, A.; Dedoussisa, V. A Heterogeneous Infill Technique for Fused Deposition Modeling. *Procedia Manuf.* **2020**, *51*, 642–648. [\[CrossRef\]](#)
- Cader, M.; Zaborniak, M.; Stączek, M. Analiza dokładności odwzorowania modeli CAD części polimerowych wytwarzanych z zastosowaniem reprezentatywnych technik addytywnych w procesie produkcji w konwencji Przemysł 4.0. *Polimers* **2019**, *LXIV*, 436–441. [\[CrossRef\]](#)
- Budzik, G.; Zaborniak, M.; Rocznik, J. Analysis of the influence of selected Slicer parameters on the mapping accuracy in the FFF method. *Polimery* **2022**, *67*, 483. [\[CrossRef\]](#)
- Armiliotta, A.; Bianchi, S.; Cavallaro, M.; Minnella, S. Edge quality in fused deposition modeling: II. Experimental verification. *Rapid Prototyp. J.* **2017**, *23*, 686–695. [\[CrossRef\]](#)
- Chockalingam, K.; Karthic, M.; Jawahar, N. Development of thermal and structural deformation model to predict the part build dimensional error in fused deposition modeling. *Int. J. Adv. Des. Manuf. Technol.* **2018**, *11*, 27–37.
- Allison, J.; Sharpe, C.; Seepersad, C.C. A test part for evaluating the accuracy and resolution of a polymer powder bed fusion process. *J. Mech. Des.* **2017**, *139*, 100902. [\[CrossRef\]](#)
- Liu, J.; Yu, H. Concurrent deposition path planning and structural topology optimization for additive manufacturing. *Rapid Prototyp. J.* **2017**, *23*, 930–942. [\[CrossRef\]](#)
- Costa, A.E.; Ferreira da Silva, A.; Sousa Carneiro, O. A study on extruded filament bonding in fused filament fabrication. *Rapid Prototyp. J.* **2018**, *25*, 555–565. [\[CrossRef\]](#)
- Nath, P.; Olson, J.D.; Mahadevan, S.; Lee, Y.T.T. Optimization of Fused Filament Fabrication Process Parameters under Uncertainty to Maximize Part Geometry Accuracy. *Addit. Manuf.* **2020**, *35*, 101331. [\[CrossRef\]](#) [\[PubMed\]](#)

14. Minetola, P.; Calignano, F.; Galati, M. Comparing Geometric Tolerance Capabilities of Additive Manufacturing Systems for Polymers. *Addit. Manuf.* **2020**, *32*, 101103. [[CrossRef](#)]
15. Moroni, G.; Petrò, S.; Polini, W. Geometrical Product Specification and Verification in Additive Manufacturing. *CIRP Ann.-Manuf. Technol.* **2017**, *66*, 157–160. [[CrossRef](#)]
16. Radhakrishnan, L.; Rajendran, P.; Biswal, R.; Goswami, A.G.; Ganesan, A. Machine Learning Approach to Predict Feature Dimensions for Fused Deposition Modelling. *Trans. Indian Inst. Met.* **2023**, *76*, 315–321. [[CrossRef](#)]
17. Mahmood, S.; Qureshi, A.J.; Talamona, D. Taguchi Based Process Optimization for Dimension and Tolerance Control for Fused Deposition Modelling. *Addit. Manuf.* **2018**, *21*, 183–190. [[CrossRef](#)]
18. PN/EN ISO/ASTM 52900:2017-06; Additive Manufacturing—General Principles—Terminology. ISO: Geneva, Switzerland; ASTM International: West Conshohocken, PA, USA, 2017. Available online: <https://www.pkn.pl/> (accessed on 15 May 2024).
19. PN/EN ISO 17296-2:2016-10; Additive Manufacturing—General Principles—Part 2: Overview of Process Categories and Feedstock. ISO: Geneva, Switzerland; ASTM International: West Conshohocken, PA, USA, 2016. Available online: <https://www.pkn.pl/> (accessed on 15 May 2024).
20. PN/EN ISO 17296-3:2016-10; Additive Manufacturing—General Principles—Part 3: Principal Characteristics and Appropriate Research Methods. ISO: Geneva, Switzerland; ASTM International: West Conshohocken, PA, USA, 2016. Available online: <https://www.pkn.pl/> (accessed on 15 May 2024).
21. PN/EN ISO 17296-4:2016-10; Additive Manufacturing—General Principles—Part 4: Overview of Data Processing. ISO: Geneva, Switzerland; ASTM International: West Conshohocken, PA, USA, 2016. Available online: <https://standards.iteh.ai/catalog/standards/cen/5b10b8ed-c472-49d7-a4fd-335eb8de2e11/en-iso-17296-4-2016> (accessed on 15 May 2024).
22. ISO/ASTM 52902:2019; Additive Manufacturing—Test Artifacts—Geometric Capability Assessment of Additive Manufacturing Systems. ISO: Geneva, Switzerland; ASTM International: West Conshohocken, PA, USA, 2019. Available online: <https://www.iso.org/> (accessed on 15 May 2024).
23. ISO/ASTM TR 52912:2020; Additive Manufacturing—Design—Functionally Graded Additive Manufacturing. ISO: Geneva, Switzerland; ASTM International: West Conshohocken, PA, USA, 2020. Available online: <https://www.iso.org/> (accessed on 15 May 2024).
24. ISO/ASTM 52915:2020; Specification for Additive Manufacturing (AMF). ISO: Geneva, Switzerland; ASTM International: West Conshohocken, PA, USA, 2020. Available online: <https://www.iso.org/> (accessed on 15 May 2024).
25. ISO 17295:2023; Additive Manufacturing—General Principles Part Positioning, Coordinates and Orientation. ISO: Geneva, Switzerland; ASTM International: West Conshohocken, PA, USA, 2023. Available online: <https://www.iso.org/> (accessed on 15 May 2024).
26. PN-EN ISO 10360-6:2003; Geometrical product specifications (GPS)—Acceptance and Reverification Tests for Coordinate Measuring Machines (CMM)—Part 6: Estimation of Errors in Computing Gaussian Associated Features. ISO: Geneva, Switzerland; ASTM International: West Conshohocken, PA, USA, 2023. Available online: <https://sklep.pkn.pl/pn-en-iso-10360-6-2003p.html> (accessed on 15 May 2024).

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