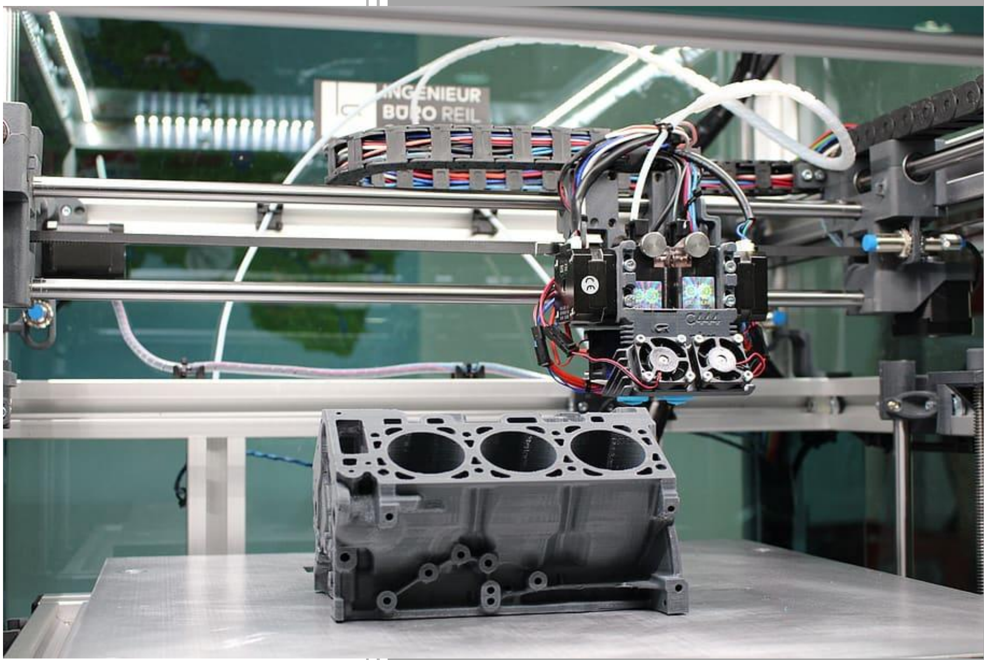
Module 3. Industrial and Personal 3D Printers



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3.1 Types of 3D industrial and personal Printers

Three-dimensional (3D) printing marked a great revolution in fabrication; its presence is becoming more and more intense in many fields. It's actively used, not only on a personal level but also on an industrial scale, in production sector, engineering, medicine, education, science and various other fields.

On a personal level, 3D printing allows to create models -even complex original objects- or to adapt existing products very quickly, in small quantities, with accuracy. This is especially important, as there is no need for specialized tools and equipment to make a prototype or to create, for example, an artistic object. On the other hand, this technology is also gaining ground at the industrial level where, of course, the requirements are different, both in terms of the quantity of objects and their reliability, properties and reproducibility.

The obvious advantages of additive technology, e.g. production speed, safety, cost reduction and product quality, make the complete transition to it only a matter of time. Thanks to digital design and easy data transmission, everyone can minimize the time from the conception of an idea to its implementation, with safety both in the printing process and the resulting products.

What is certain is that 3D printing is a technology that has come to stay and we will see it applied more and more to many areas of our lives. It is now one of the technologies included in most academic and public Libraries due to its cost-effectiveness and ease of availability, helping in the education and development of know-how, always with safety in their use. [(1)]

3.1.1 The use of 3D printing technologies in industry

Industrial 3D Printing is emerging as a revolutionary technology that is going to change production methods as we know them, especially when we refer to mass production and mass personalization customization. The way, the speed and the result of the adoption of additive manufacturing technologies depend on the industry and of course the strategy of each company. In any case, the application of 3D printing technologies in the industry is a future challenge to achieve more flexible systems which will be based on internet and IT technologies. With the future of production in mind, the key question is whether additive technologies will be able to replace classic production lines. [(8)]

In the following table we present the main advantages and limitations of additive manufacturing with regard to industrial production.

Pros	Cons
Additive construction allows design freedom while complexity does not limit production.	Technologies have a lower rate of production than traditional methods.
Machining processes are to be eliminated, saving the relevant costs and time.	In complex cases, a significant effort is required in the definition of the parameters, the preparation and the general design.
The possibility of optimal design is given, for low weight constructions, which would be impossible with the classical production methods.	Many times the production process is not completed by the end of printing, as additional processing may be required for surface quality and dimensional accuracy.
	There is often a limit to the size that can be printed, based on the capabilities of the 3D printing machine, and economies of scale are not achieved due to discontinuous production.

A very detailed and systematic study is required to determine the effectiveness of 3D printing technologies in industry and to what extent their application will transform production.

1. **Economies of scale**

3D printing technologies are currently lagging behind in this area. Nevertheless, additive construction is an industry that is constantly evolving and improving, in order to be able to replace the traditional production methods at some point. [3]

2. **On demand manufacturing**

3D printing technologies allow to significantly reduce the life cycle of products, especially in the design part. In addition, new supply chain management models will be created, reducing the risk posed by conventional inventory management models.

3. **Product Personalization**

3D printing allows the creation of personalized products, tailored to the personal needs of their users. In addition, new models are to emerge, in which customers will play an active role in the product design and production process.

4. **Flexibility**

The development of the supply chain on the basis of 3D printing will create more flexible networks, bringing production closer to the final consumer. The reduction of transports of finished products will have a significant impact on the distribution channels and more generally in the sector of distribution and distribution of products.

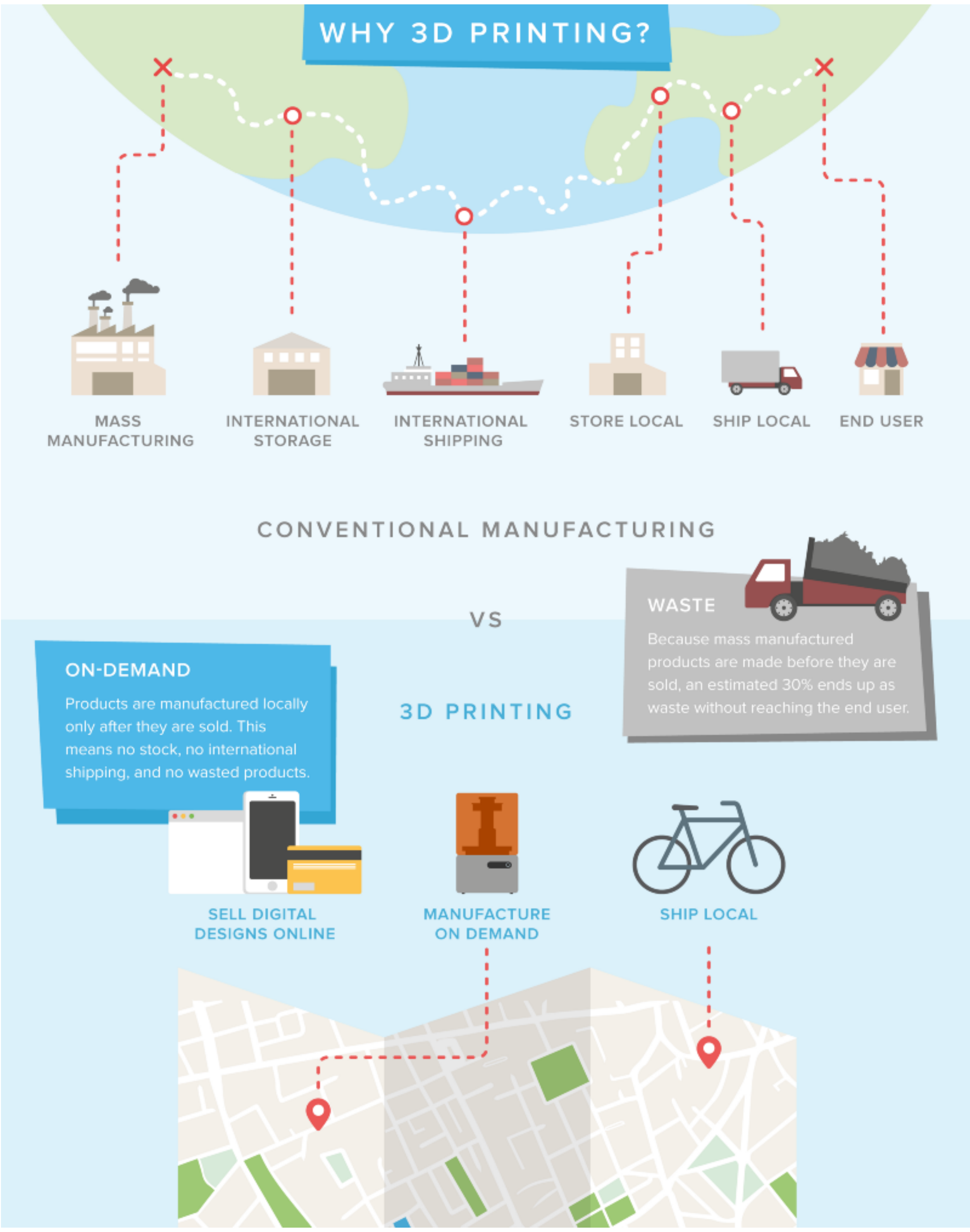


Figure 1: Distributed vs centralized manufacturing. Image courtesy of 3D Hubs. [1]

3.1.2 Technologies

Today there are numerous technologies that implement Additive Manufacturing. We will summarize the most common of them, with a view to their applicability in the commercial printers. [(14)]

VAT Photopolymerization

This technology uses a liquid photopolymer resin tank, from which the model is structured per layer. An ultraviolet radiation is used to harden the resin where needed, while a platform moves the object down after coating of each layer.

Digital Light Processing (DLP) technology uses a normal light source with a liquid crystal display panel. The vat of liquid polymer is exposed to UV light. A projector that sits under the resin container, projects slices of the 3D image on the resin layers. The first layer of polymer that is exposed to the UV light hardens and the process continues to the 2nd and all successive layers in the photopolymer. The process continues until the 3D model is built.

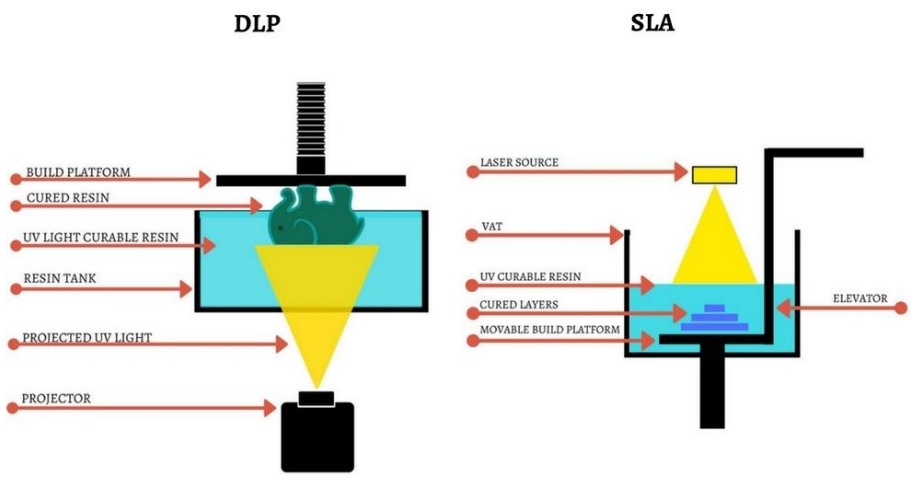


Figure 2: DLP and SLA techniques

Stereolithography (SLA) is the oldest 3D printing technology still used today. A laser beam is used to harden the polymer. The SLA 3D printer directs UV laser to two galvanometers which directs them to correct X and Y coordinates that are traced out to a cross-section of the model. The UV laser beam moves continuously across the print are hardening the photopolymer as it goes. The 3D printing process breaks the 3D design into multiple sets of coordinates for each layer along the lines that are sent to two galvanometers. [(10), (21), (22)]

Pros of 3D printing using resins	*Cons of 3D printing using resins*
Better resolution	More expensive
Faster printing process	No option for composite prints
Stronger finished products	Difficult and messy post-processing

Material Jetting

This technology creates objects in a way similar to a two-dimensional inkjet printer. The material is poured from a moving extruder onto a platform, where it is solidified using ultraviolet radiation, and the model is built per layer. The machines of this method differ in their complexity and the way the material is available for construction. The materials used are limited in number, as are the polymers and the wax is the most suitable because they are viscous and allow creating drops for the operation of this method. [(12)]

Figure 3: Material jetting industrial Printer

Pros of 3D printing using Material Jetting	*Cons of 3D printing using Material Jetting*
Full color and multi-material 3D printing	More expensive
Faster printing process	structurally weak and fragile
produce multiple parts without affecting the build speed	
very smooth surface (ideal for making aesthetical prototypes)	

Binder Jetting

Binder Jetting technology uses two types of materials: one in powder form and a binder. The second is used for connection between the layers of dust that form. It is usually in wet form, while the building material is in powder form. A head moves on the level of the print and deposits layers of the two materials alternately. After completing each layer, the object to be printed moves down to continue the process with the upper levels.

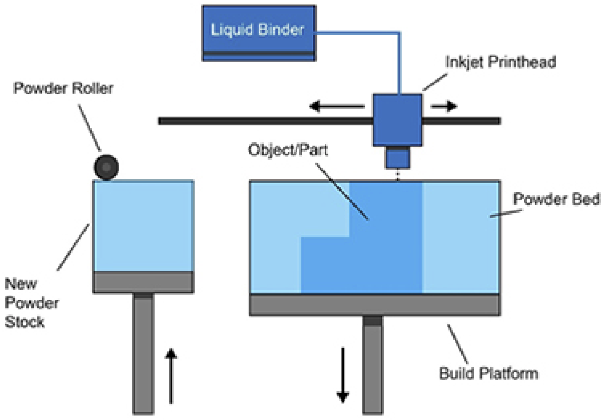


Figure 4: The Binder Jetting Principle

Material Extrusion

Fuse Deposition Modeling technology is a common Material Extrusion technology. The material accumulates in one extruder, where it is heated and then deposited in layers. The extruder can move horizontally, while a platform moves vertically after creating each layer. This technology is widespread, especially in low cost, home 3D printers.

This method has many parameters that affect its quality final model. The difference of Fuse Deposition Modeling is that while it is one more production technology per layer, it is differentiated as to the fact that the material enters under constant pressure and in a continuous manner, giving greater accuracy in the final result.

Powder Bed Fusion

The Powder Bed Fusion (PBF) includes the following printing technologies: Direct metal laser sintering - (DMLS), Electron beam melting (EBM), Selective heat sintering - (SHS), Selective laser melting - (SLM), Selective laser sintering - (SLS).

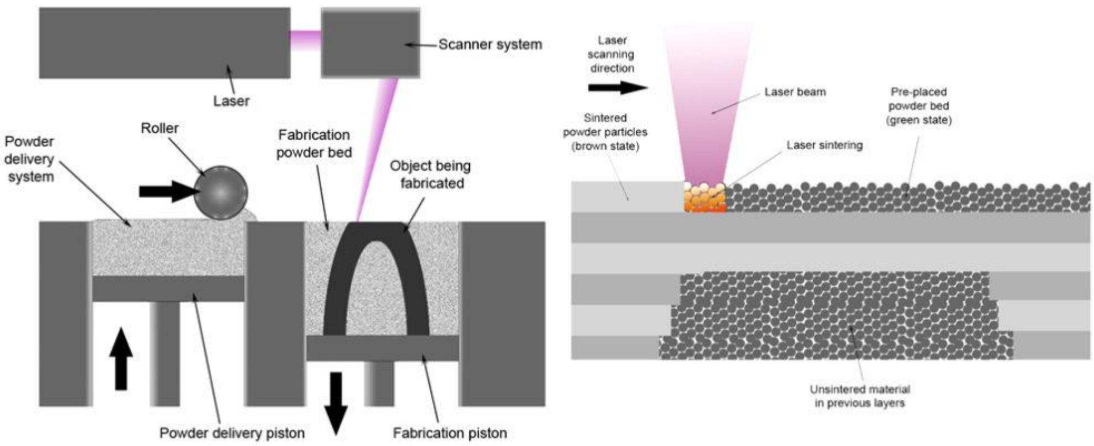


Figure 5: How Powder Bed Fusion works

Powder Bed Fusion technologies use a beam or electron beam for melting the material, which is in powder form. The fusion processes includes successive dust passes through levels using one roller mechanism while the printing platform descends to create of the next level. A tank next to the print area provides the material for each level. DMLS technology is the same as SLS, with the difference that metal is used instead of plastic. SHS technology is differentiated from the rest in that it has to do with the use of a thermal printing head for melting the material. [(18)]

Sheet Lamination

These procedures include Ultrasonic Additive Manufacturing and Laminated Object Manufacturing. The first process uses metal leaves, which are connected by the method of ultrasonic welding. The second technology uses a similar method of connection per layer, with the difference that paper is used instead of metal and simple gluing. The items produced by this method are mainly used for aesthetic purposes or optical models and not suitable for construction uses. Ultrasonic welding technology uses metals such as aluminum, copper, stainless steel and titanium. [(9)]

Directed Energy Deposition

This is a fairly complex printing process, used primarily to repair existing objects. A typical machine of this technology consists of an extruder, attached to an arm, which deposits the molten material in a specific area, where it solidifies. The process is quite similar to the method of depositing material, but in this method the movement of the extruder is not limited to a specific level and can be moved in multiple directions, using four or five axis machines. The process can work with polymeric or ceramic materials; however it is mainly used with metals, in the form of powder or thin wire. [(18)]

Construction 3D Printing (c3Dp)

3D Construction Printing (3DCP) refers to various technologies that use 3D printing as a core method to construct buildings or construction components. 3D printing in the construction industry and in particular the 3D concrete printing has comparative advantages over conventional manufacturing methods.

Figure 6: Houses at the process of 3D construction

The main features of 3D Printing methods is freedom in geometry and form of construction, speed completion of projects, the avoidance of the use of formwork, the contribution to the reduction of waste, their generally environmentally friendly nature and safety.

The predominant technologies of 3D construction printing are additive construction, Autonomous Robotic Construction System (ARCS), Large scale Additive Manufacturing (LSAM), or Freeform construction (FC), used to refer to **concrete extrusion technologies**.

There is a variety of 3D printing methods used at construction scale, with the main ones being extrusion (concrete/cement, wax, foam, polymers), powder bonding (polymer bond, reactive bond, sintering), and additive welding.

Figure 7: The first steel 3D Printed Bridge in Amsterdam

Demonstrations of construction 3D printing technologies have included building of houses, construction components, bridges, civil infrastructure, follies, and sculptures. [(5), (28)]

Massivit's proprietary gel dispensing printing technology (GDP)

Massivit has developed a technology that allows printing of large, full-scale object parts, up to 1.8 meters tall, at considerably high speed. Massivit's photosensitive gel hardens when exposed to UV light, which enables models to cure while printing, requiring little to no support structures. This facilitates delivering support-less non-vertical hollow parts as solid objects straight off the printer, while enabling fast and economical printing –saving on printing material and printing time– with advanced geometric freedom. The end parts are lightweight, durable, and receptive to a variety of post-processing methods.

The system is optimizable for visual arts and graphic communications and is able to print a variety of shapes and forms. It has, for example, printed a 3D model of the famous 'Strati' – a car created and developed by Local Motors.

Figure 8: UPV students in AIJU with a real life size of a cartoon horse 3Dprinted by a Massivit machine

3.1.3 Differences between industrial and home desktop 3D printers

What Makes a Printer Industrial?

Industrial FDM printers are designed for repeatability and reliability. To ensure this, they feature closer control of the processing parameters during printing. These are the key elements that differentiate the home 3D printer from the Industrial [4,6]:

- **Large-enough volume** to print large pieces or dozens of smaller parts (300+ mm)
- **Extruder temperature** upwards of 350 ºC to print reliably with engineering-grade filaments, such as PEEK, Ultem, and carbon-fiber infused polymers
- **Heated build chamber** that can hold a consistent temperature (at least 80 ºC) for long durations to prevent part warping or cracking
- **Automation** of process variables for consistency and less manual calibration [(13)]

Accuracy

Generally the geometric tolerances and part accuracy are dependent upon printer calibration and model complexity.

Typically **industrial FDM 3D printers** produce parts of higher accuracy than desktop FDM machines, because of the closer control of the processing parameters during printing. Industrial machines run calibration algorithms before each print, include a heated chamber to minimize the effects of rapid cooling of the molten plastic (e.g. warping) and can operate at higher printing temperatures. Most of these machines support dual extrusion. This allows for the deposition of **water-soluble support material**, which is removed in post-processing and results in smoother surfaces and makes it easier to print complex parts. [(12), (15)]

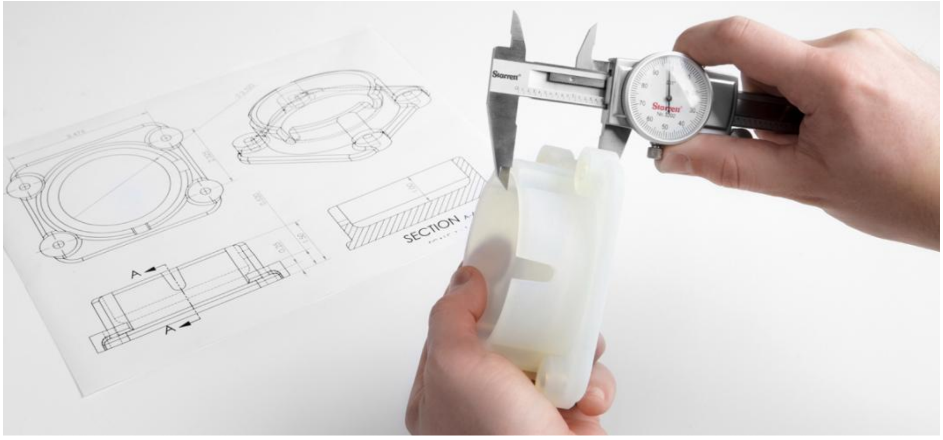


Figure 9: Accuracy is frequently a crucial factor

On the other hand, **desktop FDM 3D printers** are now catching up and there are machines that support these advanced features (i.e. calibration algorithms, heated chamber, higher printing temperatures and dual extrusion). A well calibrated basic desktop FDM machine can produce parts with fairly high **dimensional accuracy** (typically with tolerances of ± 0.5 mm) and with the same **minimum feature size** as industrial FDM machines (i.e. approx. 1 mm). This accuracy is sufficient for most applications. Most materials used in desktop FDM printing allow for critical dimensions (e.g. holes) or detailed features (e.g. threads) to be machined accurately in a post-processing step. [(13)]

Materials

The material most commonly used on desktop FDM 3D printers is PLA. When higher strength, ductility and thermal stability is needed, ABS is commonly used, which is more prone to warping (due to shrinkage) and the geometry of the printed part can prohibit its use, especially in machines that do not have a heated chamber. Another alternative material that is rising in popularity is PETG, which has material characteristics comparable to ABS and is easy to print with.

Figure 10: Rolls of plastic filaments is the main material used on 3D Printers

Industrial FDM 3D printers use mainly engineering plastics ABS, polycarbonate (PC) or Ultem. These materials are usually loaded with certain additives that alter their properties and make them particularly useful for a certain industrial need (e.g. high impact strength, thermal stability, chemical resistance and biocompatibility). Some materials printed with industrial FDM have similar material properties to injection molded parts and often times can be 'good enough' for creating functional end-parts. The temperature resistant properties of these materials also mean that they are suitable for mold-printing for low run injection molding. [(4), (6), (7), (11), (20)]

Production capabilities and cost

The **production capabilities** of an industrial FDM 3D printer are typically greater than that of a desktop 3D printer, meaning that an industrial FDM machine can complete a **large order faster** than a desktop 3D printer. Industrial 3D printers also have a **larger printing area**, which means that they can produce larger parts in one print or print more models at the same time.

Industrial FDM printers are also designed for **repeatability** and **reliability**. They can often produce the same part over and over again. Desktop FDM printers require a high level of user maintenance and regular calibration. [6]

The most important differences between 3D printers for home use (desktop) and industrial models are shown in the following table.

Type	**Desktop 3D printer**	**Industrial 3D printer**
Amount of handled materials	Mostly 1	Usually 1-2 for build and 1-2 for water-soluble support material
Dimensional accuracy	0.5%-1% (~1mm for a 10cm item)	~0.2% (0.2mm for a 10cm item)
Build volume	<10 lit	>100 lit~1000lit
Chamber	Usually open	Closed and heated, allowing precise control of material properties
Printing speed	~50mm/sec	>100mm/sec
Material types	Mostly PLA, PET-G (also ABS but difficult to use in open chambers)	ABS, PC, Ultem, etc Taking into account Durability, Thermal stability, Flexibility, Resistance to chemical agents, Biocompatibility, etc
Typical layer thickness	0.10 - 0.25 mm	0.18 - 0.5 mm
Machine cost	400€ - 4.000€	>20.000€

BeamMaker: an open hardware high-resolution digital fabricator for the masses.

The rise of personal fabrication requires an increase in printing quality, a reduction on machine cost and an increase in knowledge shared by the open hardware community. The BeamMaker designers constructed a low-cost photopolymer-based 3D printer. The printer is connected to a host computer and a digital-light-processing projector. The designers provide public access to the instructions, software, source code, parts list, user manual and STL and CAD files.

The BeamMaker printer can build objects with a high surface quality that is comparable to the quality obtained by industrial photopolymer-based 3D printers. When testing the ability to print a sample cylinder, the printer shows higher accuracy when compared to other personal 3D printers. These findings are encouraging, considering the low cost of the system. The printer cost is just $380. This is five to eight times less expensive than popular personal 3D printers available today. The cost is 30 times less expensive than a personal photopolymer 3D printer produced by a main commercial company and yet producing results of similar quality. [(2)]

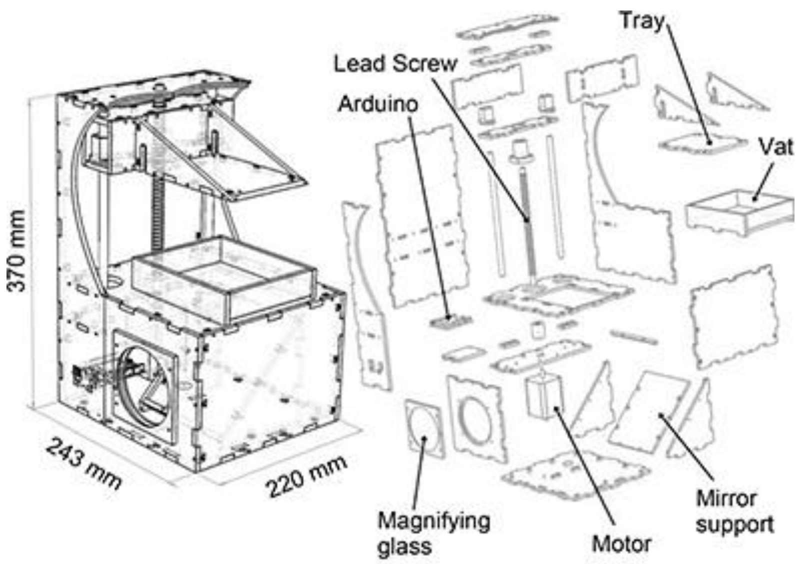
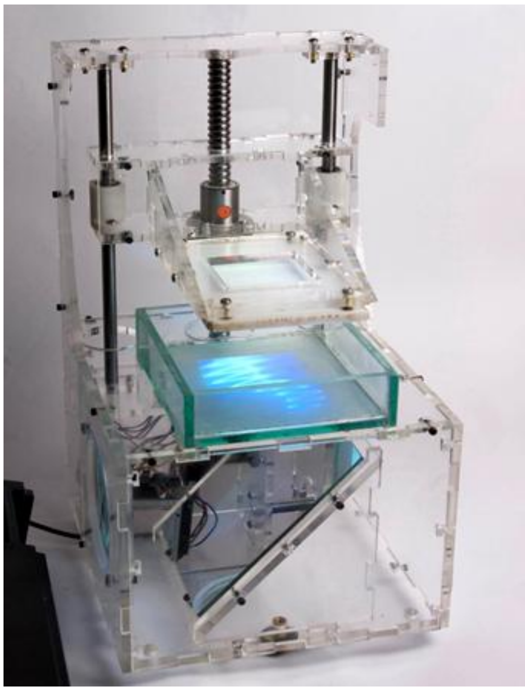


Figure 11: BeamMaker printer parts depicted in assembled view (left) and in exploded view (right)

Figure 12: BeamMaker SLA 3D printer, while prototyping a 3D object



3.2. Commercial 3D industrial Printers

Some of the most widely used Industrial 3D printing machines are illustrated here, from the most advanced to the most affordable. [11]

Big Area Additive Manufacturing (BAAM)

Figure 13: Oak Ridge National Laboratory BAAM Machine for Printing Large Parts of Polymers in 3D

One of the largest 3D printing technologies available today is the Big Area Additive Manufacturing (BAAM). Developed by Oak Ridge National Laboratory (ORNL) in partnership with Cincinnati Inc. BAAM first appeared at IMTS 2014, where it was used to three-dimensionally print an entire car. The three-dimensional printer, which uses an extruder mounted on a deck system, can create sections up to 6 x 2.4 x 2 m using thermoplastics materials such as ABS, PPS, PC, PLA and PEI. Since its introduction, BAAM has been used in a variety of applications, from full-size underwater hull prototypes to self-taught vehicles with 3D printing. [(14),12]

Figure 14: Local Motors' Strati, the first 3D car printed by Local Motors, used ORNL BAAM technology and was unveiled at IMTS in 2014

Electron Beam Additive Manufacturing (EBAM)

In the world of 3D metal printing, Sciaky offers some of the largest 3D metal printers based on EBAM (Electron Beam Additive Manufacturing) technology. For example, the EBAM 150 system has an impressive build volume of 3708 x 1575 x 1575 mm. EVAM technology uses a welding-like process that uses an electron beam to melt the metal under a wire. This means that the technology is suitable for processing a wide range of adhesives, from titanium to inconel and stainless steel. Sciaky places the EBAM system as a faster, more affordable alternative to large forged castings. The company's patented Closed-Loop Control system allows the manufacture of metal components with improved properties and microstructures for applications in the military, navy and aerospace. [13]

Figure 15: Sciaky's large EBAM 3D printer

Wire Arc Additive Manufacturing (WAAM)

Like EBAM, Wire Arc Additive Manufacturing (WAAM) also uses cable power, but it melts materials with the help of an electric arc. WAAM can manufacture components up to 10 meters long, using alloys such as titanium, nickel, stainless steel, aluminum and copper alloys. WAAM can be used to produce large metal components such as pressure vessels and aircraft fuselage frames. In addition to the final production, the technology is the ideal choice for repair and maintenance work for specific components such as turbine blades, as well as molds and dies. [14]

Figure 16: WAAM robotic 3D printer developed by Cranfield University

Large-format sand 3D printing

Perhaps the most well-known manufacturer of large size 3D printers is Voxeljet, which has been active in the area since 2002. In 2011, Voxeljet introduced the VX4000, which to date is one of the largest 3D powder printers with a build volume of 4 x 2 x In parallel with Voxeljet, ExOne offers professional powder printing systems, with a maximum build volume of up to 2.2 x 1.2 x 0.7 m. Both Voxeljet and ExOne 3D printers use Binder Jetting, where a liquid binder is selectively deposited on a layer of dust to bond the dust particles together. 3D powder printing is particularly beneficial for the foundry industry, as it offers a faster and more economical way to create large and complex powder molds and cores for metal casting. [15]

Figure 17: Voxeljet’s VX400

Dreambot3D FDM 3D

Figure 18: The Dreambot3D L-1000 model

There are 7 models with the same specifications and only difference in size:
From L-300 (300x300x300mm, 25KG)
Up to L-1000 (1000x1000x1000mm, 260KG)

- **materials**: PLA, TPU, 95A, water-soluble materials, wooden PLA; customizable ABS, PC, PETG, nylon, carbon fiber, metal filling materials, glass fiber addition materials
- **Nozzle diameter**: 0.2, 0.3, 0.4, 0.6, 0.8MM
- **Printing layer thickness**: 0.05-0.3MM
- **Printing speed**: 20-150MM
- **Positioning accuracy**: 0.011mm

https://www.dreambot3d.com/fdm-3d-printer/

Stratasys F series

Figure 19: The Stratasys F370 model

From F170 (254 x 254 x 254 mm, 227KG, 17.000€)
Up to F370 (355 x 254 x 355 mm, 227Kg, 40.000€)

- **materials**: PLA2, ABS-ESD7™, ABS-M30, ASA, Diran™ 410MF072, FDM TPU 92A, PC-ABS, ABS-CF10, QSR Support material
- **2-4 build + support materials**
- **Printing layer thickness**: 0.127-0.33MM
- **Printing speed**: 22cm^3/h
- **Accuracy**: 0.01MM

https://www.stratasys.com/3d-printers/

Stratasys F900

Figure 20: The bigger member - Stratasys F900 model

Build Area: 914.4 x 609.6 x 914.4 mm, 2869 kg,

Cost: 85.000€-200.000€

- **Print Heads: 2 build + 2 support**
- **materials**: ASA,ABS,PC,FDM Nylon,Antero,PPSF,ULTEM,ST-130
- **Printing layer thickness**: 0.127-0.5MM
- **Accuracy:** 0.015MM

https://www.stratasys.com/3d-printers/

Massivit 3D

Figure 21: Massivit 1800 Pro. LARGE-SCALE 3D printing with 2 heads

Massivit's 3D printers are using their patented Massivit's proprietary gel dispensing printing technology (GDP))

Build Area: 145cm x 111cm x 180cm

Printing heads: 2

Printing speed: 300 mm/sec linear speed 35cm on Z axis per hour

Printing quality: Normal/ Quality/ High Resolution/ Mega-Quality/ Variable Resolution

Supported materials: Dimengel 100 & 90

https://massivit3d.com/

Essentium HSE 280i HT

Figure 22: Essentium HSE 280i HT

Build Area: 695x495x600mm, 850 kg

Cost: >130,000€

materials: Almost any
Nozzle Temperature: 550ºC
Nozzle Diameters: 0.4, 0.8 mm
Print Heads: Two
Print Speed: 500 mm/s

https://www.essentium.com/3d-printers/high-speed-extrusion-280/

CreatBot PEEK-300

Figure 23: CreatBot PEEK-300

Build Area: 300x300x400mm, 100 kg

Cost: 10,000€

- **Materials:** PLA, PC, ABS, PA6, PETG, PVDF, POM-C, PP, TPU, PPSU, PEI (ULTEM), PA12, PSU, PPS, PA-CF, Medical grade PEEK, PEEK, PEKK, CF-PEEK (Carbon fiber), GF-PEEK (glass fiber)
- **Hotend max**. 500°C with dual extruder
- **Heatbed** max.200°C
- **Hot chamber** max. 120°C
- **Print Speed**: 10-150mm/s
- **Nozzle Diameter**: 0.3-1.0mm
- **Accuracy**: 0.01mm

https://www.creatbot.com/en/creatbot-peek-300.html

Anisoprint ProM IS 500

Figure 24: Anisoprint ProM IS 500

Build Area: 600x420x300mm

Cost: >140,000€

- **Up to 4 print heads**
- **materials**: PA, PC, PAEK, PEI
- **Hotend max.** 400°C with dual extruder
- **Hot chamber** max. 160°C
- **Nozzle diameter**: 0.4-1.2 mm
- **Printing layer thickness**: 60μm
- **Printing speed**: 60 cc/h

https://anisoprint.com/solutions/industrial/

3DGence F420

Figure 25: 3DGence F420

Build Area: 380x380x420mm, 350 kg

Cost: >85,000€

- **materials**: ULTEM, PEEK, PEKK, ASA, PC, HIPS
- **Print Heads:** Two
- **Hotend max**. 500°C with dual extruder
- **Hot chamber** max. 180°C
- **Nozzle diameter**: 0.4-1.2 mm
- **Printing layer thickness**: 50µm
- **Printing speed**: 400 mm/s

https://3dgence.com/3d-printers/industry-f420/

Roboze Argo

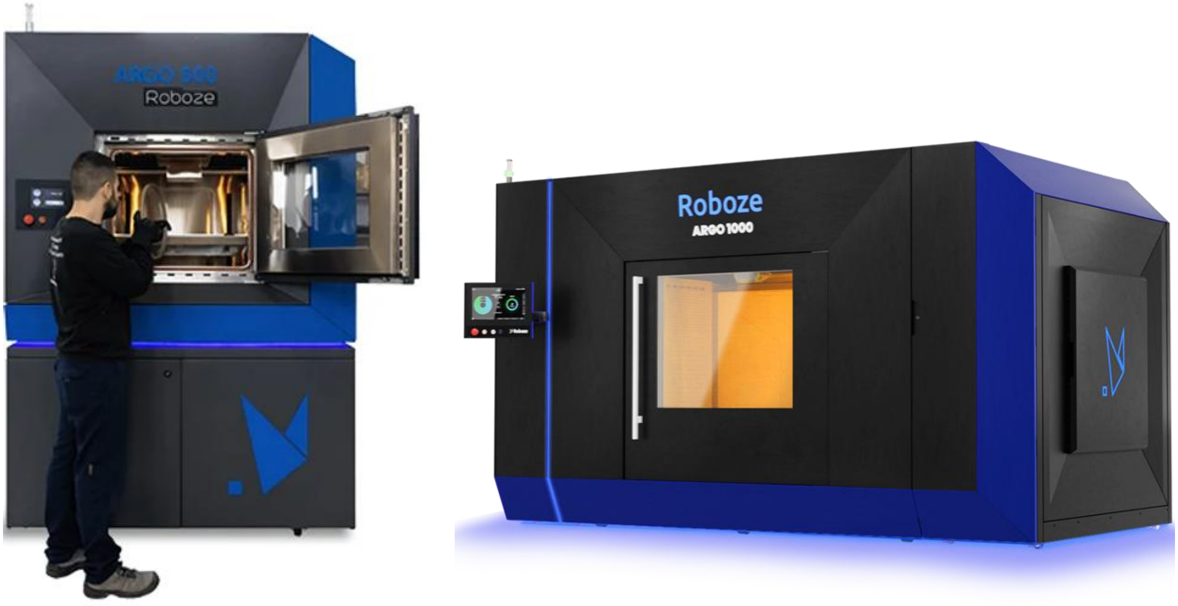


Figure 26: Argo 1000: The world's largest heated chamber 3D printer

From **Argo 350** (350x300x300mm, 1200 Kg,)

To **Argo 1000** (1000x1000x1000mm)

- **Materials**: PEEK, Carbon PEEK, ULTEM ™ AM9085F, Carbon PA, PC - LEXAN™ EXL AMHI240F, Flex-TPU, PP, FUNCTIONAL-NYLON, Strong-ABS, ULTRA-PLA, ABS-ESD
- **Hot chamber** max. 180°C
- **Hotend max**. 450°C with dual extruder
- **Accuracy**: 10µm

https://www.roboze.com/en/

Delta WASP 4070 Tech

Figure 27: Delta WASP 4070 Tech

Build Area: 400 x 400 x 700mm,90Kg,

Cost: >11.000€

- **Materials:** ABS, HIPS, PA CARBON, PMMA, TPU, PLA, PETG, PC, PC+ABS, PPS, PVA, ASA
- **Build volume**: Ø400 x h 700mm
- **Heated chamber**: heated up to 70°C
- **Minimum layer height**: 100µm
- **Print speed max**: 200 mm/s
- **Travel speed max**: 300 mm/s
- **Bed temp max**: 120 C°
- **Nozzle diameter**: 0.4-0.7 mm

https://www.3dwasp.com/en/delta-wasp-4070-industrial-x-best-industrial-3d-printer/

Cincinnati MAAM

Figure 28: Additive machine with a rigid welded frame, CNC controls, and optional single or dual extruders

Build Area: 1050 x 1015 x 1015mm, >1270KG

Cost: >210.000€

- **Materials**: filament and pellet
- **Chamber Temperature**: 90°C
- **Bed Temperature:** 150°C
- **Max Extrusion Rate**: 500 mm/s, 220 mm^3/s
- **Min Layer Height**: 0.10 mm
- **Nozzle Temperature:** 450°C
- **Nozzle diameter:** 0.6, 0.8, 1.2, 1.8, 2.4mm

https://www.e-ci.com/maam

3.3. Commercial 3D personal Printers

Following are some of the most widely used personal 3D printer models currently available on the market (2021) [8, 9, 10]

Prusa i3 MK3S+ 3D printer

Figure 29: Prusa i3 MK3S+ 3D printer

Build Area: 250×210×210 mm

Cost: 800-1000€

- **Layer height:** 0.05 - 0.35 mm
- **Nozzle:** 0.4mm default, wide range of other diameters/nozzles supported
- **Filament diameter:** 1.75 mm
- **Supported materials**: Wide range of thermoplastics, including PLA, PETG, ASA, ABS, PC (Polycarbonate), CPE, PVA/BVOH, HIPS, PP (Polypropylene), Flex, nGen, Nylon, Carbon filled, Woodfill and other filled materials.
- **Max travel speed:** 200+ mm/s
- **Max nozzle temperature:** 300°C
- **Max heatbed temperature:** 120°C
- **Print surface:** Removable magnetic steel sheets with different surface finishes, heatbed with cold corners compensation
- **Safety features:** IR filament sensor, high-quality Delta PSU with Power Panic, 3 thermistors, RPM monitoring
- **VIDEO:** https://youtu.be/hwNIzQLtHnU

https://www.prusa3d.com/original-prusa-i3-mk3s/

Monoprice Voxel

Figure 30: Monoprice Voxel

Build Area: 150 x 150 x 150 mm

Cost: 400€

- **Print Technology:** Fused Filament Fabrication (FFF)
- **Screen Type:** 2.8" Color IPS Touchscreen
- **Filament Size:** 1.75mm
- **Supported Filament Types:** ABS, PLA, Wood Fill, Copper Fill, Steel Fill, Bronze Fill
- **Nozzle Diameter:** 0.4mm
- **Layer Resolution :** 0.05 ~ 0.4 mm
- **Build Speed:** Up to 100 mm/second
- **Dimensions:** 400 x 380 x 405 mm
- **Weight :** 9.0 kg
- **VIDEO:** https://www.youtube.com/watch?v=mHl5HnuX64k

https://www.monoprice.com/product?p_id=33820

Formlabs Form 3 – 3L

Figure 31: Formlabs Form 3 – 3L

Build Area: 150x150x150 mm (Form 3), 335×200×300mm (Form 3L)

Cost: 3.500€ - 12.000€

- **Print Technology:** Low Force Stereolithography (LFS)
- **Screen Type:** 5.5" interactive touchscreen
- **Supported Types:** Materials compatibility one of: Standard resins, Engineering resins, Specialty resins, Dental resins, Medical resins
- **XY Resolution:** 25 microns
- **Laser Spot Size :** 85 microns
- **Internal Temperature :** Auto-heats to 35°C
- **Printer Dimensions :** 40.5 × 37.5 × 53 cm - 77 × 52 × 74 cm
- **Weight :** 17.5 kg - 54.4 kg
- **VIDEO:** https://www.youtube.com/watch?v=xf9oBcTzMFo

https://formlabs.com/3d-printers/

Original Prusa SL1S SPEED

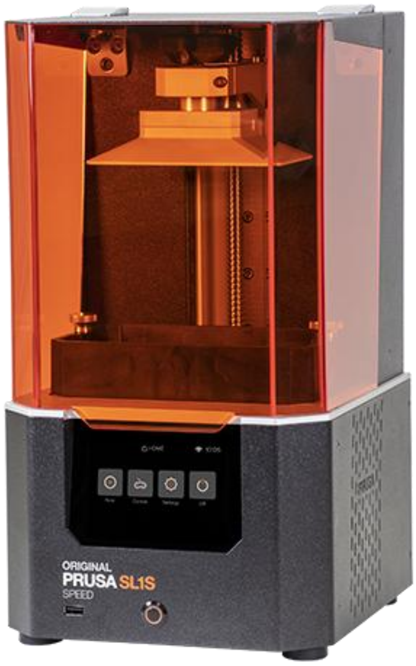


Figure 32: Original Prusa SL1S SPEED

Build Area: 127 x 80 x 150mm

Cost: 2.000€ - 2.600€ (+Curing and Washing Machine CW1S BUNDLE)

- **SLA system:** LCD and UV LED panel (MSLA)
- **Display type:** Monochrome LCD with a high-performance lens system
- **LCD resolution:** 5.96'', 2560×1620p
- **LCD lifespan / warranty:**2000 hours
- **Layer exposure time**: 1.4 – 2.5 seconds depending on material and layer height
- **Tilt times:** 3 seconds
- **Supported layer heights:** 0.025-0.1 mm
- **Minimal layer height:** 0.01 mm
- **Supported materials:** Standard UV sensitive liquid resin, 405nm, advanced materials supported
- **VIDEO:** https://youtu.be/ot5sRPVE86

https://www.prusa3d.com/original-prusa-sl1/

Monoprice Delta Mini V2

Figure 33: Monoprice Delta Mini V2

Build Area: 110 x 120 mm

Cost: 150-180€

- **Print Technology:** FFF
- **Build Volume:** ø110 x 120 mm
- Layer Resolution: High: 40 microns, Medium: 100 microns,Low: 200 microns
- **Position Precision**: 12.5 microns, Y: 12.5 microns, Z: 5 microns
- **Filament Diameter:** 1.75mm
- **Supported Filament Types:** PLA, PLA+, ABS, Wood Fill, Copper Fill, Steel Fill, Bronze Fill, etc.
- **Nozzle Diameter:** 0.4mm
- **Print Speed:** 1 ~ 170 mm/sec
- **Travel Speed:** 1 ~ 350 mm/sec
- **Offline Printing:** Yes, with microSD™ card
- **Assembled Dimensions** : 360 x 440 x 480 mm
- **Weight :** 1.0 kg
- **VIDEO:**https://www.youtube.com/watch?v=i9xtJddDgB4

https://www.monoprice.com/product?p_id=21666

LulzBot Mini 2

Figure 34: LulzBot Mini 2

Build Area: 160mm x 160mm x 180mm

Cost: 1.500€

- **Print Technology:** Fused Filament Fabrication
- **Print Volume :** 4608cm³
- **Ambient Operating Temperature:** From 5°C to 45°C
- **Operating Footprint:** 5.7cm x 40.6cm
- **Maximum Travel Speed:** 300mm/s
- **Connectivity:** USB Serial and Included 8gb SD Card
- **Maximum Print Bed Temperature:** Up to 120°C
- **Print Bed Heat Up Time:** From 23°C to 60°C in 97 seconds
- **Filament Diameter:** 2.85mm
- **Supported Materials:** Open filament system compatible with PLA, Natural and Metal PLA Blends, TPU, ABS, PETG, nGen, INOVA-1800, HIPS, HT, t-glase, Alloy 910, Polyamide, Nylon 645, Polycarbonate, PC-Max, PC+PBT, PC-ABS Alloy, PCTPE, and more.
- **Layer Resolution:** 0.05mm-0.90mm
- **Boxed Unit Weight:** 12kg
- **Boxed Dimensions:** 58.4cm x 45.7cm x 53.3cm
- **VIDEO:**https://www.youtube.com/watch?v=xBLl7l0yPtc

https://shop.lulzbot.com/lulzbot-mini-v2-0-boxed-for-retail-na-kt-pr0047na

XYZ da Vinci Nano

Figure 35: XYZ da Vinci Nano

Build Area: 120 x 120 x 120 mm

Cost: 160€

- **Print Technology :** FFF
- **Layer Resolution :** 100 - 300 microns (Orange) 100 - 400 microns (White)
- **Filament Diameter:** 1.75 mm
- **Material Compatibility:** PLA/ Antibacterial PLA / PETG / Tough PLA
- **Nozzle Diameter:** 0.3 mm (Orange) 0.4 mm (White)
- **Operating Temperature:** 15 ~ 32°C
- **Connectivity:** USB 2.0 Cable
- **Packed Dimensions**: (WxDxH) 406 x 338 x 386 mm
- **Packed Weight** :7.3 kg
- **VIDEO:** https://www.youtube.com/watch?v=WdkErqMO8nk

https://www.xyzprinting.com/en-GB/product/da-vinci-nano

Polaroid PlaySmart 3D

Figure 36: Polaroid PlaySmart 3D

Build Area: 120 x 120 x 120 mm

Cost: 600€

- **3D printing method:** Fused Filament Fabrication (FFF)
- **Maximum print volume :** 14,8 l
- **Material Diameter:** 1,75 mm
- **Print material:** PLA, PETG , ABS, CAP, Carbon, Flexible, HIPS, Laywood, Nylon, Wood
- **Layer thickness:** 0.05mm-0.3mm,
- **Optional mouthpiece diameter :** 4 mm
- **Touchscreen** : yes,
- **Printing:** from PC via USB 2,0, SD card and Via WiFi
- **Weight :** 6 kg
- **VIDEO:** https://www.youtube.com/watch?v=Uh74HSJKtZs

https://www.polaroid3d.com/playsmart3dprinter/

Peopoly Phenom

Figure 37: Peopoly Phenom

Build Area: 276 x 155 x 400 mm

Cost: 2.000€

- **Type :** MSLA (LCD+LED) approach
- **Resolution:** 72 um
- **Technology:** MSLA 3D Printing
- **Printer Size:** MSLA 3D Printing
- **Max. Build Volume**: 11.7 l.
- **Panel:** 12.5 in 4K LCD.
- **Pixel Resolution:** 3840 x 2160 pixels.
- **Bed leveling:** Manual.
- **Touchscreen**: 4.3 in color
- **Vat Volume**: 1.8 kg
- **Panel Lifespan:** 400 Hours on average (normally varies from 200-800 hours) and is a consumable.
- **VIDEO:**https://youtu.be/tLiad79gEOo

https://peopoly.net/products/phenom

3Doodler Create Plus

Figure 38: 3Doodler Create Plus

Build Area: free

Cost: 30-250€

- **Weight:** 0.16-0.4 lb
- **Length:** 5.75"
- **Power:** 3 AAA Batteries/ Micro USB / Power Adapter (100-240V)
- **Wireless:** Yes (~5 hours) / No
- **Dual Drive:** No / Yes
- **Filaments:** Eco-Plastic / ABS, PLA, Flexy, Nylon, Wood, Metal
- **VIDEO:** https://www.youtube.com/watch?v=WXcsFPBbGNQ

https://intl.the3doodler.com/collections/create

Toybox 3D Printer

Figure 39: Toybox 3D Printer

Build Area: 190 x 190 x 250 mm

Cost: 350€

- **Supported** OS's: iOS, Android or any web browser
- **Print Speed:** 60 mm/s
- **Print Resolution**: 200 microns
- **Extruder:** 4mm Smooth-Flow Extruder Head
- **Print Bed:** Easy-Peel bed
- **Compatible Systems**: STL OBJ gCode
- **Wi-Fi:** 2.4GHz band
- **LCD Screen:** Touch Screen
- **Dimensions:** 7.4" x 7.4" x 9.05"
- **Weight:** 3kg
- **Print Materials:** PLA non-toxic plastic
- **Voltage:** AC 100V-240V
- **VIDEO:** https://youtu.be/tGUgALOF0pw

https://toybox.com/

Creality Ender 3 V2

Figure 40: Creality Ender 3 V2

Build Area: 220 x 220 x 250 mm

Cost: 250€

- **Modeling Technology:** FDM
- **Filament:** PLA/TPU/PETG
- **Working Mode:** Online or SD card offline
- **Filament Diameter:** 1.75mm
- **Slicing Software:** Simplify3d/Cura
- **Machine Size :** 475x470x620mm
- **Product Weight**: 7.8KG
- **Package Weight**: 9.6KG
- **Layer Thickness:** 0.1-0.4mm
- **Print Precision:** ±0.1mm
- **Hotbed Temperature:** ≤100°
- **VIDEO:** https://youtu.be/PbWo7ZCwiKE

https://www.creality.com/goods-detail/ender-3-v2-3d-printer

Elegoo Mars 2

Figure 41: Elegoo Mars 2

Build Area: 130 x 82 x 160 mm

Cost: 200€

- **Layer Height:** 10+ microns.
- **XY Resolution:** 50 Mircons (2560 x 1620 pixels)
- **Z-Axis Accuracy:** 0.00125 mm.
- **Print Speed:** 30-50 mm/h.
- **Bed-Leveling:** Manual (assisted)
- **Display:** 3.5" full-color touchscreen.
- **Built-in Camera:** No
- **File types:** STL, SLC, OBJ
- **Connectivity:** USB
- Frame dimensions: 200 x 200 x 400 mm
- **Weight:** 6,2 kg
- **VIDEO:** https://youtu.be/xMKfqvoSYto

https://www.elegoo.com/products/elegoo-mars-2-mono-lcd-3d-printer

FlashForge Inventor 2S 3D Printer

Figure 42: FlashForge Inventor 2S 3D Printer

Build Area: 150 x 140 x 140 mm

Cost: 650€

- **Print Technology:** FFF (Fused Filament Fabrication)
- **Layer Resolution:** 50-400 microns
- **Positioning Precision:** XY: 11 microns, Z: 2.5 microns
- **Nozzle Diameter:** 0.4mm
- **Filament Diameter:** 1.75mm
- **Filament Compatibility:** PLA, PLA Color Change, Pearl, Elastic, TPU, Flexible Filament, Metal Filled Filament, and Wood Filled Filament
- **Frame & Body:** Plastic Alloy
- **Printer Dimensions (without Lid):** 420 x 420 x 420 mm
- **Connectivity:** USB Cable/USB Stick/Wi-Fi
- **VIDEO:** https://youtu.be/7bCFn6IyEoU

https://flashforge-usa.com/products/flashforge-inventor-2s-3d-printer

Glowforge 3D Laser Printer

Figure 43: Glowforge 3D Laser Printer

- **Max material depth:** 455mm for Basic and Plus; unlimited for Pro
- **Max material width:** 515 mm
- **Cutting area:** 279mm deep and 495mm wide
- **Max material height:** 50mm
- **Max material height with tray:** 13mm
- **Cost:** 2.500-6.000€
- **Glowforge exterior (Pro, Plus, and Basic):** 38″ x 20.75″ x 8.25″ (965mm x 527mm x 210mm)
- **Material Capability :** wood, fabric, leather, paper, cardboard, plexiglass (acrylic), Delrin (acetal), mylar, rubber, cork, sandpaper, foods...and more
- **Cameras:** Wide Angle Camera — Mounted on the lid, provides a view of the entire printable area, accurate within 0.25" (6mm)
- **Macro Camera :** Mounted on the head, provides extreme up-close information for autofocus, accurate within 0.004" (0.1mm)
- **Weight:** 22kg
- **VIDEO:** https://youtu.be/ysCaqh38JVQ

https://glowforge.com/

3.4. Processing Parameters of the Commercial 3D Printers

At least **two critical aspects** must be considered in order to get good characteristics of the final product with the 3D printing process. The first is related to the **procedure of the filament creation**:

- the material types, additives and the mixing method of the material which produce the filament
- the extrusion parameters and the nozzle diameter of the machine that mixes and produces the filament

Table 1: Summary of published work on optimizing the final output of FDM filament processing [(12)]

Material	Additive	Parameters for making filament	Print parameters	Significant input	Output
PLA	HPMC	Extrusion speed, extrusion temperature	Layer thickness, build orientation	Additive	Tensile strength
PLA	ABS-HIPS	Commercial	Layer type, layer thickness, build style	Layer, additive	Tensile strength, elongation, Young's modulus
PLA	Cetylated tannin (AT)	Mixing methods, extrusion temperature, screw model	Layer thickness, road width, raster angle, model temperature	Additive	Tensile strength, elongation, Young's modulus, aquatic degradation system
PLA	Wood flour (WF)	Extrusion temperature	Part fill style, layer thickness, raster angle	Additive	Microstructure, Young's modulus, melting temperatures
ABS	—	Commercial	Layer thickness, road width, raster angle	All input parameters	Surface quality and dimensional accuracy
ABS	Pigment	Commercial	Raster orientation, bead width, raster width, model temperature, color	Raster orientation	Tensile strength, compressive strength
ABS	OMMT	Extrusion speed, extrusion temperature	Model temperature, extrusion speed, nozzle diameter	Additive extrusion speed–temperature	Tensile strength, elastic modulus
ABS	Graphene oxide (GO)	Mixing methods (melt and solvent), extrusion temperature	Model temperature, build orientation	Additive mixing methods (melt and solvent)	Tensile strength and Young's modulus
PP	Short glass fiber (GF) and (POE-*g*-MA)	Mixing methods	Model temperature, layer thickness nozzle diameter, raster angle	Additive	Strength and modulus
PP	Spherical glass microspheres	Mixing methods (melt and solvent), extrusion temperature	—	Additive	Tensile, thermal, and impact properties
PP	Glass fiber	Commercial	Raster angle, layer thickness	All input parameters	Tensile strength and Young's modulus
PP	Polycarbonate (PC)	Extrusion speed, extrusion temperature	Model temperature, layer thickness, extrusion speed	All input parameters	Tensile strength

The second aspect has to do with the FDM machine itself. There are two categories of parameters that affect the printing process: the **working parameters** and the **parameters of the machine** (3D printer).

3.4.1. Machine parameters

- Nozzle diameter (defines the Layer thickness limits)

The default nozzle diameter is usually 0.4-0.5 mm on most Desktop 3D printers, while it can reach >1mm on Industrial machines. Choosing a smaller nozzle is ideal for more detail in the object being printed, making the print time slower. The smaller the nozzle, the more it affects the level of detail almost exclusively in the horizontal plane.

- Nozzle temperature

Refers to the optimum temperature for the manipulation of the material of the filament. This temperature varies, depending on the printer used and the filament type. It is recommended to start with a temperature exactly in the middle of the manufacturer's recommended settings. That is, the manufacturer recommends from a minimum temperature of 180° C to a maximum temperature of 210° C, then a good starting point is printing at 195° C. Then based on the quality of the printed object, the setting can be changed ± 5° C each time. Problems with nozzle temperature occur if it is too hot or not hot enough. In the first case a clasp / string may be encountered on the printing surface, it may be difficult to remove the supporting material, poor surface quality and noticeable odors during printing. Conversely, if the nozzle temperature is not warm enough, reduced mechanical properties are likely to be encountered due to the poor adhesion of the layer. Finally, there may still be nozzle blockages if the thread does not melt quickly enough.

- Bed temperature

Depending on the filament, the manufacturer suggests the temperature that must have developed at the heated bed. (e.g. for PLA a heated bed up to 60° C is recommended). If the temperature suggested by the filament manufacturer has not developed enough in the heated bed, the result will not be satisfactory with several problems like no or poor adhesion on the bed, causing it to fail from the beginning of the printing process. Exceeding the filament recommended temperature can cause rapid crystallization of most filaments, but mainly cause distortion of the printing pattern. An important factor for the correct temperature of the bed is the printing environment and the size of the model. [(13)]

- Chamber temperature

The quality of 3D printing can be affected by room temperatures such as printing with ABS or resin at low temperatures, there is a possibility of printing failure or poor adhesion and lower strength of the layers (not a problem with PLA) . Many manufacturers, in order to be able to control the operating temperature of their 3D printer, create a housing for temperature control, especially on industrial machines. This way there is temperature control, adjusting the desired housing temperature to provide maximum print performance. This is usually done by having the temperature sensor in the correct position so that there are correct temperature readings throughout the housing and not just in one area. Many times it is necessary to have some kind of air extraction system (eg to remove polluted air except such as Carbon Foam or filter, Air Purifier, HEPA Filter, PECO Filter etc) and to constantly clean the environment of the housing. Cooling is also quite important and for this reason special coolers, thermal cooling paste and fans are placed everywhere. Overheating should also be avoided, because it leads to problems in the equipment, reducing their lifespan or in the construction of the object itself, since there will no longer be the ideal construction temperatures. [(13)]

- Build speed

The build speed determines how fast the 3D printer motors move (e.g. on the X, Y and Z axes). The speed can be adjusted to reduce the total production time but having a poor adjustment will lead to printing imperfections and failures. If the speed is too slow then the nozzle stays in place for a long time and will cause the print to warp. If the speed is too fast then there is weak layer adhesion, there may be other overheating artifacts caused by insufficient cooling, as well as ringing. To improve printing, this setting is usually divided into minor settings such as: Outer wall / shell speed, Inner wall / shell speed, Infill speed and Top / bottom speed.

- Build size

It is the available volume of a 3D printer to build the objects. Desktop 3D printers usually have a build size of about 200x200x200 mm, while for industrial machines it can reach 1000x1000x1000 mm. In desktop machines, a big model can be created by breaking it down into smaller parts and then assembling them.

- Layer height

varies between 50 and 400 µm. Smaller layer heights produce smoother parts and create curved geometries more accurately, while larger heights produce the objects faster and at a lower cost. [(3)]

3.4.2. Working parameters

- Build orientation

Orientation has a significant impact on the printing time but also on the correct representation of the object. The direction of the loads should be taken into account mainly for the functional components (e.g. the parts that are usually located on the Z axis are very likely to detach in comparison with the XY axis, statistically there is a 5.5 times difference in tensile strength). The time that must be devoted in order to have the optimal orientation of the object in order to reduce the possibility of print failure and the amount of required support is important. Finally in the final orientation we must take into account that there is a better surface finish on the surfaces located either at the bottom or at the top of a 3D printed section. This varies from process to process depending on FDM, SLA, SLS, parts printed with Binder Jetting or Material Jetting.

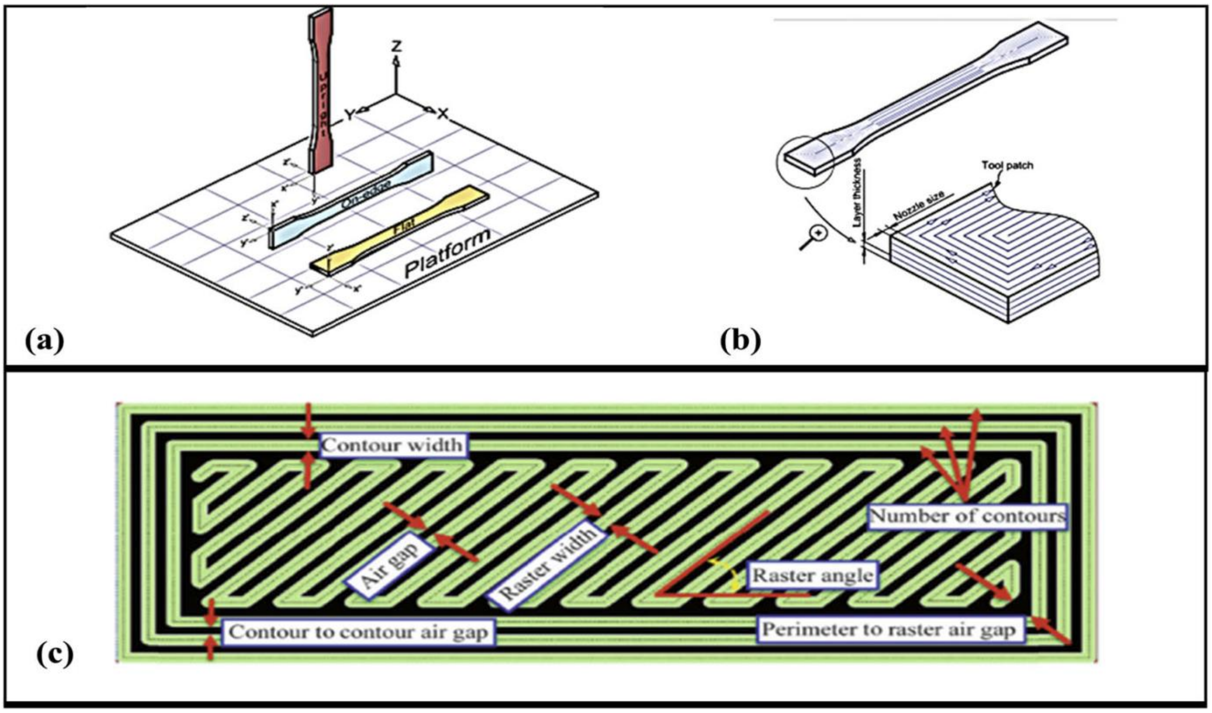


Figure (a) shows the different build orientations of the object toward the X, Y, and Z axes on the build platform.

Figure (b) presents the layer thickness deposited on the nozzle tip. The user's thickness value in a specific range is defined by the nozzle diameter and limited by the printer accuracy.

Figure (c) describes the FDM tool path explaining parameters such as raster angle, raster width, contour width, number of contours, and so forth. [(3), (12)]

Figure 44: Working parameters: Build orientation, Layer thickness and Tool path

- Infill density

Fill density determines the "fullness" of the interior of an object. Usually the density is from 0% to make a part hollow up to 100% which is completely solid. Density affects the weight of the object, ie the fuller the interior the heavier it will be. The printing time, buoyancy and the final consumption of material that will be needed are also affected. Also, any density changes can be determined in areas where we need more density (e.g. for better strength in these areas).

- Infill pattern

The infill pattern refers to the structure and shape of the material within a part. This can be done with simple lines and reach to more complex geometric shapes. Different slicer programs have several options in the filling patterns. Some of them are: Lines, Honeycomb, Grid, Triangles, Tri-hexagon, Cubic, Octet, Gyroid, Concentric etc.

- Raster angle and raster width

Raster angle refers to the rise of the raster pattern concerning the *X* axis in the lowest layer. The proper raster angle is from 0° to 90°.

Raster width is the width of the material droplets used for the raster. Raster width values vary based on the size of the nozzle tip. A larger raster width value will build the part with a stronger interior. A smaller value will require less time and material production.

- Air gap

The air gap occurs during the extrusion of the filament to the bed or the previous layer. It is the distance between the roads (rasters or contours). It can be affected by raster width, raster angle, and some other things like machine calibration.

- Contour width and number of contours

The contours are toolpaths that follow the outline of a region. Regions are defined by contours and then filled with rasters.

- Layer thickness (depending on the nozzle diameter)

The height of the slices of the 3D printing object. Thicknesses can be 0.005 in. (0.127 mm), 0.007 in. (0.178 mm), 0.010 in. (0.254 mm) and 0.013 in. (0.33 mm). Shorthand for these thicknesses are 5 slice, 7 slice, 10 slice and 13 slice, respectively. Using thinner layers increases the surface quality and dimensional accuracy.

Many studies have tried to identify the optimal parameters to improve the material consumption, mechanical properties, development time, surface finish and aesthetics of the 3D printed objects. The quality characteristics of FDM objects, such as flexural strength, hardness, tensile strength, compressive strength, dimensional accuracy, surface roughness, production time, yield strength, and ductility are the main concerns for producers and users. However, there is still no best condition for all types of parts, materials and 3D printer technologies used.

Apart from these parameters, there are also other factors that affect the final product, which are related to the technology of the 3D printer. As we have seen, apart from the FDM technology there are plenty of other types of technologies used in 3D printers, like VAT Photopolymerization, Material Jetting, Binder Jetting, etc. Each one of these types have different machine and material parameters that need to be taken into account. [(12)]

For example in SLA and SLS systems, most print parameters are predefined by the manufacturer and cannot be changed. The only parameters are the layer height and part orientation. In Material Jetting, even the layer height is predefined for each specific material.

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