Original scientific paper

Calibration of the printing process for 3D models using Vat polymerisation and investigation of the mechanical properties of TGM-7 resin

ABSTRACT

With the development of modern technology, three-dimensional graphics (3D) are increasingly making their way into various fields such as design, advertising, packaging, industry and even medicine. Three-dimensional graphic elements can be not only modelled, but also apadted for the three-dimensional printing. However, the quality of the print is highly dependent on the printing method used, technological process and on the properties of the material. In this work, the models were created using 3D graphics software and tested after 3D printing. The new acrylic resin TGM-7, developed by AmeraLabs, was used for the 3D printing. During the testing process, the models were calibrated in order to obtain accurate and high-quality models with fewer inaccuracies or defects in the future and precise connections. During the experiments, a more significant change in dimensions was observed in the lower part of the models, which could have occurred due to the deposition of the polymer. Samples printed at a 45o angle had more accurate dimensions. The mechanism of parameters compensation in the XY and YX axis was demonstrated. During the work, the mechanical properties of the material were also determined, which are important for the many applications such as packaging, advertising items or other products subject to load. The acrylic resin, printed at different angles, exhibited plastic propertie, and samples printed at a 90° angle were better able to withstand dynamic loads, which averaged 206 N. The obtained results were applied to the creation and printing of an advertising model.

Renata Gudaitiene [1]
Vygintas Minkus [1]
Andrius Darulis [2]

[1] Kauno kolegija/Higher Education Institution, Faculty of Computing, Engineering and Technologies, Department of Informatics and Media Technologies, Kaunas, Lithuania
[2] MB Labsamera, Kaunas, Lithuania

Corresponding author:
Renata Gudaitiene
e-mail:
renata.gudaitiene@go.kauko.lt

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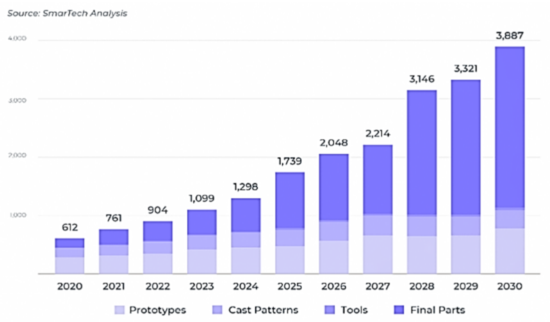
Introduction

With the development of information and multimedia technologies, three-dimensional (3D) technologies are gaining market share (Shahrubudin, Chuan & Ramlan, 2019; Dizon et al., 2018). AMFG (2021) forecasts that by 2030, the use of three-dimensional technology and the revenue generated from 3D printing will more than double, and, as can be seen in Figure 1, not so much in the production of prototypes or parts, but in the production of final goods or their structural accessories. 3D printing is the innovation of this century and, according to Barry Berman (2012), an industrial revolution that can bring original virtual designs into the tangible material world. 3D printing enables the design and production of complex geometric shapes that can be continuously edited, as they do not require any additional moulding and the design ideas are realised through digital tools (Macdonald & Wicker, 2016).

3D printing opens up new opportunities and offers great promise for companies seeking to improve production efficiency. Moreover, this technology has the potential to make important and fundamental changes in the industry and transform production (Shahrubudin, Chuan & Ramlan, 2019). The application of 3D printing can accelerate the speed of production, especially for small volumes, reducing the time and cost of production (Unifize, n.d.).

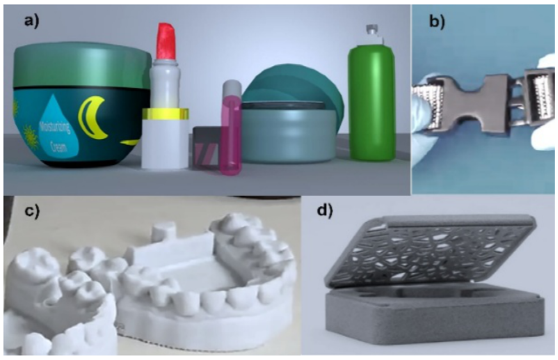


» **Figure 1:** *Revenues from polymers 3D printing in the consumer goods industry in million US dollars (AMFG, 2021)*

A 3D model is a mathematical representation of any three-dimensional object (real or imaginary) in a 3D software environment (Vaira & Linkuvienė, 2013). At the initial stage of turning an idea into a creation, it is important to choose the right 3D printer software. There are many 3D printing software options, but it is important to consider things as follows: ease of use, functionality, compatibility with different file formats and support for a complete additive manufacturing design process. The representatives of Jaycon identify 15 of the most popular 3D printing design software currently available on the market: Autodesk Fusion 360, TinkerCAD, SolidWorks, Rhino3D, SketchUp, Blender, Ultimaker Cura, Autodesk AutoCAD, CATIA, Onshape, ZBrush, FreeCAD, Kreo, Simplify3D, and Autodesk MeshMixer (Jaycon, 2024). Whether it is complex product design or simple 3D objects, the right software can simplify the design process, improve the final product and help achieve the objectives.

Three-dimensional (3D) graphical elements are widely used in many fields, such as architecture, industry (Vaira & Linkuvienė, 2013), medicine (Vaz & Kumar, 2021; Liaw & Guvendiren, 2017), and simple and intelligent packaging (Tracey et al., 2022) as well as in wick design and for advertising purposes (AmeraLabs, n.d.), and in the production of smart 3D structures (Nassar et al., 2018). 3D graphics elements can be successfully applied to 3D printing not only in mass production, but also in the production of single products or prototypes and in the development of educational stands. (Lasec group, n.d.) Some examples of products can be seen in Fig. 2.

3D printing is now useful not only for creating objects with micrometric parameters, but also for creating nanometric structures (Weitzer et al., 2022). So-called 4D technology is also on the way. It is not only possible to obtain a three-dimensional shape, but also to have a variable shape and an object that changes the position of the individual parts (Rieland, 2014). For this purpose, elastic polymeric materials- elastomers- are commonly used (Kuang et al., 2018). Manufacturing a product from such materials can lead to a complex design, which in some cases would be difficult or even impossible to obtain without three-dimensional modelling.

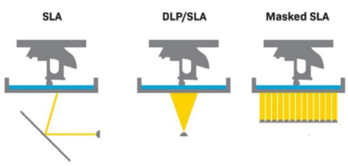


» **Figure 2:** *Examples of 3D models and products (Avid Product Development, 2024; AmeraLabs, 2023): (a) the examples of the 3D models of packaging, (b) the buckle, (c) the printed dentures, (d) the printed box*

In order to make a three-dimensional object three-dimensional and tangible, 3D printing equipment is required. A range of 3D printing techniques are used in this field (All3DP, 2023). Shahrubudin, Chuan & Ramlan (2019) identify and classify the following techniques: binder jetting, directed energy deposition, materials extrusion, materials jetting, powder bed fusion, sheet lamination, and VAT photopolymerisation.

Each printing method has its own characteristics depending on the type of material used, the equipment and the desired result (All3DP, 2023). Currently, the most widely used 3D printing technologies on the market are hot extrusion and resin VAT photopolymerisation (Štaffová et al., 2022).

VAT photopolymerisation is a commonly used 3D printing technique which generally refers to the curing of photoreactive polymers using lasers, light or ultraviolet (UV) light (Low et al., 2017) VAT polymerisation can be performed by different 3D printing technologies (Fig. 3): stereolithography (SLA) and digital light-assisted stereolithography (DLP/SLA) (3DP.Lighting., n.d.), and masked stereolithography (Masked SLA) (Wyss, 2019).



(a) (b) (c)

» **Figure 3:** *VAT polymerisation printing techniques: (a) stereolithography, (b) light-flow treatment, (c) masked stereolithography (Wyss, 2019)*

During the initial development of stereolithography, the technology was limited to liquid photopolymers as a raw material. The need to produce robust parts with high mechanical properties and functionality has led researchers to incorporate micro- and nano-sized fillers into the liquid photopolymer for a variety of applications (Chaudhary et al., 2023).

In the case of SLA, the photoinitiator and specific conditions of exposure to UV light influence, as well as any dyes, pigments or other added UV absorbers, have an impact (Stansbury & Idacavage, 2016).

Meanwhile, digital light processing is a stereolithography-like process that works with photopolymers. The main difference in these devices is the light source. Digital Light Processing (DLP) uses a more conventional light source such as an arc lamp with a liquid crystal display panel. It can cover the entire surface of a photopolymer resin vessel in one pass, so it is generally faster than stereolithography (3DP.Lighting., n.d.). The quality of objects can be affected by exposure time, wavelength and amount of energy supplied (quote). Usually, the starting material (resin) is in liquid form and is cured with the help of a polymerizing UV light source. Photopolymerization can produce very high-quality products with good surface smoothness and detail integrity.

An SLA printer can have two types of configurations: bottom-up and top-down (Shahrubudin, Chuan & Ramlan, 2019). In a top-down printer, the first layer is produced on top of a support in the resin, and subsequent layers are cured on top of the lower layers. This technology is still widely used, but the movement of the support along the Z-axis dislodges the resin, and it takes time for the resin to settle which reduces the efficiency of the process. Another type of printer works on the opposite principle: the newly produced layer is placed underneath the previous layers, and photopolymerization with UV light is carried out from below. Since the movement of the support does not move the resin, the surface of the finished structure is always very smooth and the process is faster (FormLabs, 2024a; FormLabs, 2024b).

The main advantages of 3D printing are design flexibility, customisation, waste reduction, rapid prototyping, high precision, tool avoidance and the ability to produce complex structures (Ngo et al., 2018). However, the quality of the print is strongly dependent on the printing method and process used, as well as on the design of the object (Faroze, Srivastava & Batish, 2024).

The main disadvantage is the heterogeneity of 3D printed parts due to defects between adjacent print layers or voxels or polymer relaxation and inhomogeneous monomer conversion in the prints (Štaffová et al., 2022). For this purpose, calibration shapes are printed and their dimensions evaluated (Ameralabs, n.d.).

Difficulties may also arise when trying to fit parts together in joints. In this case, it is important to recalculate and change the dimensions of the objects ready for printing, which is not a straightforward process as some parts of the object may need to be reduced and others enlarged (3D Maker Noob, 2018). Snap-fit joints are a way to connect two different components without using fasteners or permanently joining the parts so that they can be separated later. Once assembled, a snap-fit connector can be either permanent or demountable. There are several different types of joints (cantilever snap fit joints, torsional snap fit joints and annular snap fit joints), but they should all be designed to be easy to assemble by hand (Shields, 2023).

During testing, conversions and calibration of the printing equipment are carried out (3D Maker Noob, 2018). Such test calibration printing and evaluation is particularly important for newly developed or purchased materials. Synthetic polymer resins exhibit a full range of different properties such as polymer fluidity, plasticity, polymerisation and relaxation rates, varying degrees of cure, and resistance to mechanical stresses (Govaert, van der Vegt & van Drongelen, 2019).

Experimental materials and equipment

A new acrylic resin TGM-7 from AmeraLabs was used in this experiment. Table 1 shows the main chemical constituents of the resin.

Table 1
The main chemical constituents of resin

Name of chemical component	CAS Nr.	Concentration
4-(1-okso-2-propenil)-morfolinas	5517-12-4	50-55%
(oktahidro-4,7-metano-1H-indenediil)bis(metilen)diakrilatas	42594-17-2	6-9%
Difenil(2,4,6-trimetilbenzoil) fosfino oksidas	75980-60-8	1-4%

The 3D objects were modeled using Autodesk Fusion 360 software and prepared for printing using the CHITUBOX programme. All samples were printed using a masked SLA printer Elegoo Mars 3 4K. The parameters of the printing process are given in Table 2.

After 3D printing, the samples were washed with isopropanol for 14 min in a wash and cure station Anycubic Wash & Cure plus, dried in the air for 30 min and then additionally polymerized (post-cured) in a standard UV chamber Anycubic Wash & Cure 2.0 (power 25 W) with UV light source of 405 nanometers wavelength.

Determining the strength properties, the tension measurement stand was chosen: the universal 10 kN power testing machine Tinius Olsen H10KT with a 500 N force measurement sensor. Tensile measurements were made according to the ISO 527-5A standard (tensile time 5 min, distance between grips 25 mm).

Table 2

The main printing parameters of resin

Name of producing parameters	Values of parameters
UV spectrum peak	2.62 $mW \cdot cm^{-2}$
Light intensity	406.3 nm
Exposure time	1.6 s
Motor rotation deviation with respect to the Z axis	1,25 µm
Woxel size	0,035 mm

Results and discussions

Occurrence of defects

The printing process itself is not complicated, but a poorly designed and prepared model can be much more troublesome, leading to defects after printing. When modelling objects, it is necessary to consider both the design and the construction of the future product, i.e. whether the designed object will print and whether the parts will be of the right size and be able to be joined together. Incorrect decisions by the designer can lead to failure, with the object ending up with an uneven surface or being torn apart during printing due to stresses in the material.

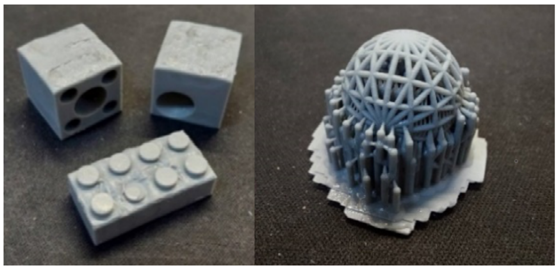
Fig. 4 (a) shows horizontally printed objects that were lifted to a height of 5 mm on supports. This 'run-out' of layers occurs when the supports do not hold the printed layer sufficiently and it begins to fall before the next layer is printed. These defects can be avoided by printing objects flat on the platform, by rotating them at an angle, or by adding more supports of appropriate parameters.

When forming holes, small surface creases may also appear on the sides of the parts. Too few composite supports can also cause the model to wobble, affecting the shape and surface smoothness of the model.

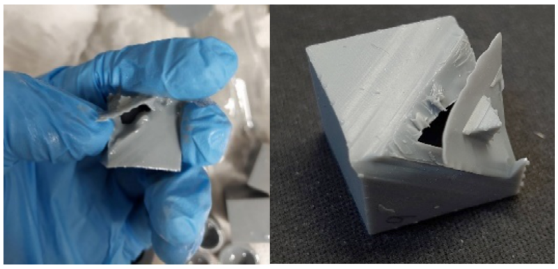
Fig. 4 (b) shows a 20 mm diameter ball on which supports have been placed by hand to support each part of the ball. The supports are visible both externally and internally, connected to each other and from object to object. Printing such balls requires far fewer supports than the shape of the model might suggest, depending on the size of the object and the thickness of the shell.

Sometimes when printing, especially for inexperienced 3D printmakers it happens that for some reason the objects are not printed and remain in the container. This is usually because the supports used could not support the weight of the object or resist the adhesion to the FEP film and fell off. The supports may not hold the object if their contact diameter is too narrow (< 0,30 mm).

In Figure 4 (c), a hollow part was modelled in order to lighten the object and save material. Unfortunately, the void and stresses inside caused the part to tear due to air ingress.



(a)



(b)

» **Figure 4:** *3D printing defects caused by the selection of the wrong supports (a) and design solution (b)*

Study of the parameters of a cube with a hole

In order to ensure the accuracy of the 3D object after printing, it is important not only to select the correct supports during the modelling process, but also to carry out the dimensional refinement and adjustment steps and the calibration process of the machine, which was done in this study. The calibration process is carried out each time a new, untested resin is selected for printing. In this work, a new AmeraLabs acrylic resin TGM-7 was used for research. The quantity and shape of the calibration parts may depend on the shape of the final product to be printed and the shape of the components and their connections. The work started with the modelling of the calibration shapes. Autodesk Fusion 360, a three-dimensional graphics programme, was chosen for the modelling of the figures on a computer. A 30 mm cube was created with the box tool and a circular hole of 20 mm diameter, 30 mm long, was formed horizontally in the centre of the cube (Fig 5, a).

The generated shape was exported to an "stl" format file.

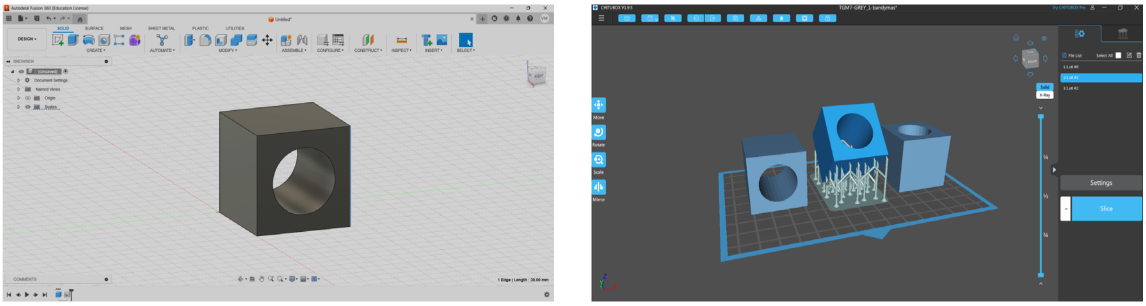
This file type is a common format for 3D printing and Computer-Aided Design (CAD) applications. The resulting file was loaded into the cutting programme CHITUBOX (Fig 5, b). Here, the shapes were copied and rotated to angles of 1-0, 2-45 and 3-90 degrees respectively and prepared for printing to investigate the dimensional change after seating and relaxation of the polymerised resin.

The model printed at 45 degrees did not have a strong contact with the printing platform, so it was lifted to a height of 5 mm from the platform and supports were placed to hold the object in place to prevent it from falling and moving during the printing process (Fig. 6). The supports can be placed automatically or manually.

In this case, the automatic placement was performed and the required parameters have been set (Fig. 6).

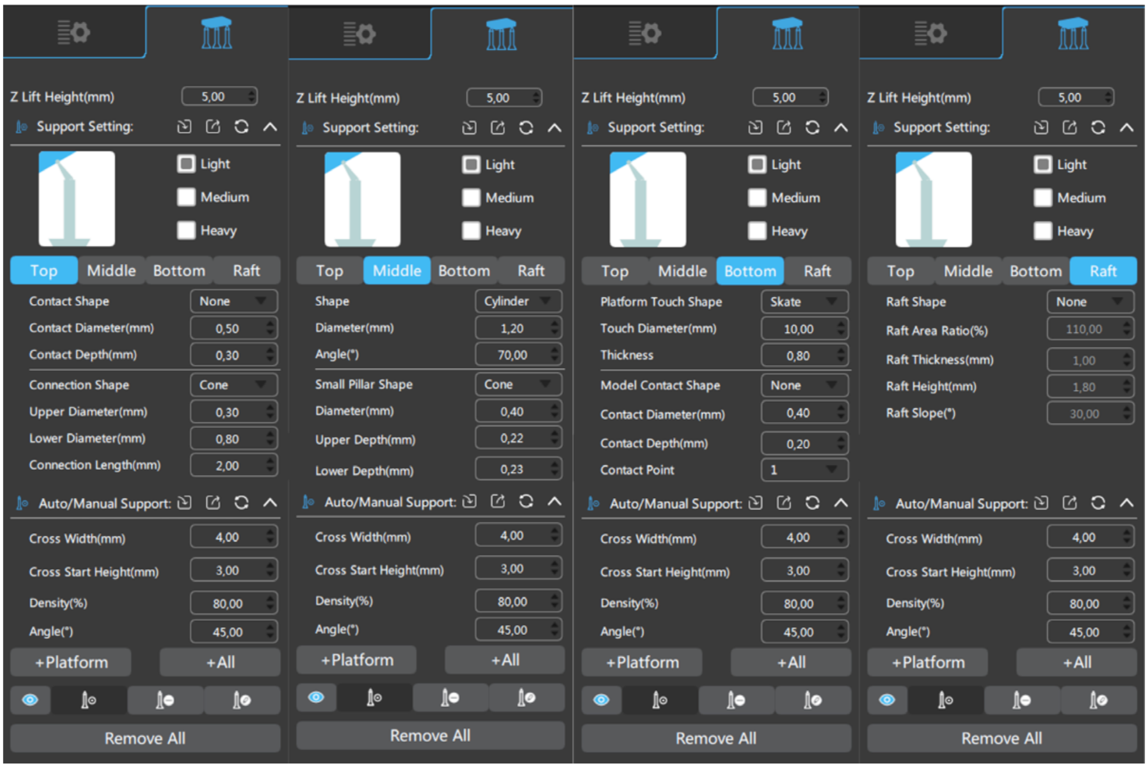
Among the support settings, lightweight supports have been selected and the shape of the base has been changed to a flat shape to better adhere to the printing platform and to make it easier to unhook the printed object.

The shape of the tip contacts was switched off and only the tip itself was adjusted, which was conical in shape with an upper diameter of 0,30 mm and a lower diameter of 0,80 mm. The middle part of the supports is cylindrical with a diameter of 1,20 mm. The diameter of the lower part was 10 mm. The correct selection of the supports is important for the surface shaping of the object in order to prevent them from



(a) (b)

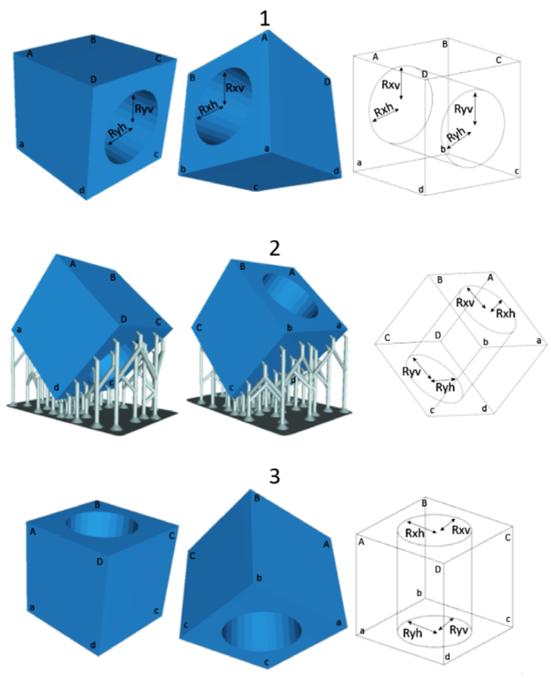
» **Figure 5:** *Object preparation for printing: a) simulated calibration cube in Autodesk Fusion 360, b) cubes (1, 2, 3) ready for printing in CHITUBOX*



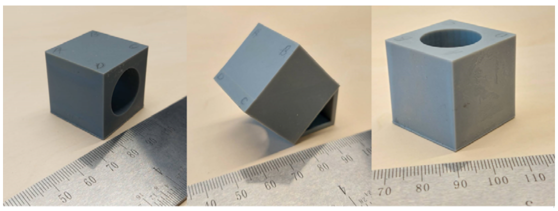
» **Figure 6:** *Support settings: a) top, b) middle, c) bottom, d) base* settling during the printing process or separating from the surface after the object has been printed. Once the supports were assembled, the appropriate print settings were selected to best suit the type of resin.

The printed objects were measured with a precision electronic caliper to estimate the overall dimensions of the cones and holes in all axial directions. The printed 3D objects (Fig. 8.) were labelled according to the scheme shown in Fig. 7. For the printing process, 4 bottom layer counts, exposure time 1,6 seconds, bottom exposure time 20 second and 0 transition layer count were set.

After the shapes were prepared for printing, the file was exported from the cutting program in "ctb" format to be recognised by the printer. In order to estimate the dimensions of the edges of the modeled and sharply rotated objects after printing, they were marked with letters, as shown in Figure 7.



» **Figure 7:** *Marking angles and holes in the calibration models*



» **Figure 8:** *Printed models separately (1, 2, 3)*

The printed objects were further hardened by polymerisation with 405 nm UV light to stabilise their parameters. The defects on the models were observed after the curing process was completed.

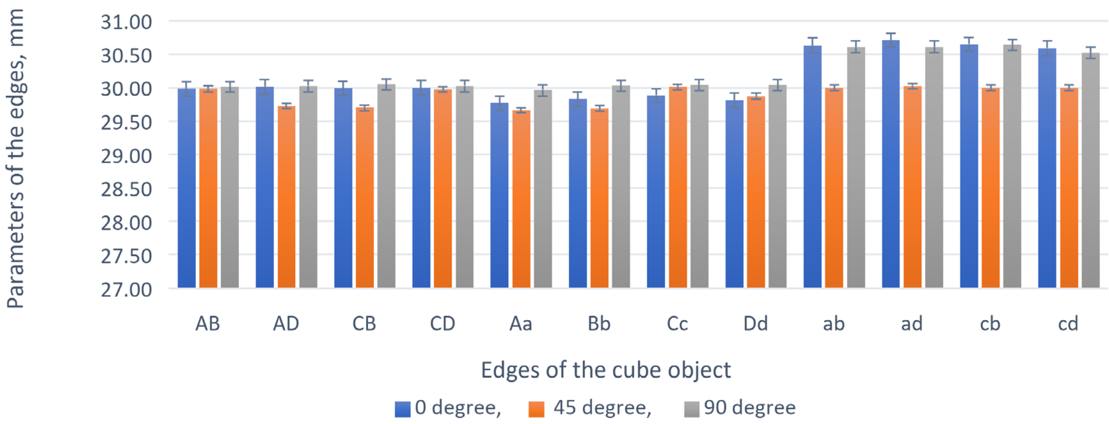
The most noticeable defects were the seating of the first cube figure in the hole during printing, the polymer shrinkage inside the hole, the 'step' effect of the second figure and the blooming of the third printed model.

As can be seen from the diagram (Fig. 9), the largest dimensional changes for the first cube model, printed at a 0 degree angle, were in the vertical axes and at the base. The edges AB, AD, CB, and CD of the first model were smaller than the edges AB, AD, CB, and CD, indicating that the bottom of the model was wider than the top by an average of 0.645 mm, or 2.19 percent of the 30 mm value set for the modeled object. The vertical edges of Aa, Bb, Cc and Dd were also shorter by 0.18 mm (0.59%) than the theoretical set dimension of 30 mm. The second model was reduced in height by 0.19 mm (0.63%). The dimensions of the horizontal edges varied only slightly. Comparing the first and third models, it can be seen that vertically there was a subsidence and the dimensions became smaller than those of the modelled objects, while at the base there was a pronounced widening of the objects by 2% on average. The smallest average change (decrease) in all dimensions was observed in the 45 degree printed object. We think that these changes in the models could have occurred due to the deposition of the polymer in relation to the vertical Z axis, as well as due to the error of the UV light source and the amount of light received through the printed polymer layer.

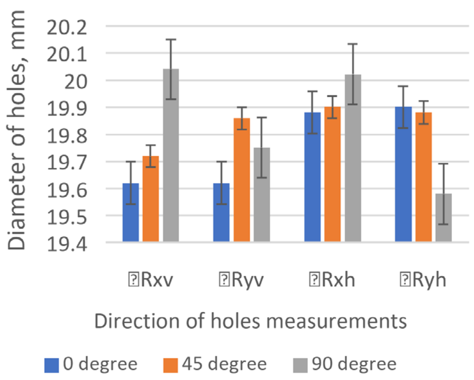
For the same reason, the diameters of the holes in the cobe models also have been changed. Theoretically, the exposure error of the UV source can be compensated through the printing software, but the quality of the software can also affect it.

The hole diameter of the first model decreased more in the vertical Z axis (Fig. 10) than in the horizontal (X and Y) axes, indicating that the hole became slightly elliptical. In the third cube model, the hole at the top of the object remained closest to the hole diameter determined by the modelled object, but at the bottom of the object, the diameter of the hole decreased in both axes, resulting in a conical shape with a smaller diameter at the bottom. The hole dimensions of the cube models printed at 45 degrees also decreased, but the average change was not as large as for the models printed at 0 and 90 degrees and averaged 0,8%.

Thus, a comparison of the three cube models printed at different angles shows that the polymer's yielding properties resulted in all the layers of the object being exposed vertically to the polymer's own weight during printing and seating. The upper parts of the models were narrower than the lower parts, and the edges which were expanded were contracted on the opposite side. In the case of the holes, the cube samples were also observed to sit with respect to the vertical axis.



» **Figure 9:** *Comparison of edges parameters of printed cube models*



» **Figure 10:** *Comparison of holes diameter of printed cubes*

In order to avoid the inaccuracies obtained, the 3D models of the cubes with holes were corrected in the software environment after printing and their dimensions were changed according to the results obtained.

Dimensional accuracy is particularly important when the objects are to be used in more complex constructions or when they are to be combined with each other.

Dimensional errors in the models can also be caused by the temperature of the printing resin (which rises from 23 to about 35 degrees from the start of the process), which affects the flow of the polymer or the quality of the printer screen.

The quality of the screen affects the uniformity of the transmitted light flux. Light intensity at different points can vary by about 20%, so dimensional accuracy can be affected by uneven light flux on the surface, especially if objects are placed in different places during printing, rotated at different angles, or placed at too small distances from each other. In order to obtain the most accurate dimensions of the model after printing, the factors mentioned above should be evaluated and tried to eliminate them as much as possible.

Calibration figure "steps"

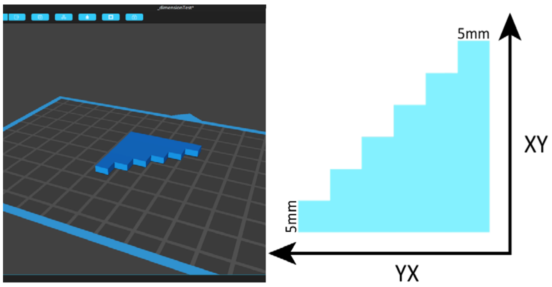
For the second type of calibration, a popular calibration figure "steps" was chosen to see how the polymer sits on average with respect to the X and Y axes. The height of the step chosen for each model was 5 mm (Fig. 11). For the first time, this part was printed 3 times without any compensation (Table 3). After measuring all the shapes, the averages were averaged and fed into a specially designed dimensional compensation calculator. This spreadsheet allows you to immediately see the percentage decrease or increase in the dimensions of a figure, as well as the compensation in millimetres (Table 4).

The averages of the overall results were then fed into the CHITUBOX software in the advanced settings section, as shown in Fig 12. After combining the results obtained for the dimensional compensation and growth of the part, the part was printed 3 more times.

The dimensions of the printed figures were measured and averaged again in the spreadsheet to check the accuracy. As can be seen from the results obtained (Fig. 11), the accuracy of the steps of the part in the XY axis was higher than in the YX axis, indicating that the polymer expanded more in the latter axis.

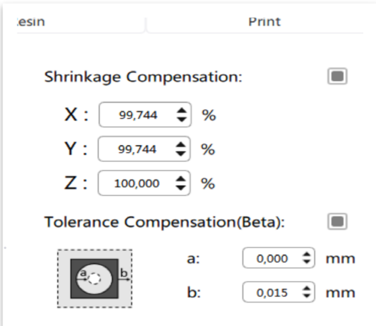
Using compensation, the resulting post-printed dimensions were more accurate and more similar to the modelled shape, as shown. However, the overall average compensation error for the YX-axis had a smaller improvement in performance than for the XY-axis.

These results suggest that the compensation mechanism could work better by specifying different percentages of compensation for the axes. Performing this calibration process with more shapes could lead to even more accurate dimensions, especially for small parts. For the sake of clarity, it should be mentioned that the uniformity of the light flux and the position of the object on the base could have had a small influence on the different relaxation of the polymer in relation to the X and Y axes.



(a) (b)

» **Figure 11:** *Calibration detail "steps" in the CHITUBOX software environment (a) and step measurement diagram (b)*



» **Figure 12:** *Calibration part "steps" print settings based on the overall average of results in the CHITUBOX software*

Table 3

Results of the dimensions of the calibration component 'steps' for different axes

Nominal, mm	Measured, mm		Measured after compensation, mm	
	XY	YX	XY	YX
5	4,94	4,97	4,94	5,00
10	9,99	10,02	9,98	10,02
15	15,01	15,05	15,02	15,03
20	20,02	20,06	20,00	20,03
25	25,03	25,04	25,00	25,00
30	30,02	30,03	29,99	29,05

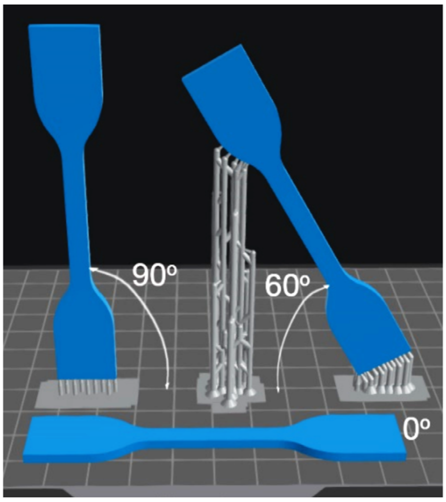
Table 4

Overall average of results of the dimensions of the calibration component 'steps'

Results	Before compensation		After compensation	
	XY	YX	XY	YX
Scale, %	99,70	99,79	99,83	100,18
Compem-sation, mm	0,026	0,004	0,02	-0,018
Avg. scale, %	99,74		100,006	
Avg. Com-pensation, mm	0,015		0,0012	

Mechanical measurements

In order to make an effective choice of material, it is important to understand the basic mechanical properties of the resin, how plastic the material is, and how much load it will be able to bear. These properties are essential as they reveal how the resin performs under different conditions, help determine the durability of the material, and the stiffness of the structural elements (Dizon et al., 2018). Therefore, in this work, the tensile strength of the selected acrylic resin TGM-7 was evaluated. The samples for investigation were printed in different angles (Fig. 13).

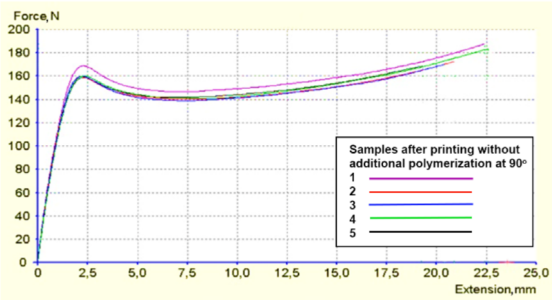


» **Figure 13:** *Samples models in different angles prepared by 3D printing for mechnical measurements*

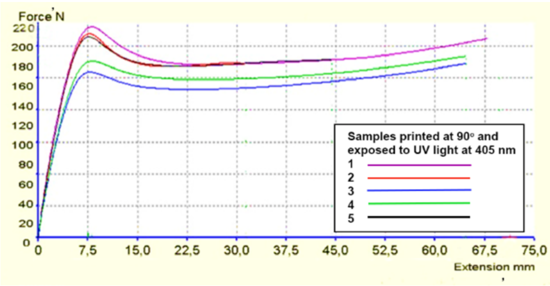
The tensile properties of the samples are also influenced by the additional exposure to UV light and the orientation of the object at a certain angle. The evaluation of these important properties will allow better informed decisions to be made to ensure optimum performance and durability of printed parts.

As can be seen from the graphs in Fig. 14, the sample printed at a 90-degree angle (a) without additional UV polymerization was able to withstand an average force of 176.4 N. The study also showed that the additional UV polymerisation gave the samples additional strength and stability. From the second graph (b) we can see that after additional polymerisation with a 405 nm light source, the load capacity of the sample increased to an average of 206 N, which is 14.6%, while some samples reached a maximum load of 220 N. The position of the samples in the curing oven may have contributed to the wider scatter in the measured results.

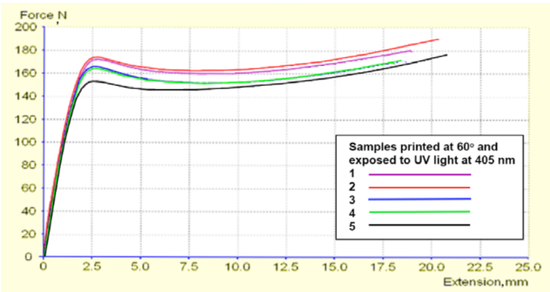
The maximum stresses of the samples and their stresses at failure were determined by investigating the effect of tensile force on the samples. As can be seen from the graph below (Figure 15), for all three samples, excepting the sample printed at a 90º angle and exposed to UV light, the maximum stress value at the necking threshold was lower than at the necking rupture point. This indicates that the material is quite plastic. The sample printed at a 90-degrees and additionally polymerised with UV light showed a higher load resistance. This demonstrates that even a low level of UV polymerisation can affect the mechanical properties of the samples.



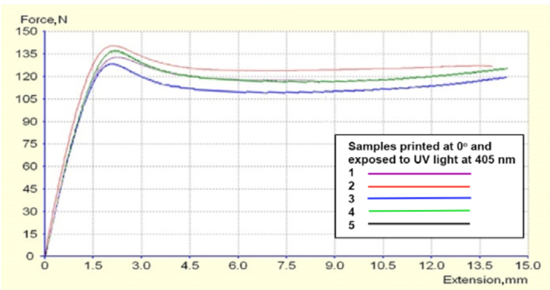
(a)



(b)



(c)

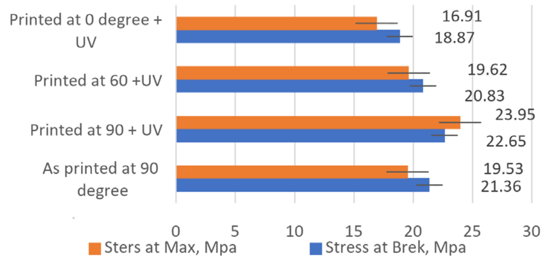


(d)

» **Figure 14:** *The dependence of the tensile force vs the elongation of the samples (tensile speed of samples – 5 minutes, the distance between the holding grips – 25 mm: a) samples after printing without additional polymerization at a 90°; b) samples exposed to UV light (at 405 nm), printed at a 90°; c) samples printed at a 60° and exposed to UV; d) samples printed at a 0° degree and exposed to UV light*

In order to investigate the stability of the sample when rotated by 60-degrees, it was found that the tensile strength of the samples decreased to an average of 177,4 N and was almost identical to that of the samples not additionally cured by the UV light source.

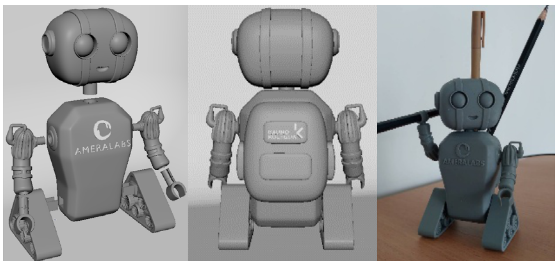
The samples placed on the platform (at 0 degrees) were even less resistant to tensile stress, with an average tensile strength of 132 N. The average elongation of the samples at the fracture limit was almost directly proportional to the change in tensile force to the next one, from 14,3 to 64,7 mm respectively.



» **Figure 15:** *Stresses of the samples at maximum and at break*

Development of the advertising model

Considering the results of measurements before and after calibration and the resistance measurements, an advertising object was created and modeled. It was important to take into account the purpose of the future product and to consider its design, so that the modeled and printed object was not only attractive, but also functional. After the analysis and search for creative solutions, it was decided to create a model of a small robot that would demonstrate the technical possibilities of resin printing and at the same time be useful to the consumer who purchased the product. For that purpose, five variants of the robot were modeled, one opf which is shown in Fig. 16.



» **Figure 16:** *A 3D model of the advertising and printed object*

Furthermore, the print orientation, having a high impact on mechanical properties, is discussed with a particular regard on the residual stress mitigation in future applications, such as 3D-printed cellular bodies.

To demonstrate the effect of calibration on the user, the robot's arms, hands, legs, head, and backpack were printed separately from the body, using different types of connectors and latches, but with preadjustment of detail parts at the joints.

The robot's functionality is manifested through the robot's hands and a modeled backpack. Its hands are sized to fit a standard pencil or thin pen with a diameter of about 7 millimeters. The backpack is designed to be large enough to hold up to 3 pencils or pens, or any other small items such as paper clips, paper clips or stapler pins.

Conclusions and recomendations

Conclusions

During this work, calibration objects were created in the Autodesk Fusion 360 programme and applied to the printing by rotating them at different angles of 0, 45 and 90 for the Chitubox programme. The original AmeraLabs TGM-7 acrylic resin was used to 3D print the models.

After the test printing of objects of different shapes, such defects as surface dripping, "blooming" defect, surface irregularities due to the selection of improperly selected supports, tearing of objects due to the absence of vent holes in hollowed parts in the object were observed. It was observed that filling the voids completely with material results in better product quality than trying to leave the voids unfilled with air gaps. This can make the product heavier, but with a small product it is worth sacrificing the amount of resin for the 3D printing for better final object quality.

After the initial visual quality assessment of the printed figures, measurements were made, and changes in shape were recorded. The real height of the cube-shaped figures decreased by an average of 110 µm. The width of the lower part was larger than the upper part by an average of 340 µm. Based on the results, the height of the objects was increased, and their width was reduced accordingly in the modeled samples.

The difference in the dimensions may be caused by the inaccuracies of the 3D printing equipment and material shrinkage. Some of such inaccuracies can be overcome by adjusting the printing parameters, orientation, and adjusting the design of the model. When the sample was rotated at 45 degrees, a slight expansion of the lower planes was also observed, resulting in the external dimensions of the model being adjusted accordingly. Printing at this angle produced the most accurate dimensions of objects.

After measuring the diameter of the holes, it was observed that the diameter of the holes when the cube-sample is in the vertical position is about 380 µm smaller in the vertical than in the horizontal position (a decrease of 110 µm), and when the printed cube is at an angle or when the hole is in the vertical position, the lower part of the hole diameter is obtained higher than the upper one due to polymer deposition, shrinking and relaxation phenomena.

Measurements of step-shaped samples showed that the overall coefficient of compensation parts can serve to bring the dimensions of the product closer to ideals. However, compensation for XY and YX planes should be done separately to have even greater accuracy in small details. The position of the model on the base and the evenness of the light flux hitting the model can also affect the parameters of the object.

After performing mechanical measurements of the sample's stretching, it was found that the acrylic resin used for the work had plastic properties after printing, and the samples printed at an angle of 90 degrees and polymerized with UV light had a higher resistance to dynamic load.

In the course of this work, applying the results obtained from the conducted research, an original advertising robot model with certain functionality was modeled, prepared for the 3D printing and printed.

Recommendations for 3D printing

Printing hollow objects without holes or with very small holes (< 2 mm) is not recommended, because it is very important to wash off the remaining resin to avoid harm to health, and closed figures do not allow this.

Before 3D printing, dimensional accuracy calibration should be performed and dimensional compensation should be applied in the slicer. If the hole is in a horizontal position, it is necessary to increase the diameter of the hole, especially in relation to the horizontal plane.

Avoid printing figures flat and raised on supports, as this requires significantly more supports than printing at an angle. Also, when printing at an angle, the dimensions of the resulting figures are more similar to the designed model.

When 3D printing samples are at an angle, it is important to place the proper supports so that the object can be printed and the polymer does not deform.

Every now and then, before printing, it is necessary to check the oil lubrication of the motor axis, as insufficient oil will cause vibrations and the object will be printed inaccurately.

If during printing there were figures that were not printed completely, or broke off and fell into the VAT (liquid container), it is recommended not to pour the resin back into the container it is held in, as debris may enter and spoil the remaining resin. It is recommended to use the printer's container clean function to collect loose debris, or use a funnel with a filter when pouring the resin back into its container to keep any debris out.

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