THE INFLUENCE OF REVERSE GEOMETRIC MODELING TO THE DIMENSIONS AND SHAPE OF THE 3D MODEL

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The aim of the study is to investigate the effect of point reduction on the dimensions of a part produced by two different additive technologies, Stereolithography (SLA) and Fused Deposition Modelling (FDM). Also, the effect of polygonization methods on the number of points and file size. For the purpose of the experiment, a part was fabricated which was made up of geometric elements, which served to investigate the influence of the reverse geometric modelling on parameter variation. Subsequently, the model was made into two samples by additive manufacturing FDM and SLA on Stratasys F370 (FDM) and Form 3 (SLA). From the fabricated samples, 3D data was collected on a Metrotom industrial CT 1500, cloud of points was obtained and polygonised in various ways in CAQ software GOM Inspect and CARE software VG Studio MAX. The evaluation as well as the process reverse modelling was performed in Autodesk Powershape software. The results show that different polygonization methods affect the number of polygonal mesh points and the volume of data. It was also found that the reduction of the points by which the polygonal network is formed leads to variations in the dimensions of the geometric features. Another important factor is the method of additive manufacturing of the component, where we have shown point reduction has a different effect for a component manufactured by SLA and a component manufactured by FDM.

KEYWORDS

3D digitalization, additive manufacturing, polygonization, reverse engineering, reverse geometric modelling

1 INTRODUCTION

Dimensional accuracy and surface quality of parts produced by additive manufacturing techniques is one of the main concerns of designers and users of these technologies. Reverse engineering is a type of engineering that uses an already created object. The goal is to create another object similar to the existing object. Reverse engineering can be applied in various fields such as engineering, healthcare, automotive, etc [PAULIC, 2014]. Within reverse engineering, the point reduction technique is popular, which allows us a higher speed in performing this process while reducing the need for storage space for the given stored projects. Since point reduction is directly related to modifying the collected data, in order to reduce the need for a certain % of collected points or to get rid of poor quality information, this technique can have a direct relation to the accuracy of reverse engineering. A part of reverse engineering is reverse geometric modelling which is characterized by various techniques in the creation of CAD models. It is based on the existence of a captured model in the form of a point cloud characterized by its topology, geometry and material density. When reconstructing it, it is important to take these properties into account which results in the use of several inverse modelling techniques.

The aim of the study is to investigate the effect of the technique on the dimensions of simple geometric features. For our study, a sample part was designed and two additive technologies FDM and SLA were used to fabricate the part, which was then scanned using an industrial CT machine whose output was a point cloud that can be polygonised in several ways. Using the acquired sample data, the effect of polygonal mesh reduction on the dimensions of the geometric features was subsequently investigated.

In the literature and technical articles, the investigation of additive manufacturing parameters on dimensional accuracy of products is commonly mentioned. An example of such research is just the study of Muhammad [Muhammad 2022], who investigated the effect of production parameters such as layer height, nozzle temperature, infill shape or printing speed on 3D printing accuracy and tried to find parameter values to optimize the production in terms of dimensional accuracy. Another study by Milde [Milde 2021] investigated the effect of part orientation during printing and its effect on surface roughness. Hidaka's research [Hidaka 2018] consisted in creating models of bridge piers assembled from point clouds. He introduced a geometric fitting method that can fit users to approximate point cloud templates. FDM and SLA additive manufacturing methods were also investigated by Nagaraju in his research, but his focus was more on the mechanical properties of the parts printed using these technologies [Nagaraju 2023]. The dimensional characteristics of ABS plastic, which was also used in our research, printed on an FDM 3D printer was addressed by Mansilla Mora in his research [Mansilla Mora 2019]. The reverse engineering technique in the form of surface charging on simple samples was also used in the study. He compared several parameters of additive manufacturing such as layer thickness, extrusion speed and production orientation. Piles [Piles 2019] used reverse engineering to remodel bone using FDM additive manufacturing, but where he focused on the procedure and methodology of CT data processing. In another study, Kovács [Kovács 2015] looked at improving the reverse engineering process. He dealt with algorithms that were based on the principle of constraint detection, which classify in a certain way the relevant surfaces to be retained to calculate the best-fit structures according to the associated constraints.

2 MATERIAL AND METODOLOGY

For the research, in a first step, a component was designed on which the influence of selected RGM features was investigated. The designed component consists of geometrical elements which are sphere, cones and cylinders. The process of creating this model was carried out in Autodesk Powershape 2022 Ultimate software. The result of CAD modelling can be seen in Fig.1.

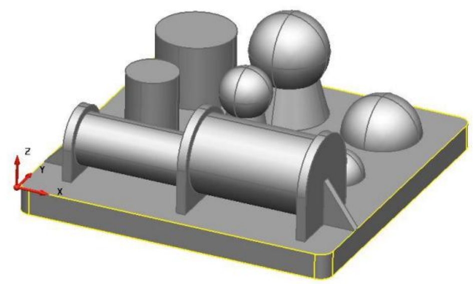
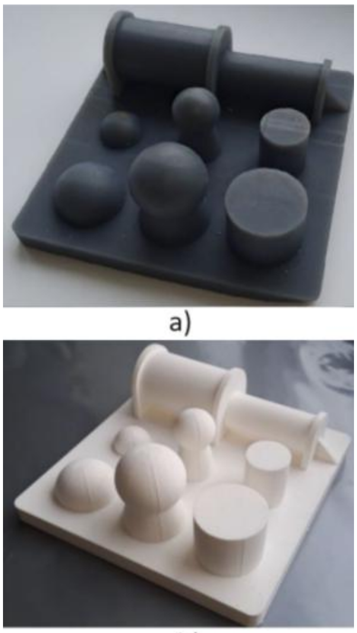


Figure 1 CAD model for research purposes

Additive manufacturing is a step towards the next generation and a revolution in the manufacturing industry. It is being used not only to produce prototypes but also to produce functional tools that can be found in applications such as electronics, sensors, robotics and medical devices [Abdulhameed 2019], [Bahnini 2018].

In the experiment, the fabrication of two designed samples was carried out by two different additive technologies. For the first sample, FDM production on the F370 from Stratasys, currently in their F123 production series, was chosen. The device offers versatility due to its access to a wide range of materials such as PC materials, elastomers and ABS. The chosen material is ABS-based under the commercial name ABS-M30 White. It is a suitable material for part shape inspection, functional prototyping and other 3D printing applications. Prior to production, the CAD model was converted to a neutral STL format and imported into GrabCAD Print as such. The latter checks the file for any errors, such as discontinuities in the mesh, which can be easily removed. The most important print parameters can be set> layer height, fill structure and support type. Other settings are automatically adjusted by the 3D printer after the model is loaded into the device.

Production of the next sample was carried out on Form 3 SLA equipment from Formlabs. Grey Pro photosensitive resin was chosen as the production material. Characterized by its high rigidity, the part maintains its exact dimensions over time. Moderate ductility, high precision and resistance to deformation over time make this resin a versatile material for a variety of engineering applications. After 3D printing, post-processing in the form of additional curing in a UV oven is advisable. The CAD model in STL format was imported into SW Preform in which the basic parameters were set. The layer height was selected as Adaptive - the program automatically calculates layer height based on the geometry of the model. To make the experiment interesting, the model was inserted into the workspace at a 45° angle, based on this fact the program automatically constructed a support structure extending into the geometric elements. In Fig.2 can be seen the 2 samples produced for the experiment.



a)

b)

Figure 2 Components manufactured for the experiment (a) SLA technology, (b) FDM technology

3 OBTAINING A 3D MODEL OD A SAMPLE PART

Digital imaging of the fabricated parts for reverse engineering purposes was performed using a Metrotom 1500 computed tomography scanner. It is a non-contact scanning device used in the analysis of parts in terms of their size or material density. The scanning parameters can be seen in Table 1.

Parameter	Value
Current	650 μA
Voltage	160 kV
Number of frames	2020
Binning	1x1
Detector resolution	2048x2048 px
Integration time	1000 ms
Position of samples	650 mm
Voxel size	0,086 mm

Table 1. Computed tomography scanning parameters

Before reverse modelling, the obtained point cloud needs to be polygonised. The output of the polygonization is a surface model, usually described in STL format, which can be imported into CAD software where reverse geometric modelling techniques can be applied. For the experiment, 2 programs designed for data polygonization were used, which were then compared with each other to determine the differences and the effect of these different polygonization methods on the point cloud from which a given STL model is formed and the size of this model. The software used for this experiment are GOM Inspect 2018 and VG Studio MAX. GOM Inspect can be used to polygonise point clouds in four ways: Less Detail, Standard, High Quality and Raw Data. Point clouds in VGL format were loaded into GOM and then polygonised as described. The output of the process is the recorded parameters such as the number of mesh points and its data size.

Method of polygon-nization	Number of points SLA	File size SLA (GB)	Number of points FDM	File size FDM (GB)
Raw data	11 649 195	4,658	11 784 501	4,44
High Quality	4 727 695	1,891	4 774 212	1,79
Standard	1 307 159	0,522	1 378 695	0,531
Less Detail	599 260	0,24	656 784	0,253

Table 2 Effect of polygonization on file size and number of points

The data from Table 2 can also be written graphically in the form of bar charts, where the effect can be observed more clearly. In Fig. 3, the effect of polygonization methods on the file size can be seen.

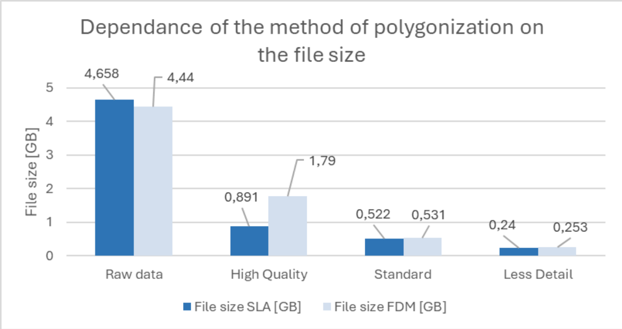


Figure 3 Comparision file size

For a complete comparison, it is necessary to analyse the data from the second graph, which discusses the comparison of polygonization methods in the GOM Inspect software and their impact on the number of points from which the resulting STL model is formed. This graph is shown in Fig. 4

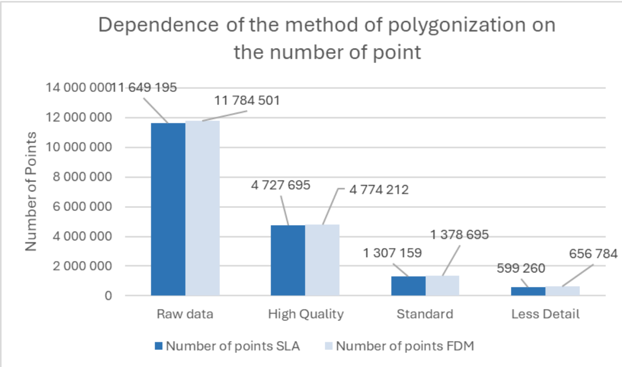


Figure 4 Comparision number of points

We can see in the individual plots that there is a huge difference between Raw data and High quality in terms of both the number of points and the size of a given file, with the High-quality method reducing noise and taking into account the high quality points. The difference between the two in file size is more than double. Of course, the effect of the number of points on the accuracy of the individual objects themselves also needs to be measured, which our research will get to in later stages. Table 3 shows the polygonization results for the VG studio MAX software. The software in question offered different types of polygonization, with the difference of how much data to consider for the creation of the STL model. These were specifically the Quick, Fast, Normal, Precise and Super precise methods. We can compare the principle and operation of each method to the methods we used in the previous software.

Method of polygon-nization	Number of points SLA	File size SLA (GB)	Number of points FDM	File size FDM (GB)
Quick	12 323 142	1,237	70 563 446	11,469
Super Precise	3 766 990	0,379	35 233 154	4,704
Precise	2 661 582	0,269	29 087 486	3,403
Normal	672 819	0,068	672 828	0,066
Fast	475 483	0,048	8 665 904	0,895

Table 3 Data of polygonization in VG studio MAX

Again, bar graphs were also made for Table 3 to express the dependence between the polygonization method and the number of points, or the size of a given set. These dependencies can be observed graphically in Fig. 5 and Fig. 6.

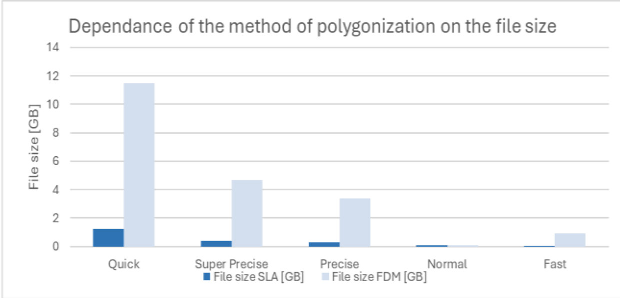


Figure 5 Comparison file size

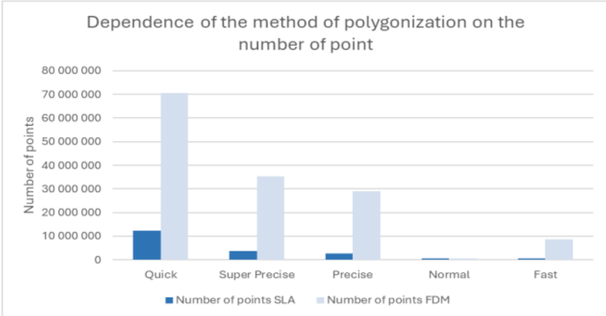


Figure 6 Comparison number of points

In the graphs that express the dependencies of the polygonization method in VG Studio MAX software on the file size and the number of points, a significant difference between the sample produced using SLA technology and the sample produced using FDM technology can be seen. This difference is due to the fact that in FDM printing, the interior of the part is made up of a filler structure called infill. It is because of this that the number of dots is significantly larger because the CT scanner has also taken data from this structure, whereas a sample produced by SLA technology is a solid part, so there is not a complex structure made up of a large number of dots. In the Normal method, the number of points is the same for both SLA and FDM, because due to the reduction of points, the internal structure of the sample has just been isolated, and therefore the polygon model is only made up of the external structure for both samples.

4 REVERSE GEOMETRIC MODELING

In this part of the research, we set out to show the effect of this reduction on the dimensions of simple geometric elements. The investigation and evaluation of the effect was carried out using Autodesk Powershape CAD software which has reverse CAD modelling features as well as a polygonal mesh manipulation module. The investigation of the impact of the reduction was carried out on polygonal models that consisted of all the points collected, i.e. the points were not reduced in any way. Before importing the polygonal model into the Powershape SW environment, it was necessary to define a coordinate system, which was created in the GOM Inspect CAQ system using the 3-2-1 constitution method. This involves the creation of an SS based on the location of six points on the surfaces of the model. The individual digits represent the number of points in a particular plane, in this case ZZZ-YYX. Three points were placed on top of the square base thus setting the direction and origin of the Z-axis, which will indicate the height of the model. Two points were placed on one side wall of the base (right) giving the direction of the X-axis and the origin of the Y-axis, and the last point on the other giving the origin of the X-axis. This procedure was used to set up both polygonal models. Due to its large data volume, the RawData polygonal models could not be imported into Powershape. Therefore, geometric elements were extracted separately using GOM Inspect by feature selection based on geometric shape.

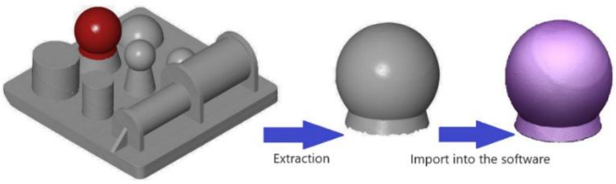


Figure 7 RGM process of spherical element

Network reduction is understood as a reduction in the number of points - triangles, which significantly reduces the amount of coded information about the network model, i.e. reduces the size of the file. Network reduction is a common practice in practice since data reduction has a faster response when manipulating the model.

The procedure of this experiment was to create 9 copies of the unreduced network of a given extracted feature, on which network reduction was performed with a difference of 10% between each copy. Subsequently, area was fit to the reduced networks using the Manual Segment function. Through Manual Segment, the area parameters are calculated based on the marked points/triangles through the Triangle Selection function, it further provides the choice of fitting such as central, inner and outer. The Triangle Selection function allows you to select points/triangles depending on their colour, specified discontinuity angle, horizontal angle or length. In this case, the discontinuity angle selection was used with a specified value of 5 with the middle snapping method of the area which is preset by the software. Once the element surface was created, parameters such as diameter and its position in Y and Z coordinates were read from this. The X coordinate deals with the length of the element, which is not under investigation, so we ignore it. To find the number of points of the selected element, the Distribution function was used to separate the mesh from the irrelevant geometry - the sidewalls. After partitioning, the "nodes" values were subtracted by the Selection Information function.

4.1 *Effect of mesh reduction on the D20 horizontal cylinder*

To investigate the effect of mesh reduction on the D20 horizontal cylinder, an inverse geometric modelling procedure was carried out, which was described in more detail earlier in the paper. The analysis of the number of points as a function of the diameter of a given horizontal cylinder was performed on the investigated element. In Tab. 4, the data from the measurement of each diameter of the horizontal cylinder D20 and the number of points from which the diameter was calculated are given.

Reduction [%]	Number of points SLA	Diameter SLA [mm]	Number of points FDM	Diameter FDM [mm]
-	544 012	20,01924	550 431	20,00379
10	481 326	20,01145	488 838	20,0608
20	425 806	20,01186	429 656	20,06603
30	373 903	20,01623	362 189	20,06477
40	235 709	20,0134	319 632	20,06575
50	231 125	20,02102	205 007	20,06861
60	206 415	20,03479	199 603	20,0711
70	152 223	20,01795	151 830	20,07009
80	97 558	20,02872	95 494	20,0721
90	48 872	20,08555	47 395	20,07467

Table 4 The number of points during reduction on the cylindrical surface

A line chart was also produced for graphical display, based on the data in Tab. 4. This graph is shown in Fig. 8.

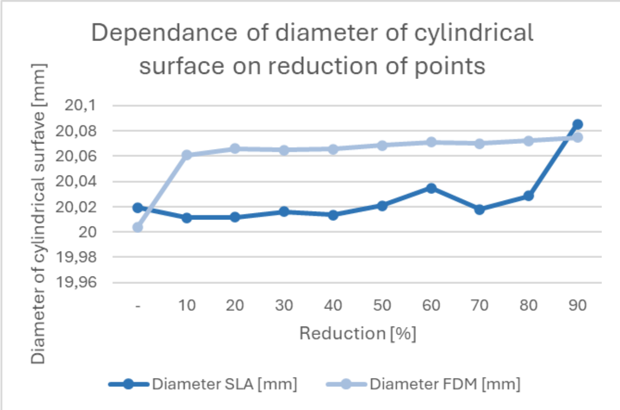


Figure 8 Dependence of diameter of cylindrical surface on reduction of points

For the sample that was produced by the sla technology, a slight fluctuation of the values can be observed. The exception is the diameter measured at 90% reduction, which differs from the other diameters by about 0.04-0.06 mm. The opposite is true for the sample produced by FDM. For this sample, we can detect a deviation from the original measured value already at 10% reduction of about 0.06 mm. The other values of the diameters differ only in the order of thousandths of a millimetre.

In addition to the cylinder diameter, the effect of the reduction on the position of the element was also investigated. A plot of the deviations from position can be seen in Fig. 9.

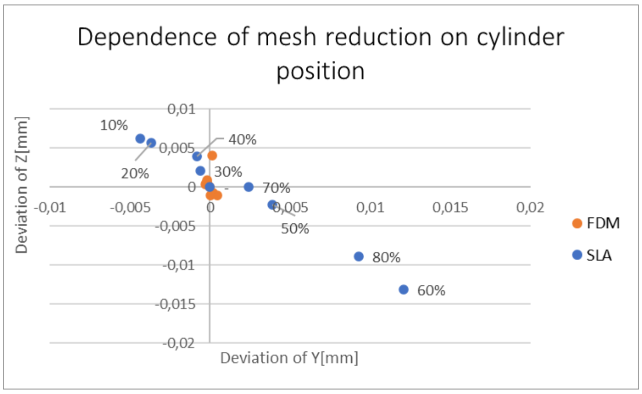


Figure 9 Position of cylinder

From the graph in Fig.9, the reduction on the SLA model had the greatest effect on the change of the cylindrical surface position. The copies of the sample produced by SLA technology deviated more from the original position than the copies of the sample produced by FDM technology. The smaller deviations on the FDM specimen can be explained by a more solid network due to the imaging of the smooth surface of the cylindrical feature on the specimen.

4.2 Effect of mesh reduction on the D30 sphere

The procedure for investigating the impact of mesh reduction on sphere D30 was followed in the same way as was done in the previous case. Parameters such as the mean and number of points, and later the deviation of the position from the unreduced mesh, were measured in the same way. Tab. 5 shows the data obtained from the measurements.

Reduction [%]	Number of points SLA	Diameter SLA [mm]	Number of points FDM	Diameter FDM [mm]
-	451 874	29,8776	462 430	30,0711
10	406 946	29,8786	414 706	30,0727
20	354 639	29,8764	361 312	30,0714
30	311 782	29,8758	320 385	30,0726
40	255 096	29,8803	265 444	30,0713
50	222 377	29,878	218 349	30,0731
60	167 075	29,8788	178 098	30,0739
70	119 996	29,882	132 103	30,0741
80	85 735	29,8821	895 59	30,0723
90	51 875	29,8871	40 551	30,076

Table 5 The number of points during reduction on the spherical surface

In the same way, a line diagram was constructed for this case, which can be seen in Fig. 10

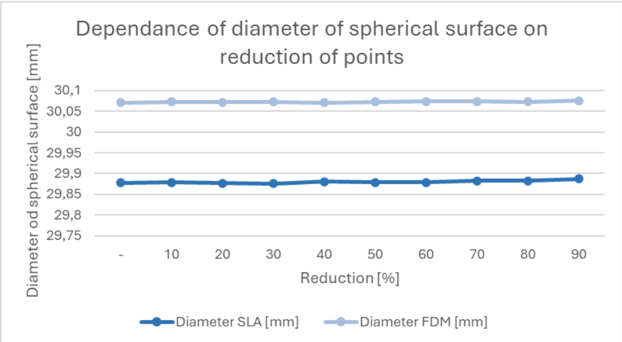


Figure 10 Dependence of diameter of spherical surface on reduction of points

The graph does not show a significant difference between the score reductions. Only the accuracy of the individual prints can be seen, with SLA printing showing shrinkage of the part and FDM printing showing an addition over the CAD model. When detecting the dot reduction on the position of the feature, a small effect of dot reduction can be seen, which at the largest deviation equates to a value of 0.012 mm in the X-axis. This value is not significant. An illustration of the individual deviations can be seen in Fig. 11.

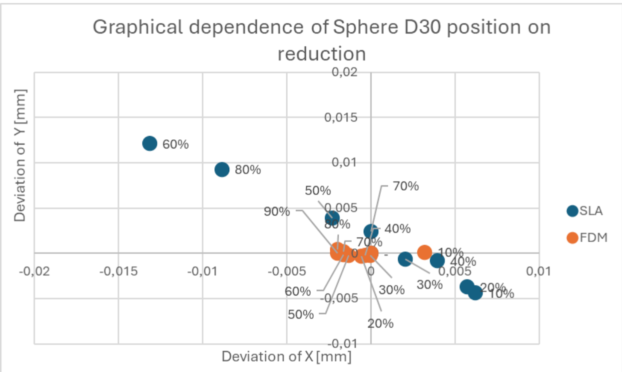


Figure 11 Graphical dependence of Sphere D30 position on reduction

4.3 Effect of mesh reduction on the Cone D20

The experiment carried out on the Cone element was similar to the previous two cases. The difference was in the measured parameter. In contrast to the diameter of the element, the parameter Cone Angle was chosen, thanks to which we can equally well evaluate the effect of point reduction on the cone. The data from the measurements have been written down and can be seen in Tab. 6 and in Fig. 12.

Reduction [%]	Number of points SLA	Cone angle SLA [°]	Number of points FDM	Cone angle FDM [°]
-	185 862	9,88379	185 637	10,04675
10	167 656	9,88176	165 148	10,04722
20	146 738	9,86666	144 064	10,05333
30	127 375	9,88237	126 205	10,04614
40	106 472	9,8841	104 750	10,04598
50	82 891	9,86974	89 538	10,04643
60	67 929	9,86898	68 678	10,04562
70	50 738	9,89108	47 372	10,04645
80	32 338	9,88902	31 262	10,05778
90	14 192	9,8872	15 031	10,05637

Table 6 The number of points during reduction on the cone angle

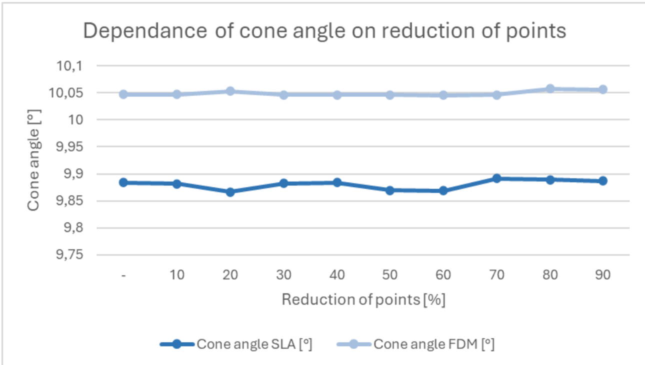


Figure 12 Dependence of diameter of cone angle on reduction of points

When analysing the cone area, it is possible to notice a subtle variation in the cone angle values for the sample produced by SLA technology. For the FDM sample, this variation was not as noticeable and was on the order of hundredths of a degree. If we look at the variation values of the individual samples, we can equally observe a difference that does not affect the result very much and therefore does not have a significant effect on the observed element. Fig. 13 shows the data on this issue in the form of a dot plot. It can be seen in the plot that the deviation from the original dimension is only minimal. At 80% and 90% point reductions for the samples produced by FDM it is possible to see a more significant deviation in the X-axis, which was a magnitude of 0.003mm at 80% reduction and 0.0029mm at 90% reduction, which means that it was a non-significant result anyway.

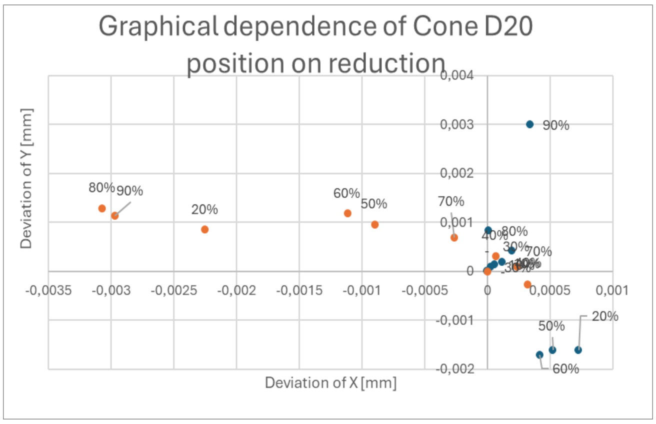
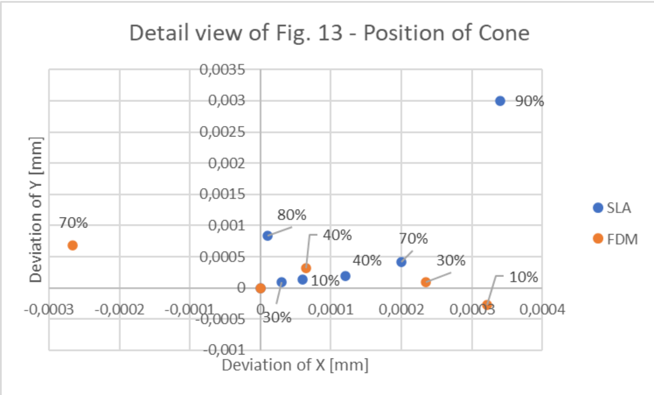


Figure 13 Graphical dependence of Cone D20 position on reduction

In Fig. 14, a close-up view of the region around the center of the coordinate system can be observed.



5 CONCLUSIONS

The aim of this work was to investigate the effects of point reduction on the dimensions and position of selected simple geometric shapes. Also, the study focused on the analysis of polygonization techniques of GOM Inspect and VG Studio MAX software. In addition to the fact that the latter software has more methods to polygonise the resulting process, it therefore offers more possibilities for the user to manipulate and modify the obtained data as much as he/she wants before the actual measurement. The GOM Inspect software thus has a smaller number of methods to go by but is just as capable and the variety of these polygonization techniques is equally evident there. The size of the files relative to the number of points from which the Polygon 3D model was created for the GOM Inspect software seemed to be larger compared to the VG Studio MAX software. From the measured values, it was evident that for a model formed by a similar number of points, the size of a given saved file was three to four times larger. Within the same software, the file size was directly proportional. The only exception in this case was the sample produced by FDM technology in the VG Studio MAX software, where the Quick method collected up to more than 70 million points. In that case, the file size was larger for a given number of points compared to other methods in the same software.

In order to investigate the effects of point reduction on the dimensions and position of simple geometric shapes, it was necessary to create copies of scans of both fabricated parts. Thus, in this approach, 10 copies were created for each manufactured part, which were then subjected to point reduction. Each copy differed from each other with a difference of 10% point reduction. In order to work faster and to put less load on the computing equipment, only the feature under investigation was imported into the GOM Inspect measurement software. The most affected element with respect to the change in the observed dimension was the horizontal cylinder D20. The diameter values varied with a range of 0.07 millimetres for both samples produced. The difference between the samples was that for the FDM sample this difference occurred at 10% point reduction, for the SLA sample the diameter values of the horizontal cylinder D20 fluctuated relatively around similar values until the 90% reduction when the diameter value of the horizontal cylinder D20 changed from 20.028mm to 20.085mm. The other observed elements were not affected to such an extent by the point reduction, with the highest difference for the diameter of sphere D30 being 0.01mm, and for the inclination angle of cone D20, the highest difference measured was 0.03°.

The position of the geometric objects was as much affected as their dimensions. The largest deviations from the original position occurred at 90% point reduction. Specifically, for the horizontal cylinder on the sample produced by SLA technology, the deviation at 90% point reduction was found to be 0.047mm in the Y-axis and 0.06mm in the Z-axis. The same deviations also occurred for the D30 sphere position measurements at the same point reduction. For the D20 cone measurements, similar values of deviation were not measured anymore.

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