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3D PRINTING OF THE CROSS OF MALTA MECHANISM. CASE STUDY

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Rezumat: The manufacture of parts using 3D printing has spread to all areas of economic and social life, providing important support for technological education in secondary and higher education. Various principles of 3D printing are presented, along with the materials used by each 3D printing solution. For the FDM 3D printing process, the principle diagram, the stages of the process, and the parameters that need to be set to obtain the G-code program are presented. The paper also presents the principal diagram of a Maltese cross-type spherical mechanism characterized by the fact that the axes of the driving and driven elements are concurrent (and perpendicular). The mechanism was analyzed kinematically, revealing the variation in relative speed between the indexer and the driven element (hemisphere). The paper addresses additive manufacturing using the FDM 3D printing process on an assembly considered a case study, the Maltese cross.
Keywords: FEM, Maltese cross, additive manufacturing, 3D printing.

1. INTRODUCTION

3D printing technologies are enjoying increased popularity due to the relatively low cost required to start creating parts (affordable equipment and materials), the accessibility of information sources, and the versatility provided by resistance to external factors (no special operating environment required). For these reasons, 3D printing is applicable in various fields, such as:

In the medical industry: In medicine, 3D printing has a wide range of applications. From patient-specific implants to complex surgical planning models, 3D printing in healthcare has improved accuracy, reduced costs, and shortened patient recovery times.

Customized dental implants. Using data from computer-aided design (CAD) models and CT scans, 3D printers produce implants that offer a proper, customized fit, improving patient comfort and prosthesis functionality [12].

Limb prostheses. The possibility of creating customized prostheses (using procedures similar to those used for dental implants) for each patient to ensure optimal functionality and aesthetic acceptability [3,17].

Surgical planning and testing models. Surgeons can use this technology by working with research teams to create exact replicas of a patient's organ or body parts for better preoperative strategies. The result is surgical procedures with a higher degree of precision, safety, and efficiency [1,18,19].

Drug delivery devices. Designed to deliver precise doses, these devices, made using 3D printing techniques, facilitate the use of treatments tailored to the specific needs of the patient [16].

Food industry: In the food industry, 3D printing is mainly used to create customized products. For example: making customized three-dimensional objects out of chocolate for cakes.

A wide variety of foods are suitable for this purpose: chocolate, candy, and flat foods such as cookies, pasta, and pizza.

NASA is exploring this technology to create 3D-printed food in order to reduce waste and to create diets that meet the nutritional needs of astronauts.

In 2018, Italian bioengineer Giuseppe Scionti developed a technology that allows the creation of plant-based fibers that mimic the texture and nutritional values of meat using a customized 3D bioprinter [21].

Transportation industry: For cars, trucks, and airplanes, 3D printing has enabled changes in the concept of design, production, and maintenance. Urbee is recognized as the first car whose body was 3D printed. While other vehicles have incorporated 3D-printed parts, Urbee used this technology in the manufacturing process for the entire outer shell. This innovative approach allows for complex geometries, fewer parts, and potentially lighter vehicles [9].

Aerospace industry. The aerospace industry has used 3D printing to produce lightweight and robust components. The main reason for reducing the weight of components is to decrease the amount of fuel required by the aircraft, but also to improve maneuverability in reaching its destination, resulting in lower costs over its lifetime [10].

Automotive industry. In the automotive sector, 3D printing is completely transforming product development. From conceptual design to spare parts manufacturing and maintenance, both automotive companies and their users are taking advantage of this technology.

With the help of 3D printing technologies such as selective laser sintering (SLS) and fused deposition modeling (FDM), manufacturers can test and refine new automotive concepts in a short period of time. This acceleration in the prototyping and product approval phase leads to faster innovation and reduces the time to market [11].

Education: 3D printing couldn't help but make its way into education. 3D printing is generally used to intuitively create objects that stimulate students' creativity. During the pandemic, this technology was also used to produce protective equipment (masks). In specific cases, 3D printing is used to produce bone and organ models that help pupils and students study and understand anatomy without the need for cadaver dissection.

With the help of 3D printing, creative ideas can take concrete form, allowing students to learn practical design skills (sketching, designing, prototyping) [2].

The arms and ammunition industry: In 2012, the American group Defense Distributed announced plans to design a 3D-printed plastic firearm. The blueprints could be downloaded and reproduced by anyone with a 3D printer. After Defense Distributed revealed these plans, questions arose about the effects that consumer-level 3D printing and CNC machining would have, with negative consequences for the effectiveness of arms and ammunition control [25].

Hobby: Starting in 2005, magazines began publishing articles about the possible artistic applications of 3D printing technology. Commercially available 3D printers were increasingly capable of being used for practical household applications, such as decorative objects. Spurred by falling prices and rising quality, it is estimated that 2 million people worldwide have purchased a 3D printer for hobby use since 2019 [4].

3D printing technologies can be classified according to the following criteria:

According to the method of processing the material used:

-The base material consists of liquid polymers, which are solidified upon contact with light from a laser source.

-The base material undergoes melting, deposition, and solidification processes. These processes allow the use of both metals and plastics.

By the method used to obtain the shape:

-The part is obtained directly in 3D. This process has the disadvantage of increased difficulty in programming and controlling the processing systems.

-The part is built gradually from 2D sections. The CAD model is sectioned horizontally into a large number of parts spaced at tenths of a millimeter.

ISO/ASTM52900-15 defines seven categories of additive manufacturing (AM) processes [27].

These are: Tank photopolymerization (stereolithography); Material spraying; Binder spraying; Powder bed fusion; Material extrusion; Direct energy deposition; Laminating.

The main differences between the processes lie in how the layers are deposited to generate parts and in the materials used.

Each method has advantages and disadvantages, which is why some companies offer a range of powders and polymers as materials for building parts. Others sometimes use standard paper as a material to produce a durable prototype.

The main considerations when choosing a machine are generally speed, the cost of the 3D printer, the cost of the printed prototype, the choice and cost of materials, and color capabilities. Printers that work directly with metals are generally expensive. However, less expensive printers can be used to make a mold, which is then used to design metal parts.

Materials used in FDM 3D printing

Plastic is the most common material for FDM 3D printing. Various polymers can also be used, including acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polylactic acid (PLA), high-density polyethylene (HDPE), PC/ABS, polyethylene terephthalate (PETG), polyphenylsulfone (PPSU), and high-impact polystyrene (HIPS). The polymer is in the form of filament. In addition, fluoropolymers, such as PTFE tubes, are used in the process due to the material's ability to withstand high temperatures. This ability is particularly useful in filament transfer. Recently, carbon fiber reinforced filaments have begun to be used, as well as solutions for producing composite parts using FDM 3D printing.

Different variants of FDM allow the use of a variety of materials. These can be (Table 1) [24]: thermoplastic polymers—the most commonly used in FDM; composite materials with polymer matrix and resistant fibers; slurries and clays - used especially with casting technology; ecological mixtures of ceramic or metallic powders and polymeric binders; food pastes; biological pastes, used in bioprinting.

Table 1. Materials that can be used for 3D printing - FDM [24]

Material class	Examples	Post-processing requirements	Aplications
Thermoplastic polymers	PLA= polylactic acid, also known as poly(lactic acid) or polylactide, PETG=polyethylene terephthalate, ABS= acrylonitrile butadiene styrene, ASA= acrylonitrile styrene acrylate, HDPE= high-density polyethylene, PPSF= poli fenil sulfona, PC= polycarbonate, Ultem 9085= polyether imides, PEEK= polyether ketones, recycled plastics	removal of supports	General purpose. These materials have different physical properties, such as heat resistance, UV resistance, storage requirements, ease of printing, cost, and chemical tolerance. They are available in a variety of formulations to suit specific applications (such as ESD material blends or the addition of flame retardants).
Composite materials with polymer matrix	GFRP= glass fiber reinforced plastic, CFRP= carbon fiber reinforced polymers	removal of supports	Structural applications
Sludge and clay	Alumina= aluminum oxide, Zirconia= zirconium dioxide, Kaolin	-removal of the support, -oven drying and sintering	Insulation, applications in dentistry and dental technology, handicrafts
Environmentally friendly mixtures of ceramic powders/ binders	Zirconia= Zirconium dioxide, Calcium phosphate		structural ceramics, piezoelectric components
Environmentally friendly mixtures of metal powders/ binders	Stainless steel, Titanium alloys, Inconel = superalloy based on nickel and chromium	removal of the support, sintering	Tools, accessories, mechanical parts
Environmentally friendly mixtures of ceramic or metallic powders and binders	Stainless steel, iron, Tricalcium phosphate, Yttrium-stabilized zirconia	removal of the support, sintering	Mechanical parts, implants
Pasta	Chocolate, sugar	removal of supports	
Biological materials	Organic ink		bioprinted organs and bioprinted scaffolds to support bone tissue growth
Conductive polymer composite materials	Composites with carbon black,	annealing for lower conductivity	sensors

	graphene, carbon nanotubes, or copper nanoparticles		
Ceramic material derived from polymers	PLA= polylactic acid, PC= polycarbonate, nylon alloys, PP = polypropylene, PETG= polyethylene terephthalate glycol, PET= polyethylene terephthalate and copolyesters, flexible materials (including: flexible PLA, thermoplastic elastomer, and thermoplastic polyurethane filaments)	To make SiOC(N) first, the printed polymer is dipped in PDC, absorbed, then sintered.	heat exchangers, radiators, scaffolds for bone tissue growth, chemical/gas filters, custom scientific equipment

3D printing excels due to increased design flexibility, cost-effective production of complex geometries, and rapid prototyping.

The limitations are determined by the materials used, their properties, potential structural weaknesses, and dimensional constraints [26].

Advantages of 3D printing:

-Allows the design of complex parts.
-Allows prototypes to be produced in a short time.
-On-demand production of parts reduces the need for storage space.
-Allows the production of strong, lightweight parts that are important in the automotive and aerospace industries.
-Rapid design and production—parts can be produced quickly depending on their complexity.
-Reduced waste—only the material needed to make the part is used.
-Increased cost efficiency—time is saved by reducing the manufacturing process to a single step.
-Accessibility—thanks to the emergence of service providers for this purpose.
-Environmentally friendly—reduces material waste and lowers fuel consumption due to the low weight of the parts.

Disadvantages of 3D printing:

-Limited use of material types.
-Construction dimensions are limited by the space in the printing chambers, with large parts requiring subsequent joining.
-After printing, most parts require additional mechanical operations (post-processing) such as cleaning, deburring, and, if necessary, removing supports.
-The unit cost is not reduced for mass production.
-Part structure—during the production process, layers may delaminate due to stresses caused by thermal shrinkage.
-Inaccuracies in execution—some 3D printers have low tolerances, thus requiring additional mechanical operations to meet the specifications in the working drawings. Also, the parts are subject to thermal contraction, resulting in differences between the dimensions in the CAD drawing and those of the part obtained after the 3D printing process.
-Copyright circumvention – increased accessibility to this technology carries the risk of counterfeit products spreading.

2. MATERIALS AND METHODS

The 3D printer (Figure 1) creates parts by depositing thermoplastic material, in the form of melted filament, layer by layer, on a build table. The materials used in this process include ABS, PLA, PETG, PEI, and other polymers, which are supplied in the form of filament wound on spools. The filament is pushed by a feed mechanism into a heated extruder where it is melted. From there, the molten material passes through a calibrated nozzle and is deposited along a trajectory programmed by the G-code program. The printer continuously moves the extruder assembly, depositing the molten material in a specific layer. After finishing the deposition in that layer, the layer is incremented (moving on to the next layer) by vertically moving either the work table (usually) or the extruder head, depending on the configuration of the 3D printing equipment. The parts are built by depositing layer upon layer of material [10, 14].

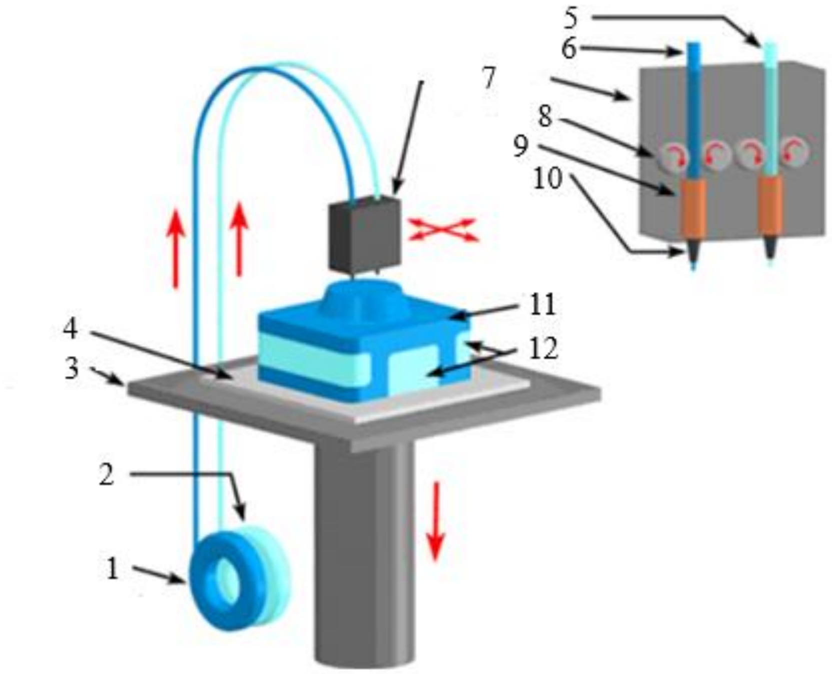


Fig. 1. Schematic diagram of an FDM 3D printer [14]: 1-printing part material roll; 2-roll support material; 3-printing platform; 4-foam base; 5-support filament; 6-filament for part; 7-extrusion head; 8-drive wheels; 9-liquefier; 10-extrusion nozzle; 11-printed part; 12-support printed part

2.1. Steps for creating a part using FDM 3D printing

The following steps are required to create a part using 3D printing:
-create a solid model of the part in a CAD application (SolidWorks, SolidEdge, Creo CAD, etc.), check it, and save it in STL format;
-using a specialized application for the respective printer that allows obtaining the G-code program necessary for 3D printing, in which the following steps will be followed:
-importing the 3D model into the application;
-establishing the most suitable position on the printer's work table by rotating and translating; the position will be chosen to minimize the number of supports needed to hold the deposited material, maximize the construction base of the part, and reduce material consumption and printing time;
-choosing the printing material, installing the roll of printing material, and choosing the diameter of the printing nozzle;
-setting the printing parameters in the application (see the next subchapter);
-the slicing operation, which obtains the material deposition surfaces (on the printing elements: shell, infill – with the pattern and infill degree –, support, etc.) in each layer;
-checking the printing mode of the G-code program and, if errors are detected, redefining the printing parameters;
-generating the G-code program and transmitting it to the 3D printer (via USB stick, USB cable, Wi-Fi, etc.);
-3D printing of the part;
-post-3D printing operations: removing the part from the work table, removing supports, cleaning burrs, corrections, etc.

2.2. Technological parameters of FDM 3D printing

To obtain the G-code file, starting from the STL format file of the part to be printed, using a specialized program that performs the slicing process, it is necessary to provide it with a series of parameters, including: the diameter of the filament used; nozzle diameter; layer height; number of layers of the inner and outer contours of the part;

infill density; infill pattern; printing speeds of different parts of the part: layers, infill, platform, support, etc.; extruder temperature; printing table temperature, etc.;

These parameters are also determined by the characteristics of the printer used (its capabilities). As a rule, the nozzle diameter is 0.4 mm, the thickness of the deposited layer is between 0.08-0.4 mm, the table temperature is 50-60°C, and the extruder temperature depends on the printing material used. The manufacturer of the printing material provides the recommended range of extruder and printing table temperatures.

2.3. Schematic diagram of the Maltese cross spherical mechanism

The Maltese cross mechanism, also known as the Geneva mechanism [1], is designed to convert continuous rotary motion into intermittent motion. It is used to achieve indexed rotations. Figure 2 shows such a mechanism [1].

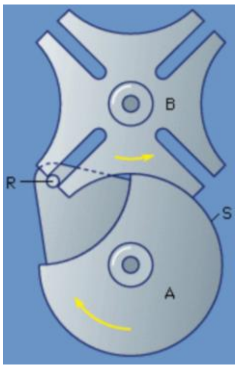


Fig. 2. Maltese cross mechanism [1]

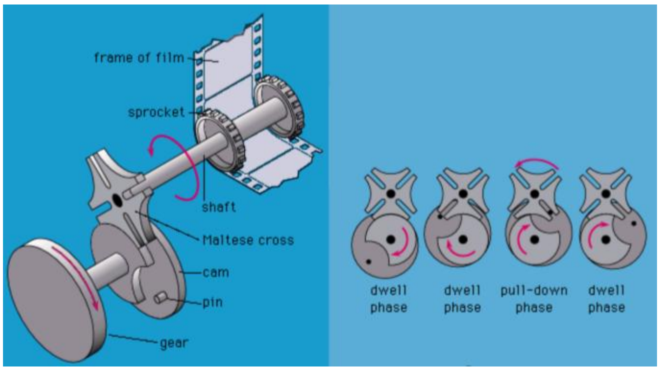


Fig. 3. The use of the Maltese cross mechanism in the film industry [1]

Wheel A, equipped with indexer R, performs continuous rotation and is the driving wheel. During the rotation of wheel A, indexer R enters one of the n channels of wheel B, which is thus driven into rotational motion. At a certain point, after wheel A has rotated through an angle of 360°/n, the indexer exits the channel so that wheel B comes to a standstill. Wheel A continues to rotate, bringing indexer R into the next channel of wheel B, which is thus driven into rotational motion again. In this way, after wheel A has made n rotations, wheel B makes a single rotation. If T is the period of a complete rotation of wheel B, it actually rotates only T/n and remains stationary the rest of the time, making n stops. The surface S of wheel A blocks the rotation of wheel B as long as it is not driven by indexer R, ensuring that indexer R enters the next channel.

Initially, the mechanism was used in the film industry, fig. 3, [1].

There are several design variants: flat Maltese cross mechanism with external contact (Fig. 2); flat Maltese cross mechanism with internal contact (Fig. 4) [2]; spherical Maltese cross mechanism, in which the wheel axes are concurrent (Fig. 5) [3].

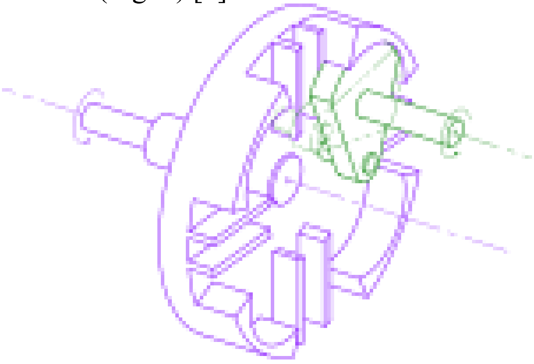


Fig. 4. Flat Maltese cross mechanism with internal contact [2]

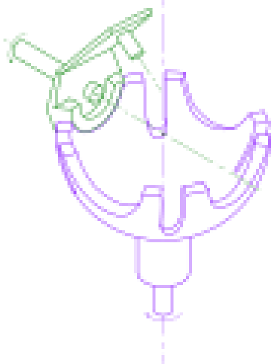


Fig. 5. Maltese cross spherical mechanism [3]

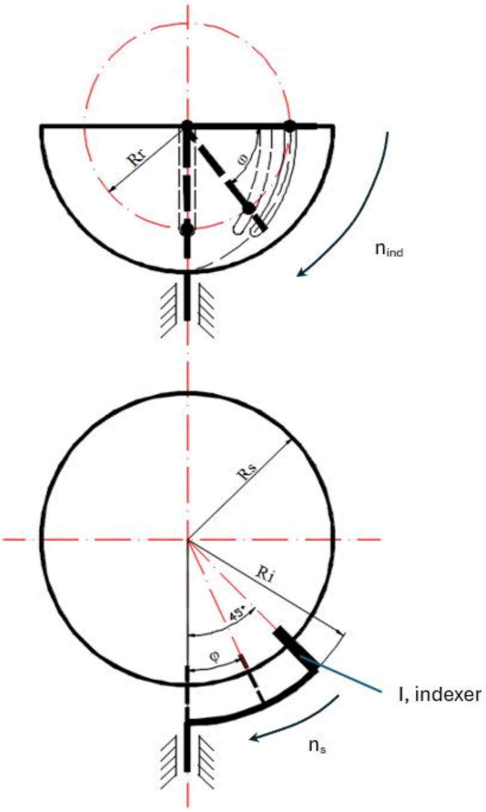


Fig. 6. Schematic diagram of the Maltese cross spherical mechanism

The hemisphere with radius Rs has n channels (4 channels in the case shown in Figure 6). An indexer, I, which rotates around an axis concurrent (and perpendicular) to the axis of rotation of the hemisphere, enters one of these channels and drives the sphere into rotational motion.

In the case where the hemisphere has 4 channels (arranged at 90° on the outer circumference of the hemisphere), we will consider that the indexer enters the channel at an angle of 45° to the axis of rotation of the indexer – fig. 3.5 – in the plane of rotation of the hemisphere. In the plane of rotation of the indexer, at the moment of entering the channel, we consider the angle to be 0° and it will exit the channel at an angle of 180°. For the rest of the rotation (between 180° and 360°), the indexer does not come into contact with the hemisphere, which remains stationary.

The indexer support has radius Ri, and the indexer rotation radius (in the rotation plane) is Rr.

We denote by ω the angle at which the indexer is at a given moment, around its axis of rotation. The indexer will drive the hemisphere when ω is in the range [0°,180°].

We denote by φ the angle between the indexer and its axis of rotation in the plane of rotation of the hemisphere. In the case of the 4-channel hemisphere, the angle φ has values in the range [-45°, +45°].

2.4. Presentation of the Maltese Cross spherical mechanism

Figure 7 shows the composition of the Maltese Cross spherical mechanism.

The driven sphere, 5, is positioned on the base plate, 1, by means of the sphere support, 2, through the sphere shaft, 21, which rotates by means of rolling bearings made of radial ball bearings, 4.

The sphere is driven into intermittent rotational motion by the indexing arm, 10, positioned on the base plate, 1, by means of the indexing support, 3. The indexing arm is rotated by the indexing shaft, 11, which rotates on the rolling bearings made of 2 radial ball bearings, 4. The indexing shaft is rotated manually by the handle, 23, with the crank, 14.

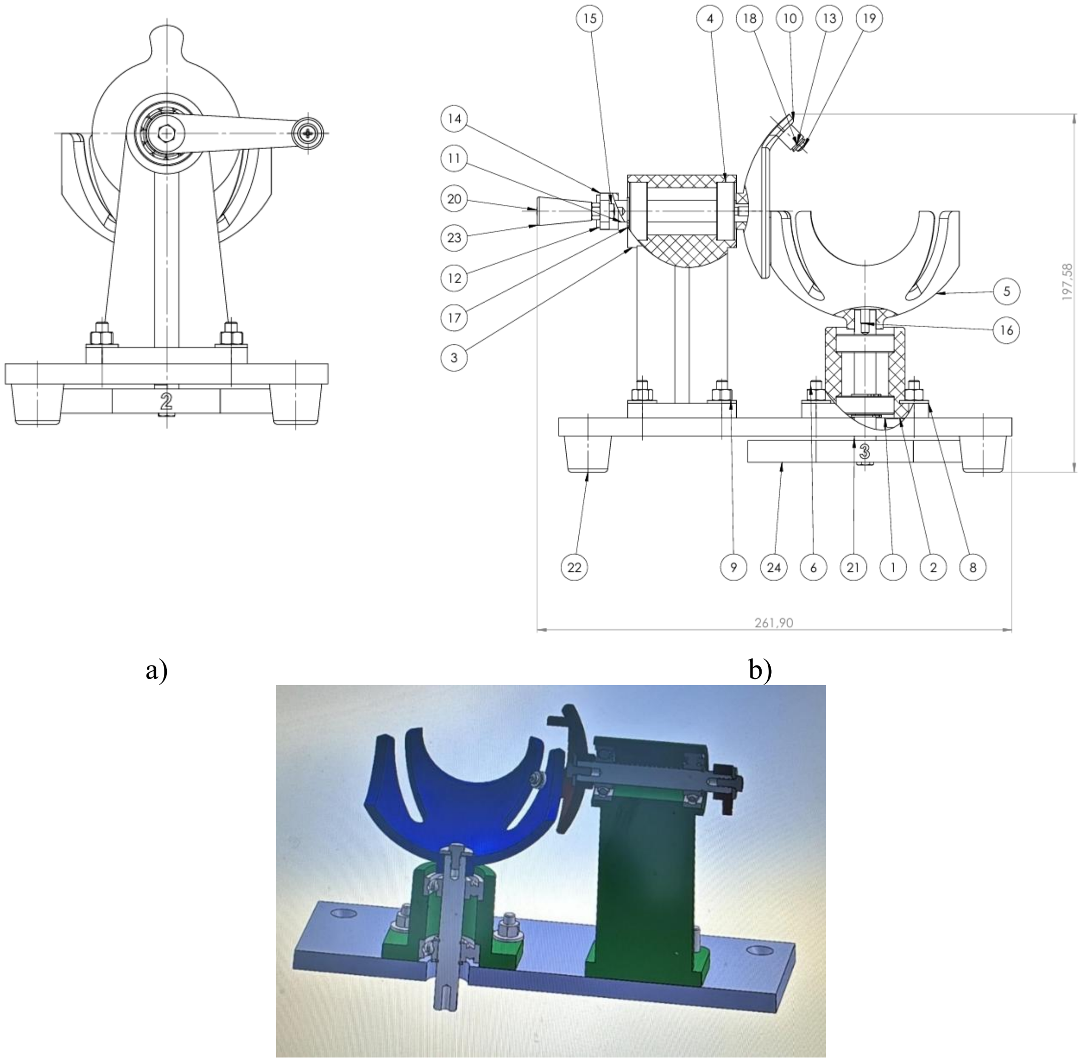
The indexing indicator, 24, located under the base plate, driven by the sphere shaft, 21, allows the 4 indexing positions of the sphere to be viewed.

The base plate is supported by 4 support legs, 22, which also serve to distance the indexing indicator from the mechanism's mounting surface.

Seeger rings, 17, are used to position the bearings on the shafts. Removable assemblies with screws, washers, and nuts (6, 7, 8, 9, 12, 15, 16, 18, 19, 20) were used to secure the mechanism components.

Since the indexer is made of plastic (PLA) that comes into contact with the channel of the driven sphere, also made of plastic (PLA), a steel indexer bushing, 13, was used to ensure a better friction coefficient.

All the mechanism's parts, except for the standardised ones, were designed in the SolidWorks CAD program, which then allowed the model to be generated in STL format for 3D printing of the parts.



a) b)

c)

Fig. 7. Maltese cross spherical mechanism: a) general view; b) mechanism detail; c) 3D view of mechanism

2. RESULTS AND DISCUSSIONS

Two types of printers were used for 3D printing the parts designed in subsection 4: the Raise 3D Pro2 Plus printer and the Bambu Lab X1-Carbon printer.

Two printers were used to reduce the time needed to produce all the parts of the Maltese cross spherical mechanism.

The Raise 3D Pro2 Plus printer has two extruder heads, while the Bambu Lab X1-Carbon printer has a single print head.

Table 2 shows the main features of the Raise 3D Pro2 Plus printer, and the technical specifications of the BAMBU LAB X1 Carbon COMBO printer are presented in Table 3.

Table 2. Key features of the Raise 3D Pro2 Plus printer

Technical specifications	
Print dimensions	305x305x605 / 280x305x605 (mm)
Filament diameter	1,75 (mm)
Extruders	2 (buc)
Nozzle diameter	0,2/0,4/0,6/0,8(mm)
Layer thickness	(0,01-0,25)mm
Print speed	(30-150)mm/s
Printing temperature	maximum 300(°C)
Print bed heating	maximum 110(°C)

Compatible materials	PLA, ABS, HIPS, PC, TPU, TPE, NYLON, PETG, ASA, PP, composites (reinforced with: glass fiber, carbon fiber; metal particles; wood)
Monitoring	Live camera (real time)
Connectivity	WiFi, Ethernet
File format	GCODE, STL, OBJ, 3MF
Software	IdeaMaker

BAMBU LAB X1 Carbon COMBO is a 3D printer with Fused Deposition Modeling (FDM) technology and CoreXY mechanism. The printer has a print volume of 250 x 250 x 250 mm and a direct feed system. It is equipped with a single 0.4 mm nozzle and can reach a maximum extruder head temperature of 300 °C and 110 °C for the work table. The printing table is made of steel, and the frame is made of plastic and aluminum.

It is capable of printing with 1.75 mm filaments and can use filaments made of common plastics (PLA, ABS, PETG, flexible) or high-quality materials (PC, PA, PEEK, ASA, polymer-reinforced carbon fiber). The recommended software is Bambu Studio or Cura.

The Bambu Studio program was used in this article.

Table 3. Technical specifications of the BAMBU LAB X1 Carbon COMBO printer

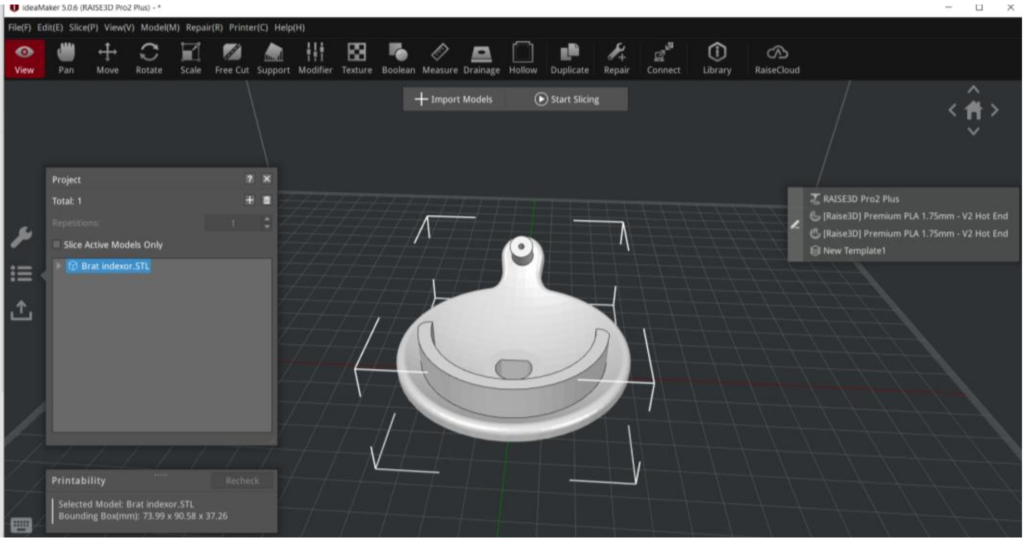
Feature	Details
Usable wire diameter	1.75 mm
Maximum nozzle temperature	300 ºC
Wire feeding system	Da
Maximum print speed	500 mm/s
Construction volume	256 mm x 256 mm x 256 mm
Maximum temperature of the construction table	110 ºC
Construction table material	Oțel flexibil
Construction table leveling system	Automat
Maximum energy consumption	1000 W
Voltage	AC: 100 V240 V (50-60 Hz)
Total weight	14.13 kg

5.2. Programs used for printers

The programs used to create the G-codes were: ideaMaker version 5.0.6 for the Raise 3D Pro2 Plus printer (Fig. 8) and Bambu Sudio version 2.1.1.52 for the BAMBU LAB X1 Carbon COMBO printer (Fig. 9).

The following parts were made on the Bambu Studio printer: the driven hemisphere, hemisphere support, and indexer support; the following parts were made on the Raise 3D Pro2 Plus printer: the indexer arm, crank, handle, indexing indicator, and the four support legs.

Fig. 10 shows the assembly mechanism parts (without the assembly elements).

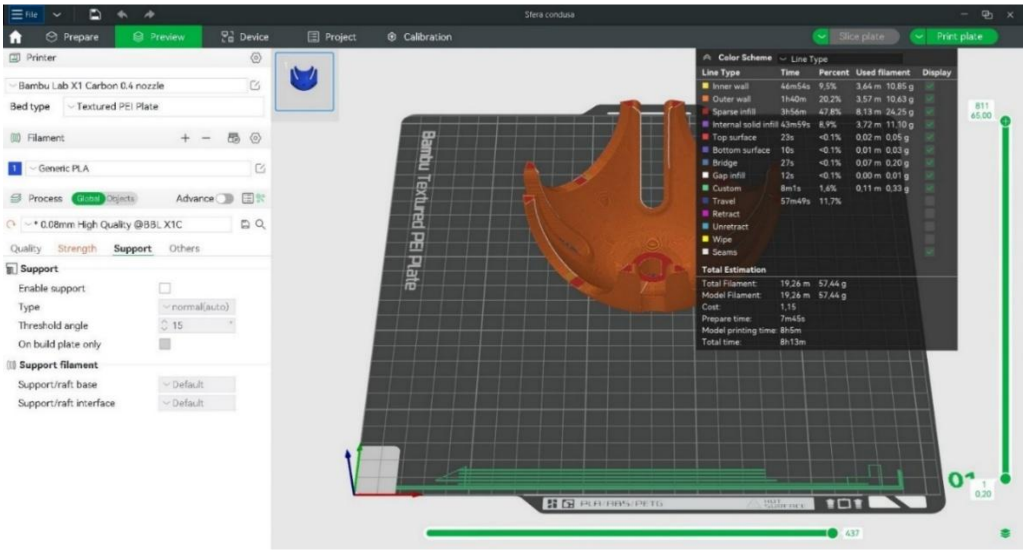


Total: 1
Repetitions: 1
☐ Slice Active Models Only
Brat indexor.STL

RAISE3D Pro2 Plus
[Raise3D] Premium PLA 1.75mm - V2 Hot End
[Raise3D] Premium PLA 1.75mm - V2 Hot End
New Template1

Selected Model: Brat indexor.STL
Bounding Box(mm): 73.99 x 90.58 x 37.26

Fig. 8. The ideaMaker program window



Printer: Bambu Lab X1 Carbon 0.4 nozzle
Bed type: Textured PEI Plate
Filament: 1 Generic PLA
Process: Global
* 0.08mm High Quality @BBL X1C
Quality | Strength | Support | Others

Support
Enable support ☐
Type: normal(auto)
Threshold angle: 15
On build plate only ☐

Support filament
Support/raft base: Default
Support/raft interface: Default

Color Scheme: Line Type

Line Type	Time	Percent	Used filament		Display
🟨 Inner wall	46m54s	9,5%	3,64 m	10,85 g	✓
🟧 Outer wall	1h40m	20,2%	3,57 m	10,63 g	✓
🟥 Sparse infill	3h56m	47,8%	8,13 m	24,25 g	✓
🟪 Internal solid infill	43m59s	8,9%	3,72 m	11,10 g	✓
🟥 Top surface	23s	<0.1%	0,02 m	0,05 g	✓
🟪 Bottom surface	10s	<0.1%	0,01 m	0,03 g	✓
🟦 Bridge	27s	<0.1%	0,07 m	0,20 g	✓
⬜ Gap infill	12s	<0.1%	0,00 m	0,01 g	✓
🟩 Custom	8m1s	1,6%	0,11 m	0,33 g	✓
🟦 Travel	57m49s	11,7%			☐
🟪 Retract					☐
🟦 Unretract					☐
🟨 Wipe					☐
⬜ Seams					✓

Total Estimation

Total Filament:	19,26 m	57,44 g
Model Filament:	19,26 m	57,44 g
Cost:	1,15	
Prepare time:	7m45s	
Model printing time:	8h5m	
Total time:	8h13m	

Fig. 9. The Bambu Studio program window

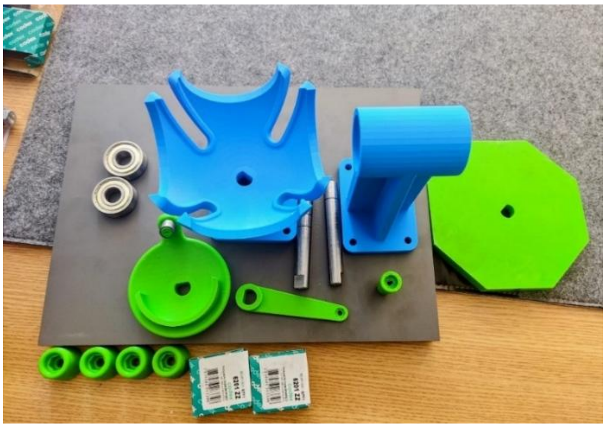


Fig. 10. Mechanism landmarks before assembly

5.3. Choosing the material for 3D printing

For 3D printing of parts using the Raise 3D Pro2 Plus printer, a green PLA HD filament with a diameter of 1.75 mm manufactured by Fiberlogy (Poland) was chosen. The manufacturer recommends that the extruder temperature be between 200-230°C and the print bed temperature between 50-60°C.

For printing, the extruder temperature was set to 215°C and the print bed temperature to 60°C – fig. 11.

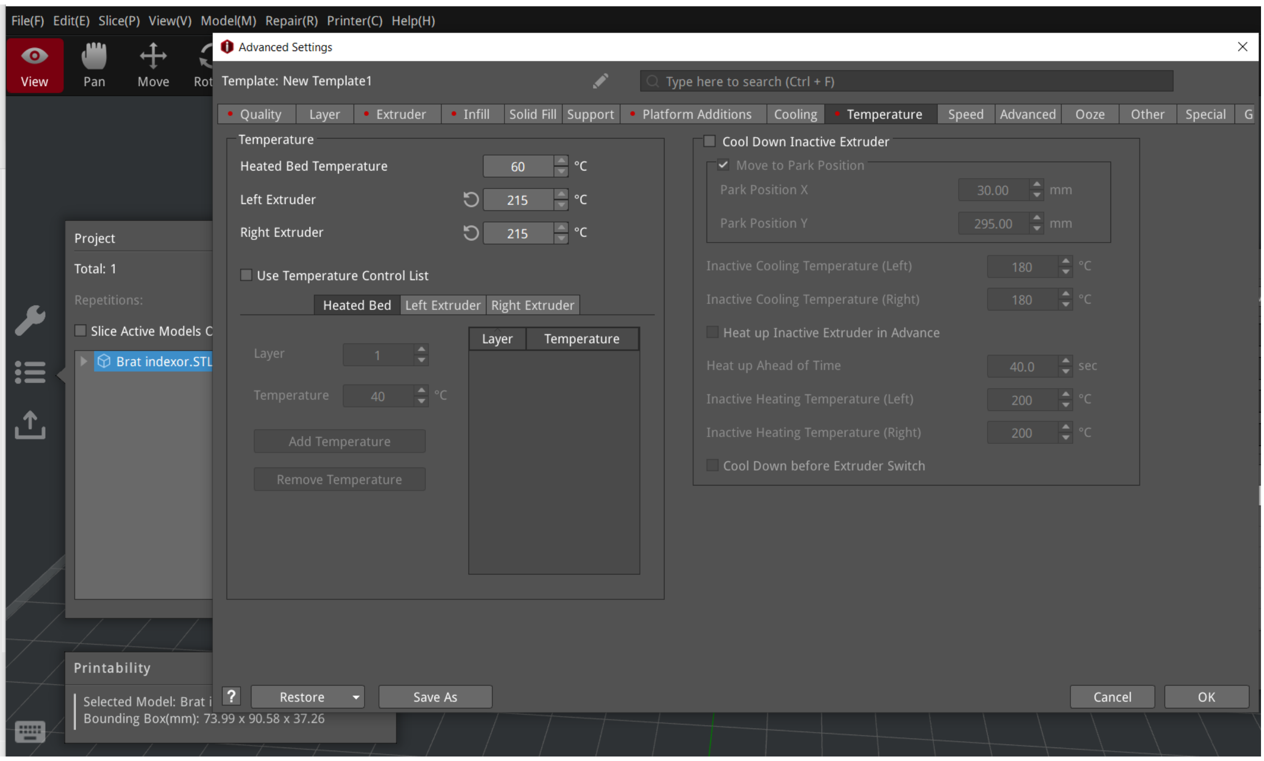
The print layer height was the same for all parts: 0.1 mm.

For 3D printing of the parts on the Bambu Lab printer, a blue PLA Basic filament produced by Bambu Lab with a diameter of 1.75 mm was used. The manufacturer recommends that the extruder temperature be between 190-220°C and the printing bed temperature be between 50-60°C.

For printing, an extruder temperature of 220°C and a printing table temperature of 55°C were used – fig. 12.

The height of the printing layer was the same for all parts: 0.08 mm.

The height of the print layer greatly influences the time required to produce the part (the lower the height, the longer the production time), but it also influences the fineness (accuracy) of the part. A low height was chosen for superior quality.



Template: New Template1

Temperature

Heated Bed Temperature 60 °C

Left Extruder 215 °C

Right Extruder 215 °C

☐ Use Temperature Control List

Heated Bed | Left Extruder | Right Extruder

Layer 1

Temperature 40 °C

Layer	Temperature

☐ Cool Down Inactive Extruder

☑ Move to Park Position

Park Position X 30.00 mm

Park Position Y 295.00 mm

Inactive Cooling Temperature (Left) 180 °C

Inactive Cooling Temperature (Right) 180 °C

☐ Heat up Inactive Extruder in Advance

Heat up Ahead of Time 40.0 sec

Inactive Heating Temperature (Left) 200 °C

Inactive Heating Temperature (Right) 200 °C

☐ Cool Down before Extruder Switch

Project

Total: 1

Repetitions:

☐ Slice Active Models C

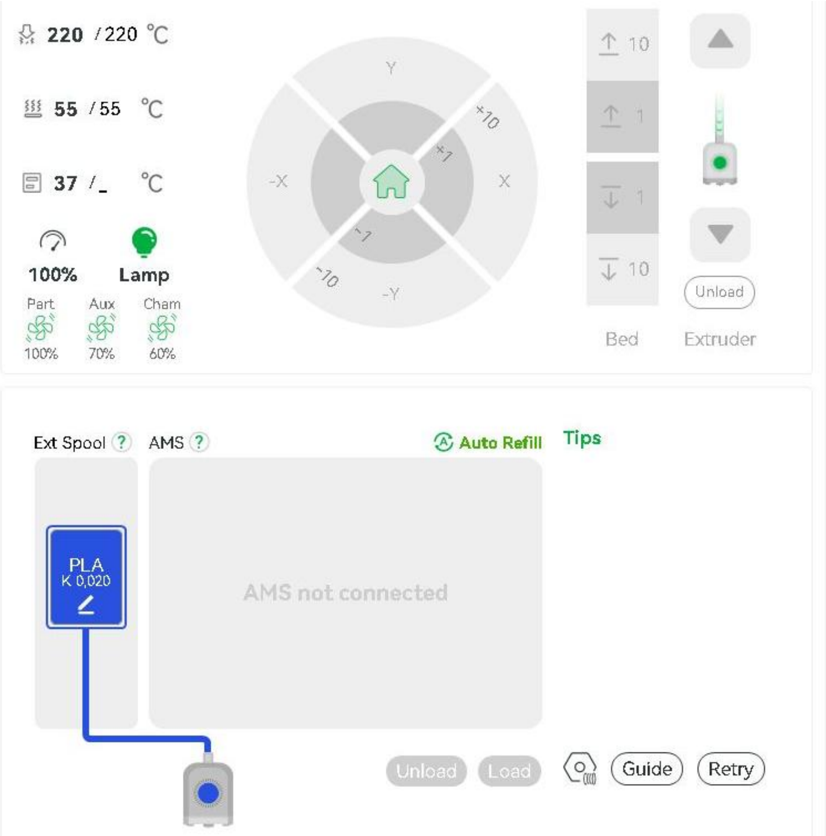
Brat indexor.STL

Printability

Selected Model: Brat i

Bounding Box(mm): 73.99 x 90.58 x 37.26

Fig. 11. Setting the extruder and print bed temperatures for the Raise 3D Pro2 Plus printer



220 / 220 °C

55 / 55 °C

37 / _ °C

100%

Part 100%

Aux 70%

Cham 60%

PLA

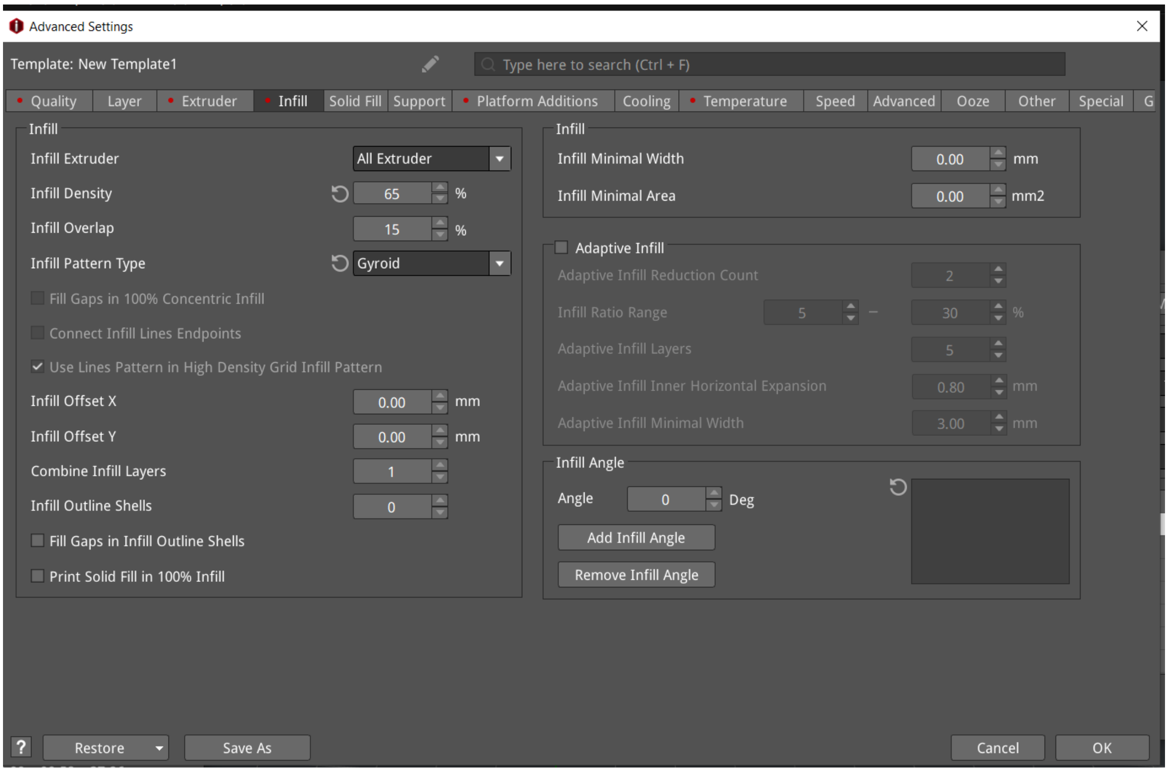
K 0,020

Fig. 12. Setting the extruder and print bed temperatures for the Bambu Lab printer

5.4. Choosing the infill pattern

Choosing an infill pattern is important because it ensures the rigidity of the part at a low infill level.

For all parts printed on the two printers, the Gyroid infill pattern was chosen, which ensures good rigidity, even if the printing time was longer – Figures 13 and 14.



Template: New Template1

Infill

Infill Extruder: All Extruder
Infill Density: 65 %
Infill Overlap: 15 %
Infill Pattern Type: Gyroid
☐ Fill Gaps in 100% Concentric Infill
☐ Connect Infill Lines Endpoints
☑ Use Lines Pattern in High Density Grid Infill Pattern
Infill Offset X: 0.00 mm
Infill Offset Y: 0.00 mm
Combine Infill Layers: 1
Infill Outline Shells: 0
☐ Fill Gaps in Infill Outline Shells
☐ Print Solid Fill in 100% Infill

Infill

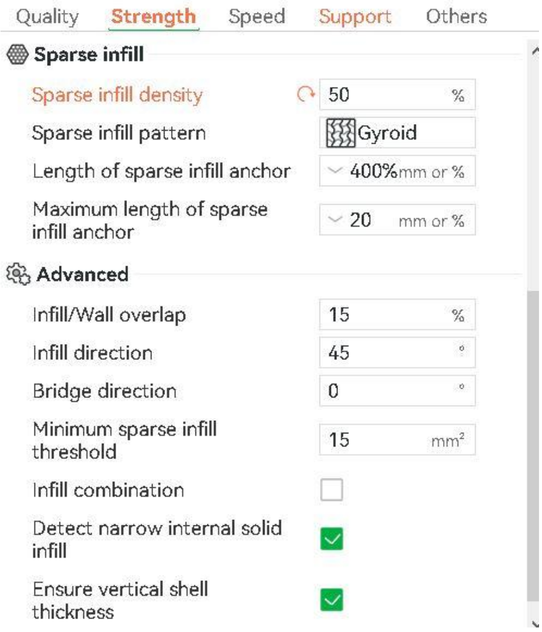
Infill Minimal Width: 0.00 mm
Infill Minimal Area: 0.00 mm2

☐ Adaptive Infill
Adaptive Infill Reduction Count: 2
Infill Ratio Range: 5 – 30 %
Adaptive Infill Layers: 5
Adaptive Infill Inner Horizontal Expansion: 0.80 mm
Adaptive Infill Minimal Width: 3.00 mm

Infill Angle

Angle: 0 Deg

Fig. 13. Selecting the Gyroid model in the ideaMaker program



Sparse infill

Sparse infill density: 50 %
Sparse infill pattern: Gyroid
Length of sparse infill anchor: 400% mm or %
Maximum length of sparse infill anchor: 20 mm or %

Advanced

Infill/Wall overlap: 15 %
Infill direction: 45 °
Bridge direction: 0 °
Minimum sparse infill threshold: 15 mm²
Infill combination: ☐
Detect narrow internal solid infill: ☑
Ensure vertical shell thickness: ☑

Fig. 14. Selecting the Gyroid model in Bambu Studio

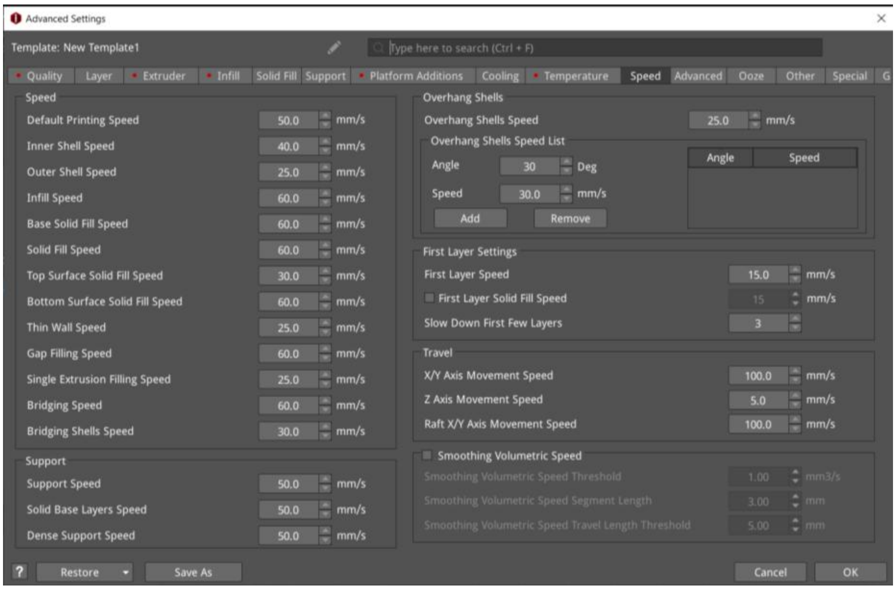
The degree of filling was chosen differently depending on the role played by each benchmark within the mechanism (the stresses to which it could be subjected).

5.5. Choosing print speeds

Print speeds play an important role in ensuring good quality 3D printed parts, preventing printing defects, and even avoiding print failures (layers separating from each other or the part separating from the print bed, etc.). Programs that allow G-code creation have preset print speeds for each type of print element within the part: support, platform, outer shell, inner shell, and infill. The speed depends on the type of printer and is recommended by the manufacturer.

Printing speeds greatly influence the time it takes to produce the parts.

For the Raise 3D Pro2 Plus printer, the speeds used are shown in Figure 15.



Template: New Template1

Speed
Default Printing Speed 50.0 mm/s
Inner Shell Speed 40.0 mm/s
Outer Shell Speed 25.0 mm/s
Infill Speed 60.0 mm/s
Base Solid Fill Speed 60.0 mm/s
Solid Fill Speed 60.0 mm/s
Top Surface Solid Fill Speed 30.0 mm/s
Bottom Surface Solid Fill Speed 60.0 mm/s
Thin Wall Speed 25.0 mm/s
Gap Filling Speed 60.0 mm/s
Single Extrusion Filling Speed 25.0 mm/s
Bridging Speed 60.0 mm/s
Bridging Shells Speed 30.0 mm/s

Support
Support Speed 50.0 mm/s
Solid Base Layers Speed 50.0 mm/s
Dense Support Speed 50.0 mm/s

Overhang Shells
Overhang Shells Speed 25.0 mm/s
Overhang Shells Speed List
Angle 30 Deg
Speed 30.0 mm/s

Angle	Speed

First Layer Settings
First Layer Speed 15.0 mm/s
☐ First Layer Solid Fill Speed 15 mm/s
Slow Down First Few Layers 3

Travel
X/Y Axis Movement Speed 100.0 mm/s
Z Axis Movement Speed 5.0 mm/s
Raft X/Y Axis Movement Speed 100.0 mm/s

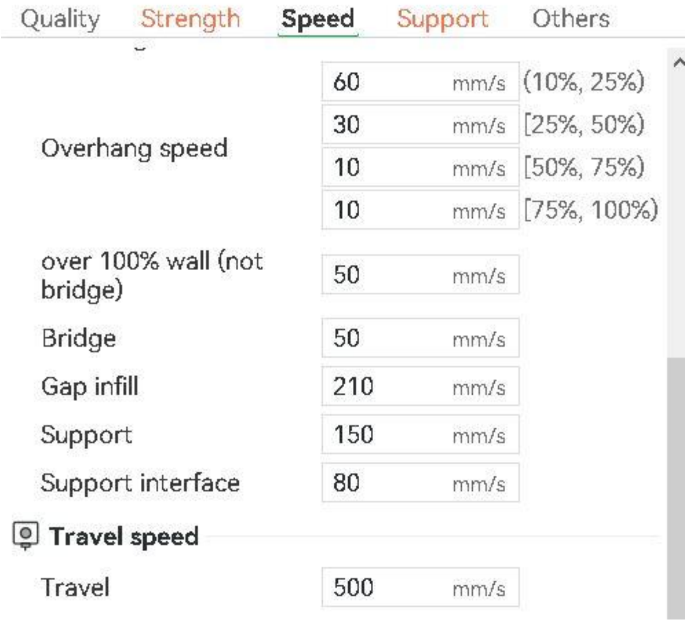
☐ Smoothing Volumetric Speed
Smoothing Volumetric Speed Threshold 1.00 mm3/s
Smoothing Volumetric Speed Segment Length 3.00 mm
Smoothing Volumetric Speed Travel Length Threshold 5.00 mm

Fig. 15. Setting print speeds for the Raise 3D Pro2 Plus printer

In the case of the Bambu Lab printer, the set printing speeds are shown in Figure 16.

A higher printing speed (60 mm/s – in general) is observed for the Bambu Lab printer compared to the Raise 3D Pro2 Plus printer (50 mm/s – in general), which can be explained by the higher mass of the print head movement system (two print heads move simultaneously).

The other printing parameters specific to each benchmark and the printing results for each benchmark are presented below.



Overhang speed
60 mm/s (10%, 25%)
30 mm/s [25%, 50%)
10 mm/s [50%, 75%)
10 mm/s [75%, 100%)
over 100% wall (not bridge) 50 mm/s
Bridge 50 mm/s
Gap infill 210 mm/s
Support 150 mm/s
Support interface 80 mm/s

Travel speed
Travel 500 mm/s

Fig. 16. Setting print speeds for the Bambu Lab printer

3.1. 3D printing of the conductive hemisphere reference

The hemispherical guide was created on a Bambu Lab printer with a fill rate of 50%. The part was positioned as shown in Figure 17a and did not require any support. The creation of the part required 19.26 m of filament (PLA Basic), and the printing time was 8 hours and 13 minutes.

The weight and cost of the filament consumed (indicated by the program) are not correct because the density and specific cost of the filament were not indicated when selecting the material. Figure 17b shows the part during printing (a) and at the end of the printing operation (b).

a. b.

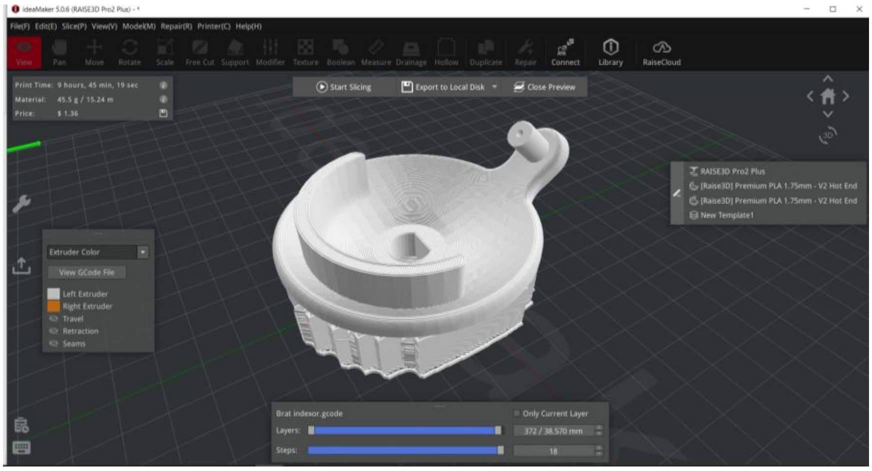
Fig. 17. Printing of the hemispherical reference mark. a. during the printing operation; b. at the end of printing.

3.2. 3D printing of the indexing arm

The indexing arm was printed on a Raise 3D Pro2 Plus printer using PLA HD filament. The infill density was 65% and required support. Figure 18 shows the preview of the part before printing, including the support.

The part required 15.24 m of filament and took 9 hours and 45 minutes to print.

Figure 19 shows the indexing arm during printing (a) and after printing (b). After printing, the part required support removal and surface cleaning.



Print Time: 9 hours, 45 min, 19 sec

Material: 45.5 g / 15.24 m

Price: $ 1.36

RAISE3D Pro2 Plus

[Raise3D] Premium PLA 1.75mm - V2 Hot End

[Raise3D] Premium PLA 1.75mm - V2 Hot End

New Template1

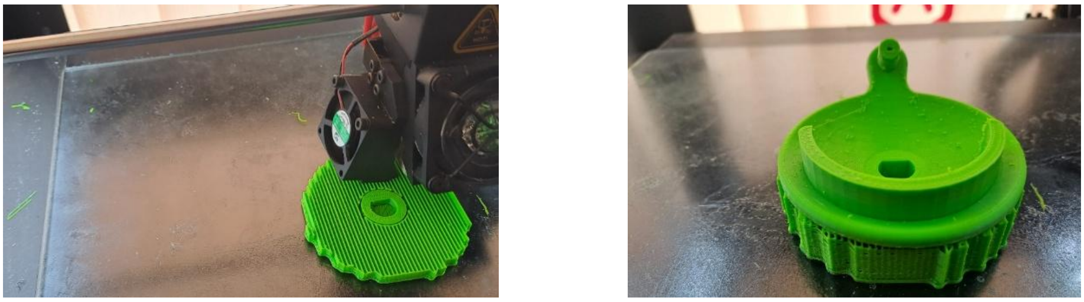
Brat indexor.gcode

☐ Only Current Layer

Layers: 372 / 38.570 mm

Steps: 18

Fig. 18. Indexer arm model in IdeaMaker software with support



a. b.

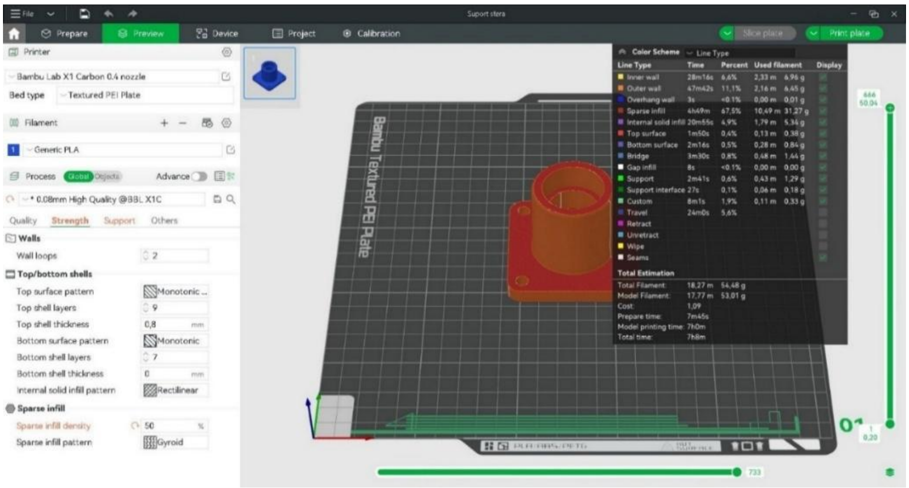
Fig. 19. Printing the indexer arm reference mark. a. during the printing operation; b. at the end of printing

3.3. 3D printing of the hemispherical support fixture

The hemispherical support was printed on a Bambu Lab printer with a fill density of 50%. The fixture was positioned as shown in Figure 20 and required support.

Printing required 18.27 m of filament (17.77 m for the actual part, the rest for support) and a working time of 7 hours and 8 minutes.

Fig. 21 shows the hemispherical support feature during printing (a) and at the end of the printing operation (b). After printing, the feature required support removal operations.



Bambu Lab X1 Carbon 0.4 nozzle
Bed type: Textured PEI Plate
1 Generic PLA
* 0.08mm High Quality @BBL X1C

Walls
Wall loops: 2
Top/bottom shells
Top surface pattern: Monotonic ...
Top shell layers: 9
Top shell thickness: 0,8 mm
Bottom surface pattern: Monotonic
Bottom shell layers: 7
Bottom shell thickness: 0 mm
Internal solid infill pattern: Rectilinear
Sparse infill
Sparse infill density: 50 %
Sparse infill pattern: Gyroid

Color Scheme: Line Type

Line Type	Time	Percent	Used filament		Display
Inner wall	28m16s	6,6%	2,33 m	6,96 g	✓
Outer wall	47m42s	11,1%	2,16 m	6,45 g	✓
Overhang wall	3s	<0.1%	0,00 m	0,01 g	✓
Sparse infill	4h49m	67,5%	10,49 m	31,27 g	✓
Internal solid infill	20m55s	4,9%	1,79 m	5,34 g	✓
Top surface	1m50s	0,4%	0,13 m	0,38 g	✓
Bottom surface	2m16s	0,5%	0,28 m	0,84 g	✓
Bridge	3m30s	0,8%	0,48 m	1,44 g	✓
Gap infill	8s	<0.1%	0,00 m	0,00 g	✓
Support	2m41s	0,6%	0,43 m	1,29 g	✓
Support interface	27s	0,1%	0,06 m	0,18 g	✓
Custom	8m1s	1,9%	0,11 m	0,33 g	✓
Travel	24m0s	5,6%			☐
Retract					☐
Unretract					☐
Wipe					☐
Seams					✓

Total Estimation
Total Filament: 18,27 m 54,48 g
Model Filament: 17,77 m 53,01 g
Cost: 1,09
Prepare time: 7m45s
Model printing time: 7h0m
Total time: 7h8m

Fig. 20. Data for printing the hemispherical support reference point

a. b.

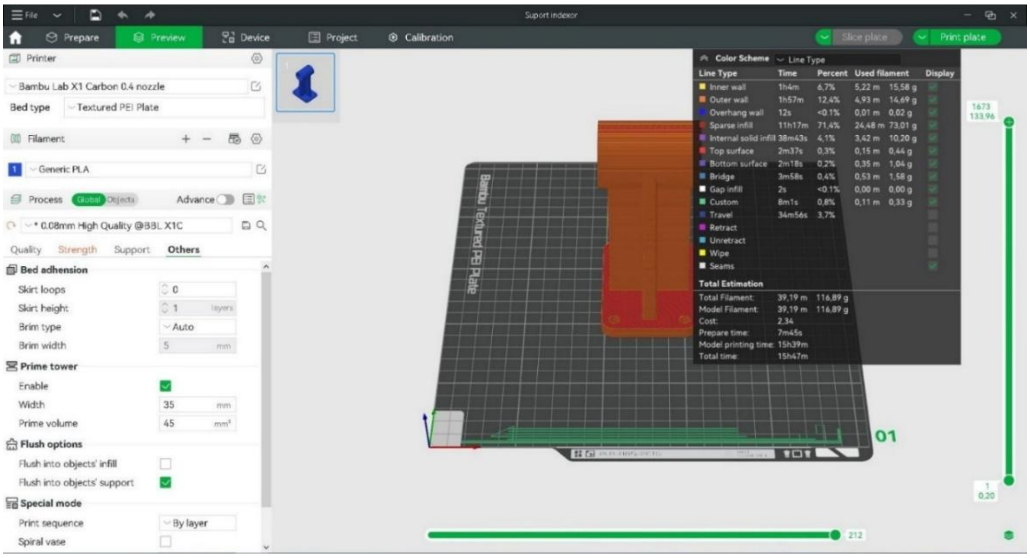
Fig. 21. Printing the hemispherical support feature. a. During the printing process (note the generation of the inner support). b. At the end of printing.

3.4. 3D printing of the indexer support part

The indexer support was printed on a Bambu Lab printer using blue PLA Basic filament, with a fill density of 50%. The part was positioned as shown in Figure 22 and did not require any support.
Printing required 39.19 m of filament and took 15 hours and 47 minutes. This was the part that required the most time and the largest amount of material.

3.5. 3D printing of the indexing indicator feature

The indexing indicator was made on a Raise 3D Pro2 Plus printer with PLA HD filament. The infill was 65% and no support was needed. Figure 23 shows the preview of the feature before printing.
Printing required 18.2 m of filament and took 10 hours and 24 minutes.



Bambu Lab X1 Carbon 0.4 nozzle
Bed type: Textured PEI Plate
1 Generic PLA
* 0.08mm High Quality @BBL X1C

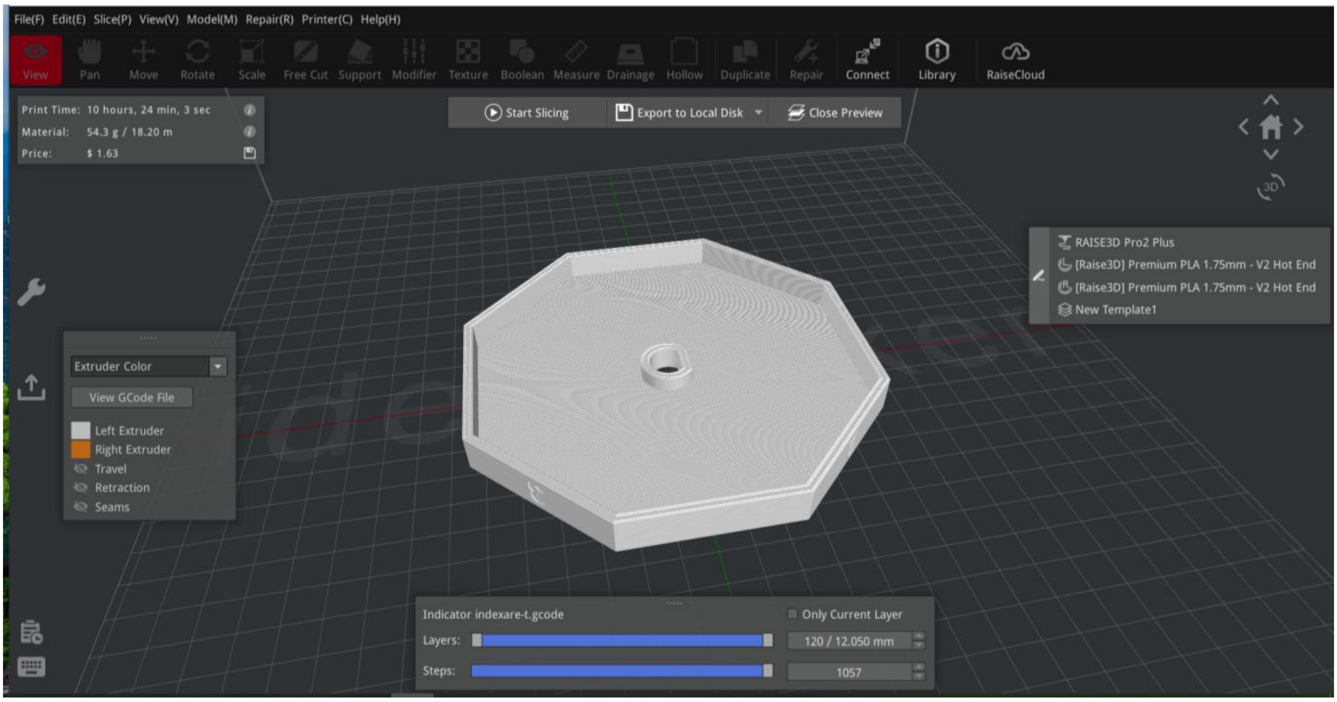
Bed adhension
Skirt loops: 0
Skirt height: 1 layers
Brim type: Auto
Brim width: 5 mm
Prime tower
Enable: ☑
Width: 35 mm
Prime volume: 45 mm³
Flush options
Flush into objects' infill: ☐
Flush into objects' support: ☑
Special mode
Print sequence: By layer
Spiral vase: ☐

Color Scheme: Line Type

Line Type	Time	Percent	Used filament		Display
Inner wall	1h4m	6,7%	5,22 m	15,58 g	✓
Outer wall	1h57m	12,4%	4,93 m	14,69 g	✓
Overhang wall	12s	<0.1%	0,01 m	0,02 g	✓
Sparse infill	11h17m	71,4%	24,48 m	73,01 g	✓
Internal solid infill	38m43s	4,1%	3,42 m	10,20 g	✓
Top surface	2m37s	0,3%	0,15 m	0,44 g	✓
Bottom surface	2m18s	0,2%	0,35 m	1,04 g	✓
Bridge	3m58s	0,4%	0,53 m	1,58 g	✓
Gap infill	2s	<0.1%	0,00 m	0,00 g	✓
Custom	8m1s	0,8%	0,11 m	0,33 g	✓
Travel	34m56s	3,7%			☐
Retract					☐
Unretract					☐
Wipe					☐
Seams					✓

Total Estimation
Total Filament: 39,19 m 116,89 g
Model Filament: 39,19 m 116,89 g
Cost: 2,34
Prepare time: 7m45s
Model printing time: 15h39m
Total time: 15h47m

Fig. 22. Data for printing the indexer support reference



Print Time: 10 hours, 24 min, 3 sec
Material: 54.3 g / 18.20 m
Price: $ 1.63

RAISE3D Pro2 Plus
[Raise3D] Premium PLA 1.75mm - V2 Hot End
[Raise3D] Premium PLA 1.75mm - V2 Hot End
New Template1

Indicator indexare-t.gcode
Layers: 120 / 12.050 mm
Steps: 1057

Fig. 23. Data for printing the indexing indicator reference

3.6. 3D printing of the crank, handle, and support leg

All these parts were made on a Raise 3D Pro2 Plus printer using PLA HD filament. The infill was 65% and, apart from the handle, no supports were required.

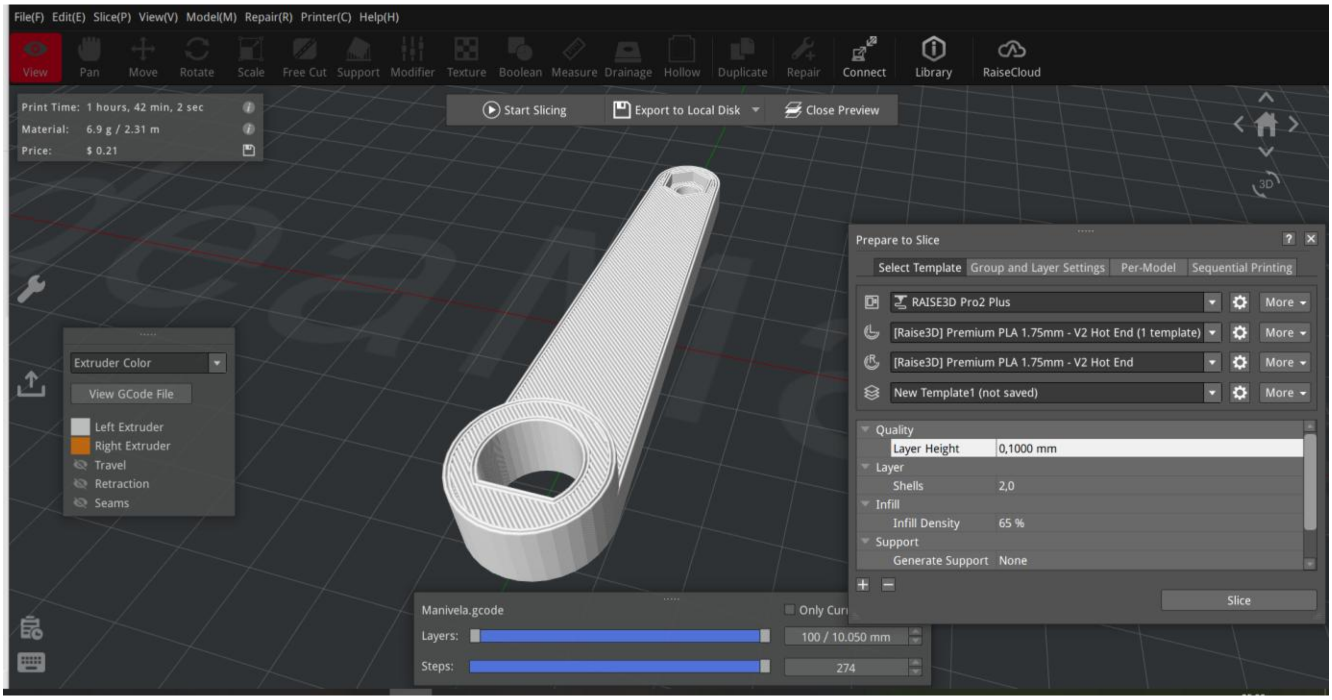
Figure 24 shows the preview of the crank part before printing.

Printing required 2.31 m of filament and took one hour and 42 minutes. Figure 25 shows the crank part after printing.

Figure 26a shows the handle part previewed before printing. This part requires support. Fig. 26b shows the internal support.

Printing required 1.18 m of filament and took one hour and 23 minutes. Fig. 27 shows the handle part after printing.

The part required the removal of the support.



Print Time: 1 hours, 42 min, 2 sec
Material: 6.9 g / 2.31 m
Price: $ 0.21

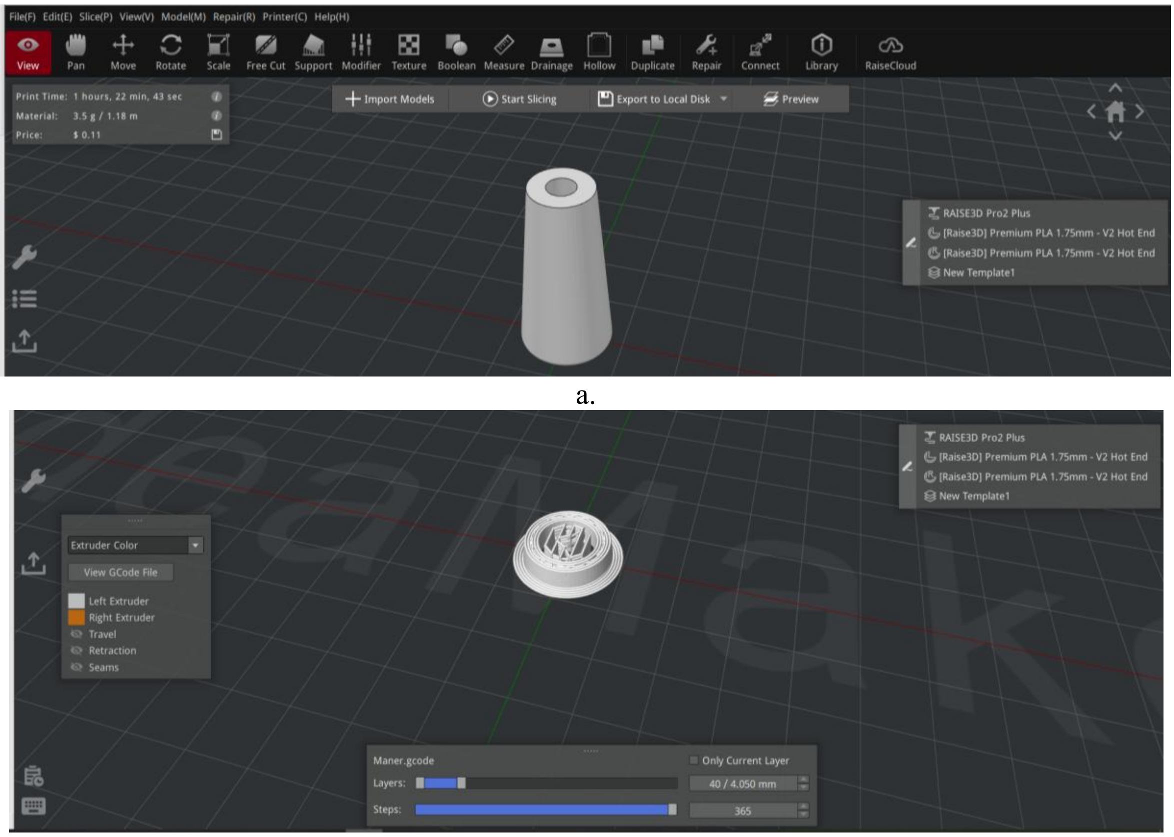
RAISE3D Pro2 Plus
[Raise3D] Premium PLA 1.75mm - V2 Hot End (1 template)
[Raise3D] Premium PLA 1.75mm - V2 Hot End
New Template1 (not saved)

Quality
Layer Height: 0,1000 mm
Layer
Shells: 2,0
Infill
Infill Density: 65 %
Support
Generate Support: None

Manivela.gcode
Layers: 100 / 10.050 mm
Steps: 274

Fig. 24. Data for printing the crank reference mark

Fig. 25. The Crank reference point at the end of the printing operation



Print Time: 1 hours, 22 min, 43 sec
Material: 3.5 g / 1.18 m
Price: $ 0.11

RAISE3D Pro2 Plus
[Raise3D] Premium PLA 1.75mm - V2 Hot End
[Raise3D] Premium PLA 1.75mm - V2 Hot End
New Template1

a.

RAISE3D Pro2 Plus
[Raise3D] Premium PLA 1.75mm - V2 Hot End
[Raise3D] Premium PLA 1.75mm - V2 Hot End
New Template1

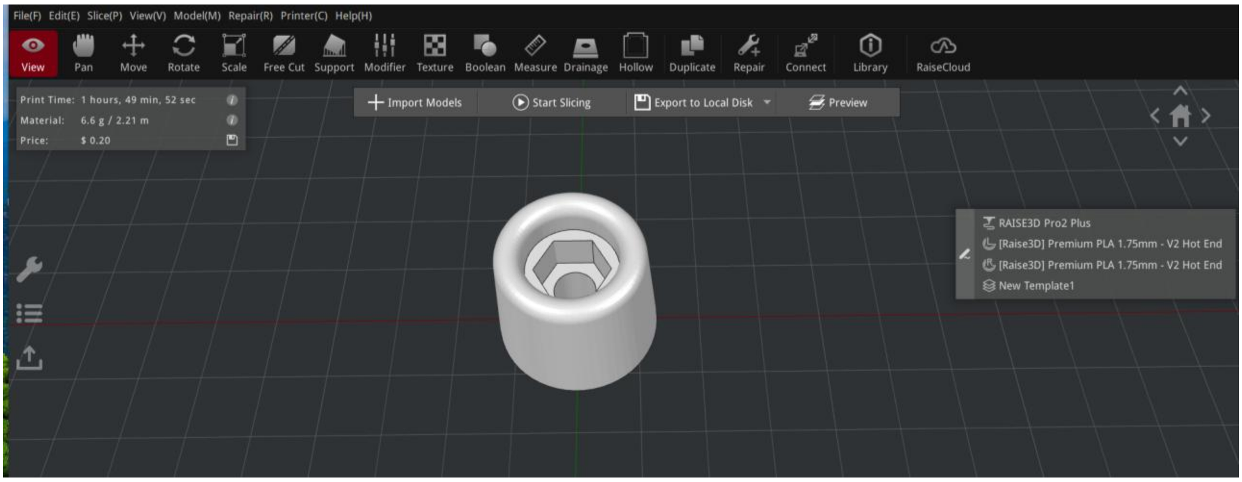
Maner.gcode
☐ Only Current Layer
Layers: 40 / 4.050 mm
Steps: 365

b.

Fig. 26. Data for printing the handle reference. a. preview of the complete model; b. preview of the model in support layers

Fig. 27. Reperul mâner la sfârșitul operației de printare

În figura 28 este reprezentat modelul reperului picior sprijin previzualizat înainte de printare.
Pentru printare au trebuit 2,21 m de fir și a fost nevoie de un timp de lucru de o oră și 50 min. În fig. 29 este prezentat reperul manivelă după terminarea operației de printare.



Print Time: 1 hours, 49 min, 52 sec
Material: 6.6 g / 2.21 m
Price: $ 0.20

RAISE3D Pro2 Plus
[Raise3D] Premium PLA 1.75mm - V2 Hot End
[Raise3D] Premium PLA 1.75mm - V2 Hot End
New Template1

Fig. 28. Data for printing the support foot reference

Fig. 29. Footrest reference point at the end of the printing operation

4. CONCLUSIONS

3D printing based on the 3D principle is widely used in the manufacture of low-volume products (one-offs or small series) using plastic filaments. For the manufacture of products from such materials, the injection molding process using specialized machines is recommended, as this solution ensures significantly higher productivity.

As shown in the paper, the time required to manufacture products using 3D printing is long, but it is a solution for unique or small-series products, or for testing design solutions on prototypes.

3D printing offers a quick transition from design (CAD solid model) to manufacturing by simply setting parameters (for 3D printing) as shown in the paper within specialized programs that then generate the G-code necessary for the 3D printer to function.

3D printing is widely used due to the affordability of such equipment, the relatively low price of the rolls of material used for printing, and the existence of various materials with relatively broad properties that can be used to make products.

Another advantage that makes this manufacturing process widespread (especially in education, but also in maintenance, healthcare, etc.) is the possibility of manufacturing parts with very complex geometries.

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