Research Assignment for Exchange Students

Medical Applications of Materials Manufactured by the AM Process

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Autores: Alexandra Morais | João Festas

Coordinator: Irene Buj

Escola Tècnica Superior
d'Enginyeria Industrial de Barcelona

Abstract

The use of 3D printing for manufacturing parts has made it possible to produce components with complex geometries according to drawings made on the computer. 3D printing offers many advantages in the manufacture of polymers and composites, including high precision, low cost, and custom geometry.

Several techniques are used in 3D printing, the ones discussed in this monograph are the main ones for polymers. These are: fused deposition modeling (FDM), Injection 3D printing (3DP), Stereolithography (SLA), and finally selective laser sintering (SLS).

The 3D printing technique has several applications, however, the focus in this project is to analyze the various medical applications and the main advantages and disadvantages associated with it.

Some of the main applications of this type of technology that will be described throughout the project are:

- Bioprinting of tissues and organs
- Customized Implants and Protheses
- Anatomical Models for Surgical Application
- Pharmaceutical Application

The main objective will be to analyze, for these procedures, what are the advantages associated with the use of 3D technology and what are the goals for the future in this field.

In addition, it will be important to mention the advantages and disadvantages of this combination (3D printing and medicine) in a more general overview, identifying numerous advantages but also potential risks that need to be taken into account.

In order to deepen the analysis further, two practical cases will be studied, ensuring their contextualization for the project and also a verification of the improvements and processes facilitated by the application of 3D technology in these fields.

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1. Prefacio

1.1 Project origin

This project arises from the development of the curricular unit "Research Assignment for Exchange Students" and has the theme "Medical Applications of Materials Manufactured by the AM Process" due to the shared decision between the student authors and the coordinating professor.

As students, our main goal would be to develop a project that would not only be related to what we have been learning during the course but also something that would be really interesting and for which we would feel motivated to research and learn more.

1.2 Pre - requirements

The main requirements for the project were the development and analysis of the various 3D printing processes and their applicability in the medical field. The intention is to study not only existing technologies but also possible new strategies for the future.

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2. Introduction

3D printing, also referred to as additive manufacturing or rapid prototyping is a process of adding material, usually layer by layer to produce objects using computerized 3D models. This technology creates objects by addition of material in order to reduce material waste and achieve high geometric accuracy. This process starts with a 3D computer mesh model that can be created by images or structures built in CAD (Computer Aided Design) software.

Additive manufacturing processes can be classified, regarding the ISO/ASTM 52900, into seven categories: Binder Jetting, Material Extrusion, Directed Energy Deposition, Material Injection, Power Bed Fusion, Sheet Lamination and VAT Photopolimerazation [1].

Recently, due to the increasing complexity and multifunctionality of products many new materials such as nanomaterials, biomaterials and smart materials have been explored. For example, the incorporation of particles, fibers or nanomaterials reinforced in polymers allows the manufacture of polymer matrix composites, which are characterized by high performance mechanical performance and excellent functionality.

That said, the use of 3D printing technology for medical purposes has become quite appealing. Thus, the potential and current use of 3D printing can be categorized into the following applications: bioprinting of tissues and organs, customized implants and protheses, anatomical models for surgical preparation and pharmaceutical application.

This type of application of 3D technology allows the customization and personalization of medical products and equipment, a better price-quality ratio, and also increased productivity due to time savings.

However, it is important to note that there are also some disadvantages associated with these technological developments, as the unrealistic expectations that are created or the safety and security, topics that are going to be deeply discussed during this assignment. Furthermore, development in medicine will still take several years, since many applications are still in the premature stages of research.

The main objectives of this project are:

- To understand the 3D printing technology, as well as the various materials used, with a main focus on FDM technology, this being one of the processes that stands out most in the medical application under study;
- To analyse of the main benefits and disadvantages of 3D printing by the FDM process;
- To study of the main printers and their properties, in order to understand which are the best for each application;
- To analyse and in-depth study of the various medical applications today;
- To analyse of two current practical cases to realize the applicability of the study in reality

3. 3D Printing: What is it and how is it processed

3D printing, also known as additive manufacturing (AM), is a method used to produce physical models having as a starting point a CAD model. This process is pretty much unlimited when it comes to shapes of the final product and it even allows obtaining porous parts. One of the most important characteristics of AM is that the final product is built by the adding of material layer-by-layer. If good accuracy is pretended, the layers need to be thin because the thinner the layer, the bigger the accuracy but the longer the time of production [2].

For the process of transformation from the 3D CAD model to the final product there are some stages to consider: after the first model in CAD, this file is converted to ".STL" which turns the geometry's surfaces into triangles; after that it is introduced into the software, creating a new type of file in which, all the surfaces that create the volume of the product get converted into layers (some different type of layers are created, supports, if necessary, depending on the shape of the final piece) [2].

Figure 1 - Phases of the addictive manufacturing process [3]

Various printing techniques have been employed to manufacture of polymer composite parts. These include fused deposition manufacturing (FDM), selective laser sintering (SLS), injection molded 3D printing, and stereolithography (SLA). [3] In addition to the processes, additive manufacturing is divided into categories, depending on how the deposition of the layers takes place. According to the ISO/ASTM 52900 there are 7 categories in which 3D printing can be divided that are presented in figure 2 and explained below: [2]

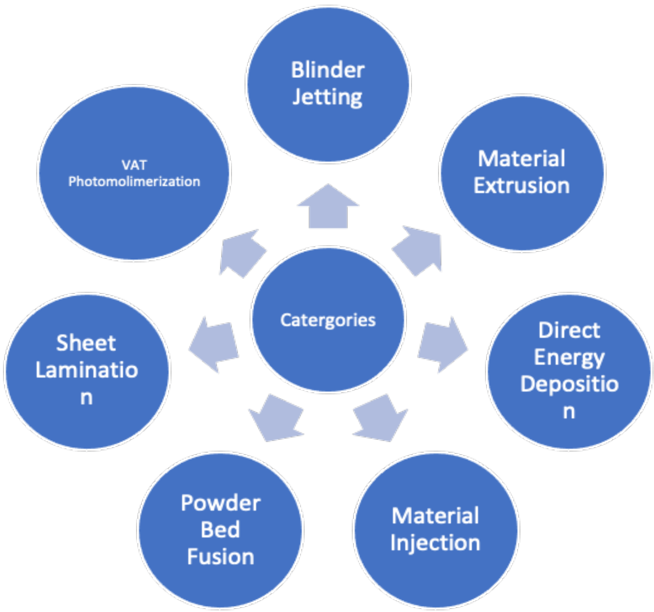

Figure 2 - Additive Manufacturing Categories [3]

3.1 Binder Jetting

This process uses two materials; a builder material in powder form and a binder that usually is a liquid. The last one acts as an adhesive between powder layers. A print head moves along X and Y axes of the machine and deposit alternate layers of powder material and binder [4], [5].

- Powder material is spread over the build platform using a roller.
- The print head deposits the binder adhesive on top of the powder where required.
- The build platform is lowered by the model's layer thickness.
- Another layer of powder is spread over the previous layer. The object is formed where the powder is bound to the liquid.
- Unbound powder remains in position surrounding the object.
- The process is repeated until the entire object has been made.

3.2 Material Extrusion

Material extrusion is a process that can be explained as the use of a continuous filament of thermoplastic that is fed from a coil, through a moving heated printer extruder head. After that, material is drawn through a nozzle, where it is heated and is then deposited layer by layer. The nozzle can move horizontally, and a platform moves up and down and vertically after each new layer is deposited. In this procedure the material is added in constant pressure and in a continuous stream. Fused Deposition Modeling (FDM) is a the most common form of material extrusion [4].

- First layer is built as nozzle deposits material where required onto the cross sectional area of first object slice.
- The following layers are added on top of previous layers.
- Layers are fused together upon deposition as the material is in a melted state.

Other process of material extrusion is known by direct ink writing (DIW), that works the same as the others, but in which a paste is extruded instead of a filament. The resultant products of this kind of process have great potential mainly in tissue scaffold templates and drug delivery due to their inherent biocompatibility [6].

3.2.1 FDM process

The FDM process is the most widely process inside the 3D printing options mostly because of its simple way of producing the objects, it being available for a lot of people and activities and because it is able to maintain a very attractive compromise between size, costs of the entire operation and the quality of the final model [2].

The machines utilized for the FDM process all have the same 4 main parts that are essential for this procedure: the plastic filament, the feeder, the printing head and the building plate. Sometimes the machines can have two printing heads, one for the construction material (to make the model) and the other for the support material (as mentioned before, some geometries require a support to also be produced) [6].

In this process, thermoplastic filaments are the raw materials used as feedstock. These are melted in the liquefier to a semi-liquid state and are then extruded onto a platform or the building plate following the path dictated by the software and at a specific temperature. After the first layer, the plate lowers a bit and the machine is ready to produce the second one. Every new layer is deposited on top of the older ones, merging with them because of the high temperatures. This is repeated until the entire model is done. The final properties of the manufactured products will depend on the selection of the material and the machine's parameters: layer resolution, build orientation, temperature, raster angle, and air gap; these will affect mechanical and thermal properties that we want to control. Interlayer distortion is considered to be the main cause of lower mechanical strength [6].

In figure 3 it can be seen, in a schematic way, the explained procedure.

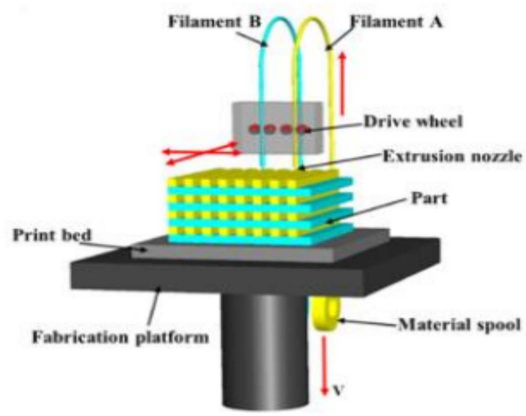

Figure 3 - FDM process schematic [2]

3.3 Direct Energy Depositio*n*

This is a more complex 3D printing process used to repair damaged components or add new material to existing ones. This process is similar to material extrusion but the nozzle is not fixed in any axis. The material is melted upon deposition with a laser or electronic beam [4].

- A4 or 5 axis arm with nozzle moves around a fixed object.
- Material is deposited from the nozzle onto existing surfaces of the object.
- Material is either provided in wire or powder form.
- Material is melted using a laser, electron beam or plasma arc upon deposition.
- Further material is added layer by layer and solidifies, creating or repairing new material features on the existing object.

3.4 Material Injection

In this process material is jetted into a platform continuously or by Drop on Demand. Since the material can be deposited in drops, there are few materials available to utilize. The print head moves horizontally across the platform. The product is then hardened by the use of UV light [4].

- The print head is positioned above build platform.
- Droplets of material are deposited from the print head onto surface where required, using either thermal or piezoelectric method.
- Droplets of material solidify and make up the first layer.
- Further layers are built up as before on top of the previous.
- Layers are allowed to cool and harden or are cured by UV light. Post processing includes removal of support material.

3.5 Powder Bed Fusion

With PBF, a laser or electron beam to melt and fuse together powder material together. There is a reservoir that provides a new layer of material after the laser is applied in the one before. Some methods require vacuum but enable the manufacture of metal and alloy parts [4].

- A layer, typically 0.1mm thick of material is spread over the build platform.
- A laser fuses the first layer or first cross section of the model.
- A new layer of powder is spread across the previous layer using a roller.
- Further layers or cross sections are fused and added.
- The process repeats until the entire model is created. Loose, unfused powder is remains in position but is removed during post processing.

3.5.1 Injection Molded process

This technology is based on powder processing. The powders are first spread on the build platform and are then selectively brought together in a standardized layer by deposition of a liquid binder, injected through the printer nozzle. After the desired 2D pattern, the platform lowers and the next layer of powder is spread. This process
is repeated until the desired part is obtained, at the end the powder that has not been integrated is removed [2].

The main advantages of this technology are the wide range of materials that can be
used and the room-temperature processing environment. Theoretically, any polymer
in the powder state can be printed by this technology [2].

In figure 4 it can be seen, in a schematic way, the explained procedure.

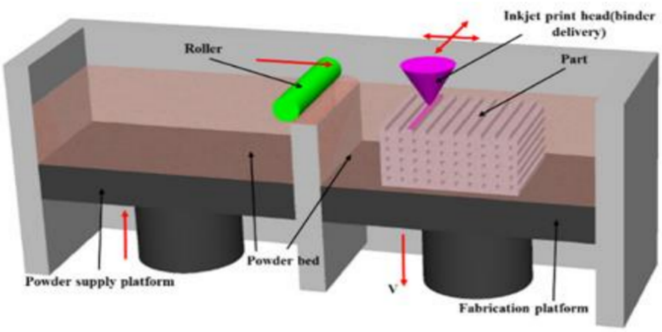

Figure 4 - Injection Molded process schematic [2]

3.5.2 SLS process

The selective laser sintering technique is similar to the 3DP technique already mentioned. Both are based on powder processing. Instead of using a liquid binder, in SLS, a laser beam selectively scans the powders to sinter them by heating to form a
solid object. The parts are built on a platform that lies immediately below the surface of a container filled with the fusible powder (by heat). A laser beam synthesizes the first layer into the shape of the object to be obtained. The platform is lowered slightly, the powder is reapplied, and the laser traces the second layer, and so on [7].
Excess powder is then removed by vacuum and, if necessary, processes and details
as coating, sintering, or infiltration are performed [6].
Although, theoretically, any thermoplastic polymer in powder form can be processed by the SLS technique, the complex consolidation behavior and molecular diffusion process during sintering have limited the choice of materials used in the SLS process. The laser can only be used for powders with low melting/sintering temperature. So far, polyamide (PA) is the most widely used in this process. Good resolution, optimum print quality and resistance to heat and chemical resistance are the main advantages of this process, as well as the possibility of Printing more complex parts. However, it is a slow process [2].
In figure 5 it can be seen, in a schematic way, the explained procedure.

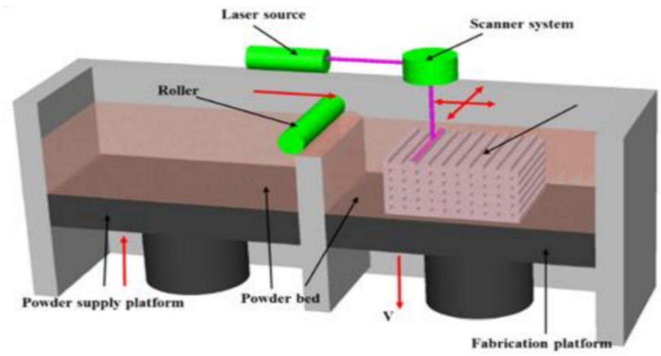

Figure 5 - SLS process schematic [2]

3.6 Sheet Lamination

It includes Ultrasonic Additive Manufacturing (UAM) and Laminated Object Manufacturing (LOM). The material utilized in the first one are ribbons or sheets of metal that are joined together by ultrasonic welding. It requires some CNC machining to remove the unwanted material. LOM uses the same approach but the material in this procedure is paper that is bound together by an adhesive. The final products in this procedures are not used for structural use [4].

- The material is positioned in place on the cutting bed.
- The material is bonded in place, over the previous layer, using the adhesive.
- The required shape is then cut from the layer, by laser or knife.
- The next layer is added.
- Steps two and three can be reversed and alternatively, the material can be cut before being positioned and bonded.

3.7 VAT Photomolimerization

Vat polymerisation uses a reservoir of liquid photopolymer resin, out of which the model is constructed, as usual, layer by layer. Like in Material Injection procedure, an UV light is used to cure or harden the resin where required (according to the model), whilst a platform moves the object downwards after each new layer is hardened [4].

- The build platform is lowered from the top of the resin vat downwards by the layer thickness.
- A UV light cures the resin layer by layer. The platform continues to move downwards and additional layers are built on top of the previous.
- Some machines use a blade which moves between layers in order to provide a smooth resin base to build the next layer on.
- After completion, the vat is drained of resin and the object removed.

3.7.1 SLA process

This technology, better known as SLA (Stereolithography), allows the construction of 3D models from a light-sensitive liquid polymer that, when exposed to radiation, solidifies. The model is built on a plate, located below the surface of a liquid bath of epoxy or acrylic resin. A UV laser source maps out the first layer. This solidifies the cross-section of the model, leaving all other areas liquid. The plate is again submerged in the polymer bath and the laser creates the second layer. The process is repeated until the model is complete. Finally, the model is placed in a UV radiation oven in order to do a more complete cure [7].

The intensity of the laser power, the scanning speed and duration of exposure affects the printing time and resolution. Photoinitiators and UV absorbers can be added to the resin to control the depth of polymerization [2].

The main advantage of SLA printing technology is the ability to print parts with high resolution and optimum surface quality. In addition, because SLA is nozzle-free technique, the problem of nozzle clogging can be avoided. Despite these advantages, the high cost of this system, the fact that it is relatively slow and the materials possible to use are very limited are the main concerns for industrial application [6]. This method was the first that showed good results for rapid prototyping [8].

In figure 6 it can be seen, in a schematic way, the explained procedure.

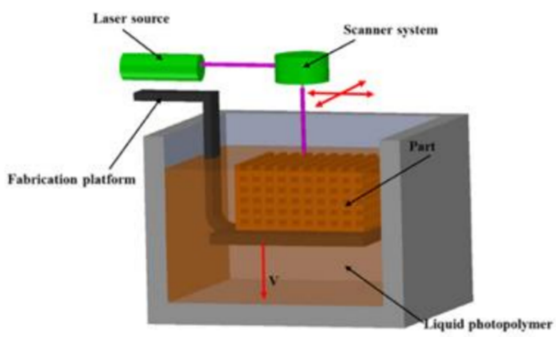

Figure 6 - SLA process schematic [2]

Each technique has its own advantages and limitations in the production of composite products. The selection of production technique depends on the starting materials, processing and resolution speed requirements, costs, and performance requirements of the final products.

4. Advantages and Disadvantages of 3D printing with FDM process

Considering the subject of the proposed project, this chapter is intended for a more detailed analysis of the FDM process. To do so, we will now analyze its main advantages and disadvantages in the table 1 [9].

Table 1 - Advantages and Disadvantages of the FDM process

Advantages	Disadvantages
Does not use toxic materials	Low construction speed
Simple post processing operations	Low resistance in the vertical direction
Cheap printers (some of them)	The precision depends on the thickness of the filament
Silent and secure technology	Possibility of surface defects
Wide range of materials	Low waterproofness
Affordable price of materials	Low resolution for small parts and fine details
Hole parts can be quickly printed	
Filament is clean and easy to change (compared with powder or liquid)	

Compared to other processes, FDM stands out mainly because of the positive properties presented above. The fact that it does not use toxic materials makes it easy to use, since it can be used in any environment, even in closed places such as offices. Furthermore, despite being a slow process for the construction of parts with complex geometry, it proves to be one of the processes with the easiest demolding, taking only the post-process about 15 minutes [8].

This is one of the most economical technologies inside the 3D printing market, since, in addition to printers, it is shown to use inexpensive materials. Added to these advantages is the fact that the process is very simple at the technological level, having contributed significantly to the easy adaptation of any user, greatly developing 3D printing in a common medium [8].

Some of the bad mechanical properties that result from this procedure need to be taken into account, mostly for very delicate applications. Adjusting the machine properties and the choosing of the right material can help with mitigating this possible bad impact [8].

Furthermore, we consider it important to extend this chapter with the main defects found in the FDM process, since these too can generate major disadvantages for the final product and therefore for the application of the procedure in general.

4.1 Staircasing effect

When fabricating a product by the FDM procedure, a manufacturing file would be generated by slicing the 3D model into a series of 2D layers with a certain thickness. As for the outer surface, it's actually approximated by the vertical edges of many adjacent layers. The successive layers create the structure of the final product and that disposition is called the "staircasing", as it can be seen in figure 7 [10].

To minimize this effect there are surface treatment solutions such as sanding, painting, application of acetone, and even the application of other specific products.

XTC, a product of the SMOTH-ON brand, is economical, rectifies the stairway the staircase effect, making it possible to paint the piece afterwards. This product can be applied on various types of surfaces such as plastic paper, foam, cardboard, ABS, PLA, SLS Prints, SLA Prints, among others [10]. Another method that can be used is the application of acetone on the surface of the object, which, depending on the exposure time the acetone, presents various levels of corrosion until it reaches the desired appearance [10].

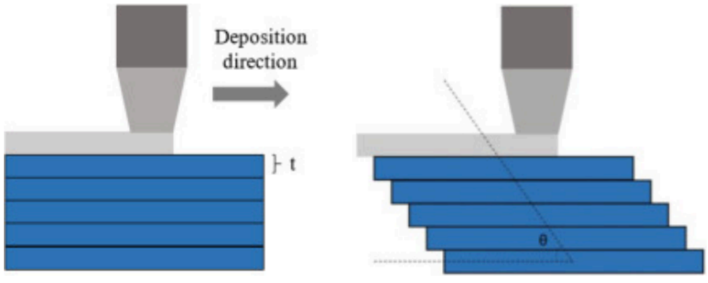

Figure 7 - Staircasing effect schematic [10]

4.2 Stringing effect

Stringing (also known as oozing, whiskers, or "hairy" prints) is the formation of tiny strings of plastic on a 3D printed item, as it can be seen in figure 8. This is usually caused by plastic leaking from the nozzle when the extruder moves to a new spot. The most frequent setting used to combat excessive stringing is called retraction. If retraction is enabled, when the extruder has finished printing one area of your object, the filament will be dragged backwards into the nozzle to prevent oozing. When it's time to start printing again, the filament will be pushed back into the nozzle, causing plastic to extrude from the tip once more [11].

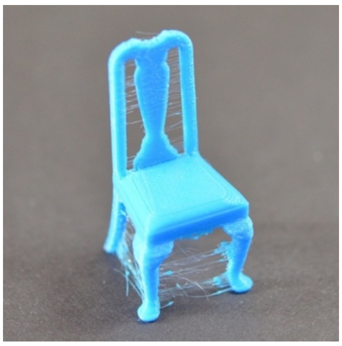

Figure 8 - Stringing effect [11]

4.3 Warping effect

Warping happens as a result of material shrinkage during 3D printing, causing the print's corners to lift and separate from the build plate, as it can be seen in figure 9. When polymers are printed, they first expand somewhat before contracting as they cool. If the material shrinks too much, the print will bend up from the build plate. Some materials shrink more than others (for example, PC shrinks more than PLA), which increases the likelihood of warping when used [12].

To avoid warping is necessary to make sure the 3D print is tightly adhered to the construction plate. The print may become loose if it does not have excellent adherence. This is especially frequent near corners [12].

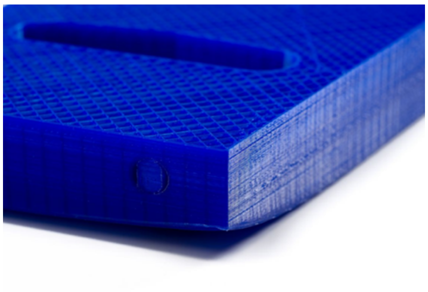

Figure 9 - Warping effect [12]

4.4 Delamination or cracking effect

Layer delamination happens when the layers of a 3D print separate or do not adhere entirely, as it can be seen in figure 10. This can occur for a variety of causes, including too-low temperatures, over-cooling, a high layer height, a contaminated hot end, and so on [13].

Figure 10 - Delamination effect [13]

The main actions that can prevent this phenomenon are:

- Increasing hot-end temperature

The first remedy to layer separation is to raise the temperature of your printer's hot-end. Layers are joined together by fusing them using heat. If the extruding material's heat is too low, it will not be able to attach to the prior layer [13].

- Adjusting Print Cooling

The fan of a 3D printer cools the freshly put down layer of plastic; but, if it is cooled too rapidly, the newly added plastic will not be able to cling to the previous layer as strongly, hence reducing the fan speed might possibly boost layer adhesion and, thus, print strength.

This is similar to the preceding point in that increasing the printing temperature will result in better layer bonding, and cooling them down too rapidly may also result in the same unpleasant consequence [13].

- Increasing flow rate

If the layers aren't attaching properly, increasing the flow rate slightly may assist since it will extrude more molten plastic, and the more material there is, the greater the adhesion.

Under-extrusion can be seen as gaps between the layers of plastic, inadequate little layers, missing layers, or even small spots on the print, and it definitely has an impact on the strength of your object [13].

- Slowing print speed

Lowering the print speed has the same effect as increasing the printing temperature in that it allows the newly extruded plastic to better connect with the preceding layer. If the print head moves too quickly, the extruded plastic may not have enough time to adhere correctly to the preceding layer.

Not only that, but printing at a faster speed can cause a slew of additional problems, such as under-extrusion (which weakens the component), ringing, certain apparent artifacts, and overall poor layer adhesion [13].

- Using a wider nozzle

The breadth of the extruded plastic is affected by the nozzle diameter. Essentially, a 0.8mm nozzle will lay down a strip of plastic twice as broad as a 0.4mm nozzle and double the contact surface area, resulting in considerably greater adhesion between the layers [13].

Because it improves the surface contact area, employing a lower layer height results in greater layer adhesion. If you increase the nozzle size while maintaining the same low layer height, all of the layers will have a lot greater contact surface area, resulting in a stronger bond.

It should be noted, however, that increasing the nozzle size will result in substantially less detailed prints in the horizontal plane (whether seen from the top or bottom) since the layers are much larger [13].

5. Common Plastic Materials

The selection of the material that will be used for the manufacture of parts by 3D printing is determinant. Each object to be produced has unique characteristics and these peculiarities need to be met by the chosen material.

To define the ideal material and avoid wasting time and investment, it is essential to consider the application of the part to be produced, the characteristics of the chosen material, and the cost of the project.

In this particular case, the study will be mainly conducted on polymers and particle-reinforced composites. In this way, a brief explanation will be given of the essential materials applied.

5.1 Polymers

A polymer is a macromolecule made up of a set of smaller molecules, known as monomers. One of the most common types of polymers used in 3D printing are thermoplastics [13].

Thermoplastics are plastics that can change state without changing their chemical properties. This makes them popular materials in 3D printing because they can be easily melted, extruded layer by layer, and immediately cooled into a shape. However, the properties that make them good for 3D printing make them unsuitable for engineering applications. Many of these thermoplastics have a relatively low melting point and are not very tough or rigid [15].

5.1.1 ABS

ABS filament is the most commonly used 3D printing polymer and is used in

car bodies, household appliances, and cell phone covers. It is a thermoplastic and contains a polybutadiene-based elastomer base that makes it more flexible and shock resistant [15].

ABS is used in 3D printing when heated between 230°C and 260°C. It is a tough material resistant material, able to easily withstand temperatures from -20ºC to 80ºC. In addition to its high strength, it is a reusable material and can be welded with chemical processes. However ABS is not biodegradable and contracts on contact with air, so the printing platform must be heated to avoid deformation. In addition, it is recommended to use a closed chamber 3D printer to limit closed chamber to limit particulate emissions when printing with ABS. ABS is mainly used in deposition modeling technologies for materialcast material. There is, however, a liquid form of ABS, which is sometimes used in stereolithography and PolyJet processes [15].

5.1.2 PLA

This thermoplastic material has the advantage of being biodegradable, unlike ABS. PLA is made from renewable raw materials such as corn starch. This material is among the easiest to print, however, it has a tendency to shrink after printing. Unlike ABS, a heated platform is not required when printing. And the temperature at which it prints is lower, between 190ºC and 230ºC. PLA is more difficult to manipulate due to its high speed of cooling and solidification. It is also important to mention that the models can deteriorate when in contact with water [15].

Despite this, the material is consistent, simple to use, and possessed a wide range of colors, making it suitable for FDM 3D printing [15].

5.1.3 PET

PET is usually seen in disposable plastic bottles. This material is the ideal filament for any part intended for contact with food. In addition, the material is very rigid and has good chemical resistance. The ideal temperatures for printing PET are 75ºC to 90ºC. PET is marketed with variants such as PETG, PETE, PETT [15].

An advantage of using PET is that no odors are released during printing and is 100% recyclable [15].

5.1.4 PC

PC is a high-strength material designed for engineering applications. The material has good temperature resistance, able to withstand any physical deformation up to around 150ºC. However, PC is prone to absorb moisture from the air, which can affect the performance and resistance. Therefore, PC should be stored in airtight containers [15].

When printing something using PET, high temperatures are required. If otherwise, the separation of the layers becomes visible due to either the use of low temperatures or due to excessive cooling. Having said this, and as an advantage to the use of PC, there are polycarbonate filaments that contain additives that allow the filaments to be printed at low temperatures [15].

5.1.5 PA

Corresponds to a synthetic polymer with good strength and a certain flexibility, moderate chemical resistance and high fatigue resistance. Objects made from polyamides are usually created from a fine, white, granular powder. However, there are some variants of the material, such as nylon, that are also available in filaments used in fused deposition molding (FDM). Because of their biocompatibility, polyamides can be used to create parts that come into contact with food (except food containing alcohol) [15].

Polyamides consist of semi-crystalline structures, have a good balance in chemical and mechanical characteristics to provide good stability, stiffness, flexibility and stiffness, flexibility and shock resistance. These advantages mean that the material has many applications across different industries and offers a high level of detail [15].

Because of their high quality, polyamides are used in the manufacture of gears, parts for the aerospace market, automation, robotics, medical prosthetics, injection molds and essentially in applications involving press fit plugs, tools with press fit inserts, components fitting inserts, components subjected to high vibrations and parts containing threaded inserts [16].

5.1.6 PP

While polypropylene is commonly utilized in the plastic injection industry, it is not frequently employed in additive manufacturing since it is not the most easily printed thermoplastic. Because PP has highly precise melting points, it is critical to manage the temperature throughout the process because it is a semi-crystalline material [17].

The main pros of this material that make it being used for some applications are the good impact and fatigue resistance, the good heat resistance and also the smooth surface finish.

5.1.7 TPU

It belongs to the family of thermoplastic elastomers and combines the best properties of thermoplastics and rubbers (thermosetting). TPU is a filament in common use in 3D printing through the manufacture of meltblown filaments, due to the fact that it is a thermoplastic elastic and combines the best properties of thermoplastics and rubbers (thermosets) [18].

This makes it ideal for printing objects that need to be flexible and elastic. TPU can be considered the latest version of TPE. TPU has rubber-like elasticity similar to rubber, high wear and abrasion resistance, high elongation at break and thermal stability [18].

In the chart below, figure 11, it is succinctly represented some properties that allow us to distinguish between some of the thermoplastics mentioned previously mentioned. Taking into account the purpose of the material, we proceeded to the analysis of the main categories of materials for this purpose, thus being able to highlight: Ease of printing; Visual quality; Maximum stress (maximum stress that the object can suffer before fracture by slow traction); Elongation at break; Impact resistance; Adhesion of the layer and heat resistance.

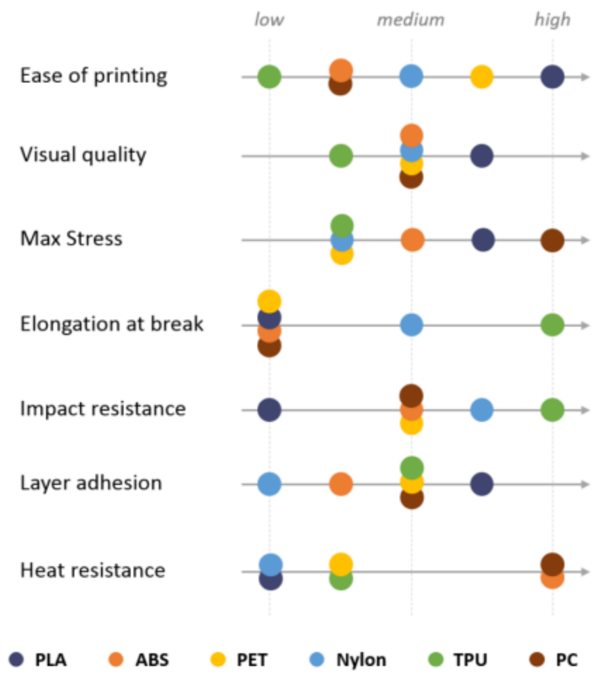

Figure 11 - Comparing chart of different materials [19]

From figure 11, you can see that PLA is the easiest material to print on, unlike TPU.
unlike TPU. As for visual quality, most materials have an average quality.

Regarding the maximum stress, PC stands out, while the elongation is not very high. Rupture already stands out the TPU, because it has an elasticity similar to that of rubber. In a similar, TPU is the material that has the best impact resistance, unlike PLA, which has the lowest. In layer adhesion, we can conclude that nylon has the least layer adhesion.

Finally, in the analysis of heat resistance, it can be said that PC and ABS take a prominent role, because as was said in the description of both polymers, they can work at higher temperatures compared to the others, therefore being the ones with the best heat resistance.

5.2 Composites

Composite materials, on the other hand, are parts composed of more than one material that, when combined, have different properties than their original materials. When we are talking about composites from an engineering point of view, it usually refers to composites with reinforcing fibers [14].

5.2.1 Reinforced by particles

Reinforcement through the use of particles is widely used to improve the properties of the polymer matrix. Particles are easy to be mixed with polymers, either in powder form for SLS or in liquid form for SLA, or to be extruded into filaments for FDM. Key issues for consideration in the 3D printing of reinforced composites include: improved Young modulus by adding glass particles, iron particles or copper particles; improved wear resistance by adding aluminum and aluminum oxide (Al2O3) and improved dielectric permittivity by adding ceramic material or tungsten particles [2].

The addition of particles in polymers also helps solve some difficulties in the printing process. One obstacle for the FDM printing process is distortion of the final printed parts, which is caused by thermal expansion of the polymer. Incorporating metal particles into polymers has been proven to be a good solution to this problem. When combined with copper and iron particles, ABS composites showed a large reduction in the coefficient of thermal expansion, leading to much reduced distortion of the printed part [2].

5.2.2 Reinforced by fibers

Fiber reinforcements can also significantly improve the properties of polymer matrix materials. For FDM processing, polymer pellets and fibers are first mixed in a blender and then delivered to the extruder to make filaments. A second extrusion process can be performed to ensure homogeneous distribution of fibers. For plot processing,
a polymeric paste and fibers were mixed and extruded directly out. Technologies
powder-based technologies are not ideal for creating fiber-reinforced composites because making a smooth powder layer is very difficult.
The most usual fibers include glass fibers and carbon fibers since they improve the mechanical properties of the polymer composite in the 3D printing area [15].

5.2.3 Metal filled polymers

Polymer-metal composites (PMCs) are thermoplastic or thermosetting polymers with metal distributed throughout. PMCs' appealing attributes include electrical properties similar to those of metals, good mechanical capabilities, and the ability to be processed using ordinary polymer processes. Some of the main materials used for 3D printing application are steelfill, copperfill and bronzefill [19].

5.2.3.1 Steelfill

SteelFill creates a shining metallic appearance. With post-processing techniques like as sanding and polishing, you may make it seem completely unique, as if it were made in a metal workshop.

SteelFill has a weak magnetic property. Because of the high steel concentration of the SteelFill substance, this filament is extremely abrasive to brass nozzles. As a result, it is advised to print with abrasion-resistant nozzles [19].

5.2.3.2 Bronzefill

A genuine metal filament that is as highly metered as physically feasible for FDM/FFF 3D printing. Not only does it look different, but it also weighs more than three to four times as much as regular PLA. BronzeFill has a matte surface that is nearly laser-sintered. It will only shine if you polish it or do some other type of post-processing [19].

5.2.3.3 Copperfill

CopperFill is a variation of bronzeFill. When you lixa and pole your impression, the true value of this 3D printing material based on PLA/PHA becomes apparent. He transforms into a marrom-avermelhada argila [19].

5.2.4 Ceramics

Stoneware, earthenware, and porcelain are examples of traditional ceramics. Technical ceramics are also known as engineering ceramics and industrial ceramics, and the list would be considerably larger if more were generated on a regular basis as bespoke solutions for specific purposes. Aluminum Nitride, Zirconia, Silicon Nitride, Silicon Carbide, and Alumina are some common technological ceramics. When compared to classical ceramics, technical ceramics have significantly better mechanical, thermal, chemical, and electrical qualities. The majority of 3D printed ceramics are classified as technical [15].
The main advantages that make the use of this type of material useful in 3D printing are:

- Aesthetics
- Tactility
- Chemical resistance
- Biocompatible
- High or low thermal conductivity, depending on formulation
- Electrical insulator
- Very difficult
- High strength-to-weight ratio

5.3 Material Properties

5.3.1 Mechanical

As for the mechanical properties of plastic materials, for example, R Roy and A Mukhopadhyay evaluated the friction and wear resistance of FDM printed ABS and PLA components against an EN 8 steel roller under low loads, fixed rotational speed of the roller, and fixed rolling time in dry conditions. They determined that dimensional variation in PLA components is greater, and the wear rate in PLA is more than in ABS. In a study conducted by H K Sezer and O Eren, an improvement in the mechanical and electrical properties of the ABS material was observed when multiwall carbon nanotubes

(MWCNTs) were dispersed uniformly in the material using a twin-screw micro compounding extruder, resulting in a 1.7 mm diameter filament creation. It was shown that specimens with a greater MWCNT ratio had better tensile strength than those with a lower ratio. S G Hernandez et al. suggested a computational framework for simulating the printing process as data while the user enters machine settings and material filament attributes. When the temperature is raised to 90°C, the mechanical characteristics improve by up to 7% [20].

5.3.2 Thermal

Regarding the thermal properties of plastic materials, for instance, L Yang et al. developed polylactic acid (PLA)/carbon nanotube (CNT) composite filaments for the FDM process in order to examine the crystallization melting characteristics and meltflow rate (MFR) for printability of the created material. In addition to rheological characteristics, the influence of CNT on tensile strength and flexural strength strengths was investigated. The introduction of CNT to PLA boosted tensile and flexural strength when compared with pure PLA, according to the data. R Kumar et al. conducted a test to investigate the compatibility of ABS and PA6 while establishing melt flow behavior via strengthening aluminum (A.L.) metal powder using twin-screwextrusion (TSE) and fused deposition modeling (FDM). The reinforcement of Al in ABS and Al in PA6 was discovered to create a minor rise in the melting point of PA6. They couldn't have been welded together based on differences in the melt flow qualities, and it was found that polymers could be welded when they had similar rheological properties [21].

5.3.3 Biocompatibility and Biodegradation

Biocompatibility is the term that is most wisely used to describe the requirements that a biomaterial or biomaterials used in a medical device must have in order to justify its application. This word can be used to describe the ability of a certain material to correctly perform an application when inside an environment with its host, for example the capability of an implanted prosthesis to exist in harmony with the surrounding tissues [22] [22].

This materials have to be completely non-cytotoxic (non harmful to the host's cells) and should allow biodegradation into smaller components that can easily be eliminated by the organism, while maintaining a healthy immune response even after they are implanted [23].

Having the knowledge that most of the implants in the market contain metal, a team of investigators (Bandyopadhyay and team) hypothesized if they could improve the biocompatibility of those impants by creating new alloys to be used on the printing of new parts. Since tantalum is the most biocompatible metal (creates an oxide layer that prevents the exchange of electrons, allowing the capture of proteins and development of osteoblast molecules), the team discovered that by adding a small amount of tantalum to titanium the great levels of biocompatibility present in pure tantalum are also reached while maintaining good load bearing and resistance to corrosion [24].

For the biomedical applications of these materials biodegradation is mandatory but some materials have a rapid degradation while others are slower so for different applications, different speeds are required [24].

5.3.4 Porosity

The porosity of the final product will affect in many different ways its efficiency. It will have a direct impact on aspects such as cell seeding efficiency, diffusion properties, and mechanical strength. One of the most important requirements a biomedical 3d part needs to achieve is the existence of interconnecting channels to enable the supply of nutrients and metabolites and to allow an healthy growth of the cells [25]. Besides that, in general, lower values of porosity lead to better mechanical properties [26].

In this context, the analysis of the final part's porosities is mandatory. There are many different methods to analyze the pores: microscopy, physico-chemical approaches (nitrogen adsorption and desorption), and capillary approaches (mercury porosimetry). However, only advanced medical imaging techniques such as micro computed tomography and magnetic resonance imaging (MRI) can provide a 3D image [25].

5.3.6 Roughness

Surface roughness is a measure of the relief variations that can be happen on a product's surface. Roughness plays an important role in the behavior of mechanical components. It can influence the sliding quality, wear resistance, corrosion resistance, sealing, and even the aesthetic appearance of a component. Usually, the aim is to get lower levels of roughness and there are some surface treatments that can be used to improve this value. However, if those treatments can be avoided, they should.

When 3D printing a product, this aspect needs to also be taken into consideration and there are some studies regarding the influence of some parameters in the final roughness. According to Hartcher-O'Brien, print speed has a great impact on this property as small variations lead to major changes in the measured results [27].

6. Common Printers

When people discuss the many sorts of 3D printers, they generally discuss the technology that power them. There are many distinct varieties of Fused Deposition Modeling, or FDM 3D printers, just as there are many different technologies. Most of the time, the Cartesian form of the 3D printer is the only one that comes to mind. However, most consumers are unaware that there are four varieties of FDM 3D printers: Cartesian, Delta, Polar, and Scara or robotic arm 3D Printers [28].

The goal of the following points is to describe these four variants of 3D printers. However, before discussing 3D printers, it is necessary to first grasp the four coordinate systems on which the printers are built [28].

Coordinate system is a general geometrical word that is not necessarily related to 3D printing, but it is necessary to comprehend this 3D printing idea in order to understand how a printer works [28].

A coordinate system is a set of reference lines or curves that is used to locate points in space. In two dimensions, it is commonly represented by an horizontal (X-axis) and a vertical (Y-axis) axes, however in three dimensions, it adds a third direction, the Z-axis, that is perpendicular to both the other two axes [28].

So, 3D printers are named after how the 3D printer detects the various locations on the build platform to produce the correct design [28].

6.1 Cartesian FDM 3D printers

This is the most prevalent FDM 3D printer type. The Cartesian coordinate system is employed by the vast majority of 3D printer makers since it is one of the most fundamental coordinate systems used [29].

Three digits, X, Y, and Z, are utilized in a Cartesian 3D printer to specify the precise the location of a point in space, as it can be seen in figure 12. The X - Y axes show a point's lateral and longitudinal location, respectively, while the Z axis indicates the point's altitude. Here, the printing bed usually moves only on the Z-axis, and the print head works two-dimensions on the X-Y plane [29].

Since it is the most widely used type of 3D printer, owners of this machines can easily locate professionals to learn more, receive professional advice, or debug their 3D printers. It is also simple to locate new parts or a suitable community of users who possess a Cartesian 3D printer similar to the one owned by the user in order to exchange resources [30].

The Cartesian 3D printer is quite simple to learn and to build for a beginner, and the structure is pretty straightforward. This type of machine relieves a lot of the tension that 3D printer owners experience during their initial learning phase.

Except for applications that are lengthy or tall in size, Cartesian 3D printers have applications in practically all sorts of product manufacture.

Examples of manufacturers that produce and sell these type of 3D printers are Ultimaker, Zortrax, Roboze, BigRep, and others [30].

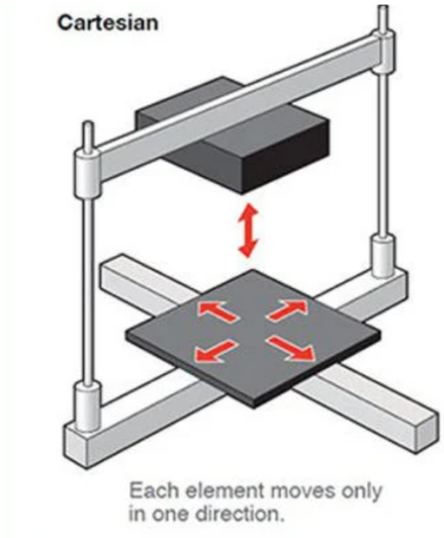

Figure 12 - Cartesian FDM 3D Printer [30]

6.2 Delta FDM 3D printers

Delta 3D printers are the second most widely used form of FDM 3D printer. Because of their towering appearance, they may easily be told apart from a Cartesian 3D printer [30].

The printhead is linked to the printer's three arms, which all work together to print the object's layers. This printer operates in a triangulation arrangement, and because the three arms work together, the build volume of the printer is a cylinder, with a circle as the base [30].

Instead of the cartesian coordinates, each of the three arms adjusts its angle to place the print head on the build platform according to the model. A number of trigonometric calculations that take into account the angle of all positioning arms are used to pinpoint the exact location [30].

The biggest benefit of a Delta 3D printer is its speed. The high speeds are possible as the extruder does not carry the weight of the stepper motor and this weight reduction is translated into increased speed [30].

The Delta 3D printer also has the benefit of being tall. Because it is designed for taller things, manufacturers rely on the delta coordinate system when designing a 3D printer for taller objects with a higher Z-axis [30].

Delta 3D printers, on the other hand, have plenty of issues. Since they cannot be utilized with Bowden extruders, the utilization of flexible materials is limited. They also have a smaller base, which limits the lateral size of the item to be produced. Furthermore, due to their size, they are typically provided in kits, which novice users find difficult to assemble, pushing them away from that sort of 3D printer [30].

Delta 3D printers may be used to create tall objects such as columns in architectural models, among other things [30].

Kossel – RepRap, Anycubic Delta, DeltaWasp, are some of the popular Delta 3D printers manufacturers [29].

There is also a new technology, proposed and developed by two swiss students that consists of a six-axis 3D printer that was based on the Delta model [29].

In figure 13 it can be seen, in a schematic way, the refered printer.

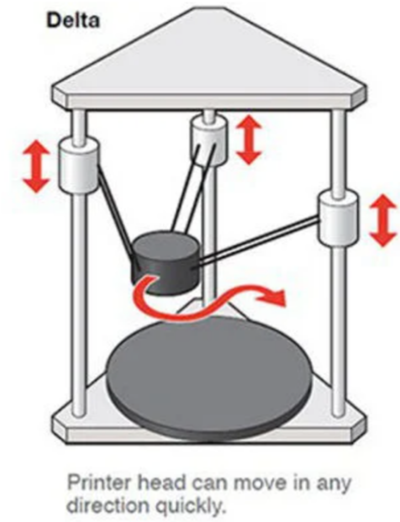

Figure 13 - Delta FDM 3D printer [30]

6.3 Polar FDM 3D printers

Polar 3D printers are not widely utilized, although they do have an unusual design, as it can be seen in figure 14. A point's location to be printed using this technique is described by simply two variables: an angle in 3D space and the displacement (or radius) from a predetermined center. As a result, and unlike a Cartesian 3D printer, they employ a circular grid rather than a square one [30].

A Polar 3D printer's build platform can move vertically and horizontally but also rotate, however the arm (printhead) or extruder can only move in the Z-direction. Much bigger items may be created in a smaller space this way [30].

Polar 3D printers may be used to create tall final products for example columns in architectural models, among other things [29].

Another advantage of this printers, when compared to the most usual Cartesian ones, is the fact that it only requires two engines (Cartesians require 3). In long term, this means that these printers lead to greater energy efficiency [29].

The popularity of this type of printers has been increasing [29].

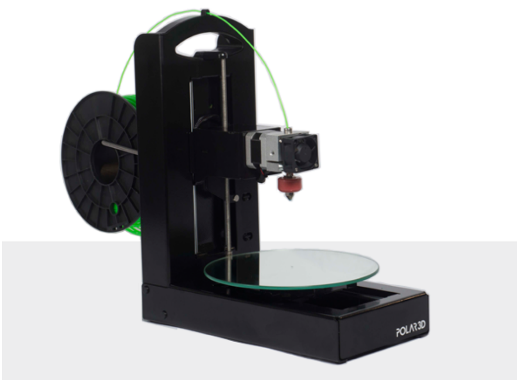

Figure 14 - Polar FDM 3D Printer [31]

6.4 Scara FDM 3D printers (robotic arm)

SCARA is an acronym for Selective Compliance Assembly Robot Arm. This is a well-known and widely employed coordinate system used in industrial robots. A SCARA 3D printer is similar to industrial robots in that it is not restricted to a build platform and can move in all conceivable directions, making it easier to manufacture geometrically complicated items, as it can be seen in figure 15. This printers move in the most human-like fashion and print quicker the other types of FDM machines [30].

They are currently used in structural projects such as bridges or buildings, and even large-scale industrial projects [30].

Although not a commonly used printing process, this FDM method is beginning to see a rise in its use. It should be noted, nevertheless, that the final print quality is not as good as conventional Cartesian printers [31].

Examples of this printers include the Dobot M1 3D printer, this were robots used by MX3D to create a smart steel bridge in the Netherlands, that even includes sensors to help understand usage and maintenance requirements [31].

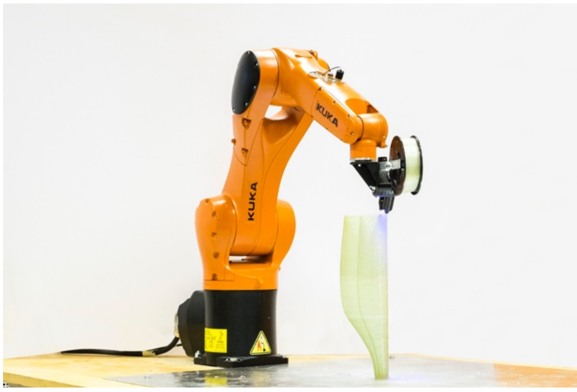

Figure 15 - SCARA FDM 3D printer [31]

6.5 Combined printers

There is a printing technique that has increasingly being combined with FDM, robocasting or direct ink writing (DIW) is an additive manufacturing technique in which a filament of 'ink' is extruded from a nozzle. The ink is usually supplied through a syringe or container and does not need to be heated to a high temperature to extrude through the nozzle for printing. Therefore, cells and bacteria can survive during the printing process, making DIW suitable and widely adopted for biology and biomedical applications [6].

The DIW technique was first developed around 1996 as a method to allow geometrically complex ceramic green bodies to be produced by additive manufacturing. A 3D CAD model is divided up into layers during the printing process similar to other additive manufacturing techniques. The ink is extruded from the nozzle in a liquid-like state and hardens quickly, exploiting the rheological property of shear thinning. In other words, the ink must have high viscosity or be gel-like to maintain the sturdy structure for the printed object before postprocesses if necessary. Depending on the ink composition, printing speed and printing environment, DIW can typically deal with moderate overhangs and large spanning regions many times the filament diameter in length, with the structure unsupported from below. DIW has many technical applications, using colloidal, polymeric, or semiconductor materials to fabricate 3D periodic structures in sensors, microfluidic networks, photonic-bandgap materials, tissueengineering scaffolds, and drug-delivery devices. There is also one application with growing focus on it is stem cell research using the hydrogel material, which is an extension of tissue engineering [6].

6.6 Machine Properties and printing parameters

6.6.1 Layer Resolution

The thickness of a single layer produced by a single run of the printer's print nozzle is referred to as layer resolution. In figure 16, it can be seen the difference between multiple layer resolutions. Layer resolution is an important element that works in tandem with the created part's construction orientation. It is directly proportionate to the printed layers' staircasing effect. Although good surface roughness may be obtained, it may result in increased time consumption. V Kova et al. tested multiple bonding techniques on PLA material in edgewise, flatwise, and upright orientations. The sample was bonded with three distinct layer thicknesses: 125mm, 250mm, and 500mm.

According to the research, as the thickness grows, the resistance to load suffers a decrease. The edgewise printed part had the best adherence in smaller layer thickness, whilst the flatwise manufactured part had the best adhesion in greater layer resolution. K G J Christiyan et al. examined the tensile and flexural strengths of nine samples of ABS with hydrous silicate composite material using different criterias. Maximum tensile and flexural strengths decreased as the products' thickness rose in parallel with print speed [5].

Figure 16 - Layer resolution [5]

6.6.2 Build Orientation

Along with later, build orientation is critical to the process. The build orientation is the angle at which the component is placed in relation to the horizontal axis of the build plate, as it can be seen in figure 17. Surface roughness and the staircase effect are determined by resolution, whereas print quality and layer organization are determined by build orientation, and fusion is directly related to the mechanical qualities of the printed part. S Raut et al. prepared specimens from ABS P400 material to evaluate tensile and flexural strengths at various orientations and three-dimensional axes; around eighteen specimens were tested, all of which were prepared in accordance with ASTM requirements.

The tensile strength grows in the x-axis, with a little rise beyond 45°, but in the y-axis, it falls until 45° before progressively rising. The maximum load in the z-axis can withstand up to 45°, which further begins to diminish as the orientation rises; the flexural strength of the piece gets reduced with increase in the orientation. Afrose et al. compared FDM-printed Polylactic Acid (PLA) parts to injection-molded parts made from the same material. The ultimate tensile stress (UTS) test was performed on about a dozen samples; these specimens were printed using three different orientations – X, Y, and 45°. Under cyclic loading conditions, PLA-45 had the longest fatigue life when contrasted with the other two configurations; samples printed in 45° orientation had the best capacity to retain strain energy, unlike the other two specimens. Y Wang et al. worked on several samples composed of polyacetal (POM) material that were printed at varied angles of 0°, 45°, and 90º. According to the results, the mechanical strength, tensile stress, and strain of anisotropic material printed at 0° angle are superior than those printed at 45° and 90° angles [5].

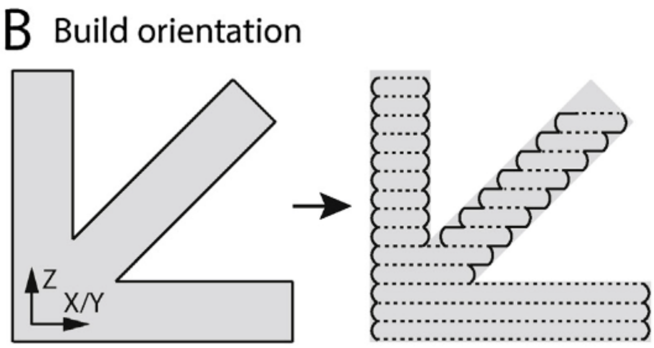

Figure 17 - Build orientation schematic [5]

6.6.3 Nozzle Temperature

The material is heated to a precise temperature as it goes through the extruder. This temperature is controlled by the thermoplastic filament's characteristics, print speed, and intended use of the same printed object. The melt fluidity and crystallization of the deposited composites are affected by the nozzle and platform temperatures [3]. S Dinget et al. investigated the link between nozzle temperature, build temperature, and the mechanical characteristics of polyetheretherketone (PEEK) and polyetherimide (PEI) (PEI). The flexural strength of PEEK rises with the first one but stabilizes after 390°C, whereas PEI exhibits no variation under 390°C although increases above 390°C. P Wang et al. studied the tensile, flexural, and impact strengths of 5 weight percent carbon fiber (C.F.) and glass fiber (G.F.) reinforced polyether-ether-ketone (PEEK) composite filaments to establish that with the rise in nozzle temperature, improved formability and melting fluidity are obtained. Also, it was discovered that increasing the print speed and layer thickness had the opposite impact on this material [5].

6.6.4 Raster angle and air gap

For FDM, the raster angle is the one formed between both the path of the nozzle and the X-axis of the base plate as it can be seen in figure 18. The raster angles of two neighboring layers diverge by 90 degrees. The raster angle has an impact on the forming accuracy and mechanical performance of the printed sample. In a printed specimen, the air gap is the space between two consecutive rasters from the same layer. It is also known as the raster-to-raster gap, and it is directly impacted by other characteristics such as the raster angle and raster thickness of the printed part. A K Sood et al. printed and evaluated an ABS P400 specimen for tensile, flexural, and impact strength to better understand how mechanical characteristics alter based mostly on air gap, among other things.

The creation of large air spaces aided in the establishment of a strong connection between the two rasters and increased overall tensile strength. Heat dissipation concerns arose as a result of the presence of tiny air gaps between two rasters rather than a single raster, leading to accumulation of tension. In terms of flexural strength, as the value of the air gap grew, so did the specimen's strength. M. Dawoud et al. conducted a study of injection molded components with FDM parts. ABS was chosen as the filament of preference since it demonstrated that maximum density was reached in I.M. with the use of negative air gaps and that the use of positive air air gaps resulted in lower density, because positive air gaps hardly allowed the rasters to contact or intersect. A negative raster of 0.05 mm achieves a density nearly similar to injection molded components for FDM parts [5].

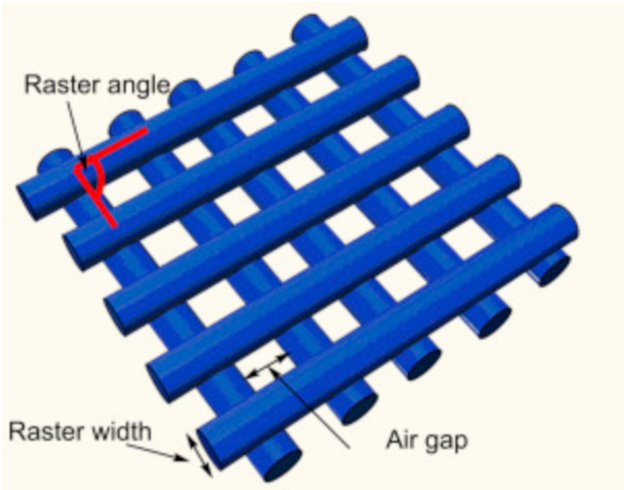

Figure 18 - Raster angle and air gap [5]

6.6.5 Infill Density and Pattern

Infill is a support structure that is printed inside an object to increase its strength, as it can be seen in figure 19. It's usually extruded in some kind of pattern. The infill density defines the amount of plastic used on the inside of the print. A higher infill density means that there is more plastic on the inside of your print, leading to a stronger object. Values of around 20% are used in most models with visual purposes but for final, to be sold, products this value has to be bigger [33]. While the shield, in every layer, is a solid entity, the interior is filled with a specific pattern that is responsible for preventing the top layers from colliding inside the object. Different types of patterns that are usually available on the printers are rectilinear, lines, concentric lines, honeycomb, etc [34].

In some researches about the influence of printer properties on the final product, Cwikla and his team, concluded, from the experimental results, that the increase in infill values leads to a reduced deformation. Besides that, the strength of the final product increases with this parameter, however, the decrease in infill density value is not directly proportional to the decrease in strength [33].

The pattern influences mostly rigidity. Patterns like linear or rectilinear offer lower values of strength and rigidity of the printed objects. Concentric lines, from its geometry, are prone to having problems regarding torsion stress limits. Most of the times the preferred pattern is the honeycomb, because it offers greater mechanical properties. However, some other aspects must be taken into consideration like economical analysis since some patterns allow for less raw material usage [33].

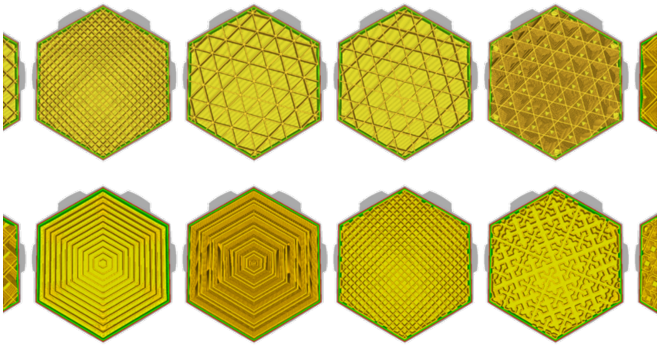

Figure 19 - Infill density and pattern schematic [5]

6.6.6. Print speed

The print speed defines the speed (in mm/s) at which the print head moves while printing. Usually, from the value defined on this setting, the printer is able to calculate the extrusion flow.

Obviously, a higher printer speed will lead to a lesser amount of time spent on the printing but it can mean that the temperature also needs to increase so that filament is properly and completely melted when extruded [33].

The quality of the printed parts might not decrease with the increasing printing speed but most of the 3D printers are not ready for such high speeds. Besides that, the rapid movements of the extruder can lead to increasing vibrations of the machine, the result is low quality of the produced parts. Light weighted extruders are more stable and offer the possibility to mitigate this issue [34].

In conclusion, a good quality printer with a light and stable extruder allows fast printing speeds without compromising the printing quality.

In the chart below, figure 20, it can be studied the relation between print speed and quality of the products produced.

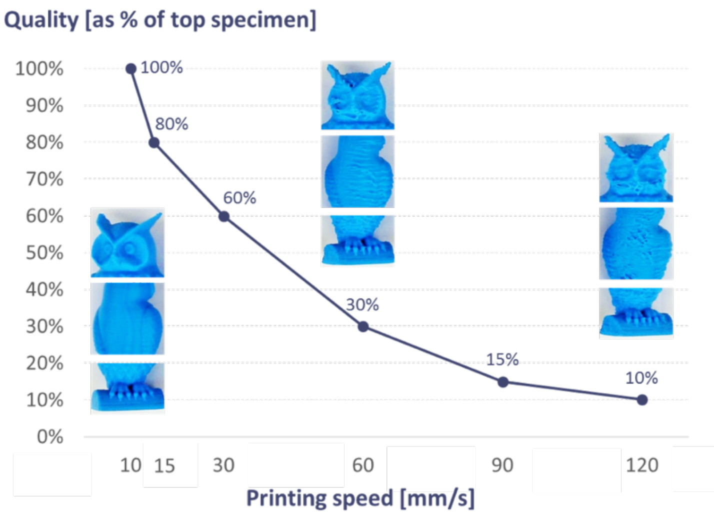

Figure 20 - Relation between quality and printing speed [33]

6.6.7 Extrusion Multipliers

The extrusion multiplier is the rate at which the printer extrudes the filament, he amount of material extruded in the unit of length travelled by extruder with given speed. With this setting and the print speed defined, the printers can calculate how fast to move the extruder motor. In general, this is setting to be adjusted for different materials being printed and for different final products since it is responsible for the final quality and to avoid certain printing issues that can happen [33], [35].

According to the research done by Cwikla and his team, the samples with less than proposed limits extrusion multiplier (0,5 to the limits 0,9-1,1) present a smaller diameter of extruded material threads and consequently, smaller surface of contact between neighboring threads which leads to a worse tensile strength. Besides that, the geometrical aspect also gets affected, as it can be seen in figure 21, since the printed objects are smaller than the nominal dimensions given for the printing job [33].

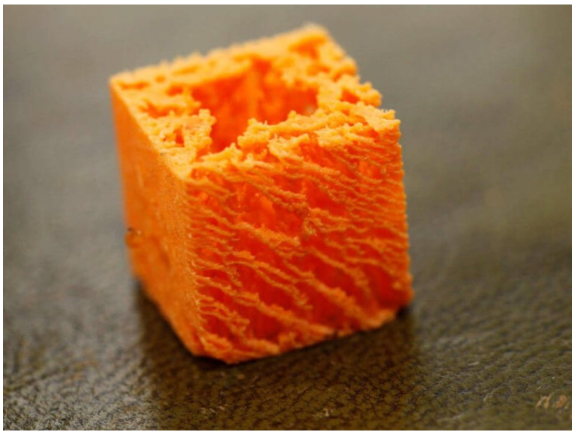

Figure 21 - Geometrical aspect of a sample [33]

6.6.8 Number of shells

Shells, also known as perimeters, are extruded outlines defining the shape of the layer, as it can be seen in figure 22. Every object you print must have at least one shell, since it is mandatory that anything has an outline. Additional shells add to an object's strength, weight, and print time. For most objects produced on a printer, 2 or 3 shells are enough for great properties. This setting can also be adjusted if there are some cracks between the layers of a printed object; with an increased number of shells, this problem can be mitigated or even eliminated [36].

Figure 22 - Number of shells [36]

7. Overview of Current Medical Applications

With the development of computerized tomography (CT) and magnetic resonance imaging (MRI) technologies, three-dimensional images of tissues and organs have become more informative and higher resolution. Using the acquired imaging data, patient-specific tissues and organs with highly complex 3D microarchitecture have been produced by 3D printing technology. Polymeric materials currently used for printing in the field of biomedical applications are based on polymers of natural origin (gelatine, alginate, collagen, etc.) or synthetic polymer molecules (polyethylene glycol (PEG), poly-l-lactic-glycolic acid (PLGA), polyvinyl alcohol, etc.). It is essential for the transplantation and for its performance to ensure that the 3D printed parts have a good interaction with the endogamous tissues [2].

In tissue engineering, scaffolds (artificial structures capable of supporting the formation of tissue in three dimensions), are critical in providing a physical link for cell infiltration and proliferation. The addition of bioactive particles in polymers has made it possible to print scaffolds with high biocompatibility. In addition, the incorporation of glass particles has improved the adhesion of cells to scaffolds made of PLA by increasing both their roughness and hydrophilicity [2].

In addition to biocompatibility, other factors, such as good mechanical properties, are important when manufacturing scaffolds from 3D printing. Good mechanical stability makes scaffolds good supports for cell activity [2].

Another example that is in increasing demand these days are bone models based on 3D printing technology used to create teaching materials for universities in the medical field or even as surgical guides in implants. Worldwide, the donation of organs to science has declined in recent years, creating an opportunity for 3D printing to successfully fill this gap in the near future. High quality machines can print structures in color and with sections that reveal important aspects of the body's structure, whether it is a soft tissue organ or even a bone. In addition, they create easily accessible structures that mimic the original properties, which can allow students to practice surgical procedures with ease [37].

Another example is in the field of dentistry. Here, 3D printing makes it possible to obtain orthodontic appliances, models that replace those that were previously made of plaster, and dental prostheses [37].

3D printing technology has been applied since the 2000s and its first uses were implemented both in dental implants and in customized prosthetics for patients. Since then, medicine and 3D printing have come together in a way that has seen many processes made easier. Currently, this technology is used for bone simulation, production of ear replicas, exoskeletons, tracheas, vascular networks, tissues and organs, among others. In addition, this process is also known as a procedure used for the pharmaceutical industry through dosing methods and medication delivery equipment.

The current medical applications of this technology can be classified into several categories: [29]

- Bioprinting of tissues and organs
- Costumized implants and prostheses
- Anatomical models for surgical preparation
- Pharmaceutical Application

In this section we intend to develop each topic a bit further in order to obtain not only a clarification of what it consists of, but also of the predictions for the future in relation to each process.

7.1 Bioprinting of tissues and organs

Today, one of the great problems facing medicine is the failure of vital organs due to age, disease, accident, insufficiency, or even birth defects. In this sense, the treatment currently known and developed is the transplantation of functional organs from other donors. However, and as it is common knowledge, the quantity of organs for transplantation is insufficient to meet the existing demand, creating endless waiting lines. Studies show that only about 18% of patients on the waiting list actually receive organs in the estimated time and that about 6% die during the wait. In addition, this type of procedure is extremely expensive, whether for the public or private sector, and requires an intensive search for a matching donor, often resulting in severe difficulties that are almost impossible to overcome [29][38].

All these problems could be solved by the regeneration of cells taken from one's own organ to create a new functional organ, avoiding the risk of rejection from one's own body and the need to take immunosuppressants for the rest of one's life. In this sense, studies have been developed that relate regenerative medicine and materials engineering, in order to develop solutions both biocompatible and compatible with 3D printers [28].

Initially, the strategy was to isolate cells from patient tissue samples, mix them with growth factors, and multiply them in the laboratory to obtain the basis for a functioning organ. However, 3D technology offers additional important advantages such as: [29]

- High precision in cell localization and high control of working speed
- High resolution
- High control of cell concentration
- High precision in the diameter of the printed cells

It is important to mention that all of this factors are related to various processes. The high precision, resolution or control can be obtained not only by FDM process but from all the others studied, depending on the parameters.

Organ printing technology then appropriates the advantages of 3D printing to produce them, layer by layer, ensuring the desired strength, porosity, and type of tissue. For this, silicones or hydrogeals are usually used [28].

The most widely used process is called bioink, based on inkjet, which deposits cell droplets and biomaterial on a substrate, forming the organ itself.
This process consists of the following stages: [29]

1. Create the organ design and its vascular architecture
2. Generate a bioprinting process plan
3. isolate the base cells
4. Differentiate the cells of the organ itself and the replicas

5. Prepare bioink reservoirs with organ-specific cells and blood vessel cells and load them into the printer
6. Printing itself
7. Placing the printed organ in a bioreactor before transplantation

Some examples of applications already successfully developed are the creation of menisci, heart valves, spinal discs, and some types of cartilage. In a more recent and still under study perspective, mainly artificial livers have been designed, and a procedure for the creation of a bioresorbable tracheal splint has also been developed in the United States and implemented in a baby with a birth defect [39], [40].

3D polymer printing has also gained some traction in the manufacture and development of tissue scaffolds. These scaffolds have as their main function, to restore organs that are malfunctioning or regenerate tissues. Being able to act in different tissues such as bone, cartilage, ligaments, or even neurons, this innovation allows patients products that are suitable for medical application due to the efficient designs allowed by this technology [42].

The creation and design of these scaffolds is a challenging task. For example, when working with bone tissue, it is necessary to take into account the mechanical and biological characteristics of each individual, as well as the network of pores to promote tissue growth and nutrient transportation. Thus computing 3D is beneficial by allowing personal configuration while taking into account the characteristics of each individual [42].

Despite the major developments that have taken place in recent years, research is expected to continue to improve significantly and exponentially. Studies are also currently underway that focus on the creation of organ tissues to screen for new therapeutic drugs that could potentially apply to a given organ, allowing for a significant decrease in research time and costs [28].

7.1.1 Building 3D Vascularized Organs

Today's replicated organs tend to be relatively simple and usually non-vascularized, aneural, thin, or hollow. These are usually powered by the patient's own vascular system. However, as this technology has developed, the tissue has become increasingly thinner, suppressing the ability to allow oxygen to flow between the patient and the transplanted organ. In this sense, today's new challenge is to print complex 3D complexes that have multicellular structures with an integrated vascular network, allowing the printing of hearts or kidneys for example [29] [43].

For this, the TIJ printers are proving to be the most promising [28].

7.2 Customized Implants and Protheses

This type of process has been explored for several years and therefore shows great development when compared to other applications. From an X-ray, MRI or CT scan, transferring it into a digital mode suitable for 3D printing, it is possible to achieve any kind of geometry, sometimes in less than 24 hours. This procedure has been applied for the manufacture of dental, spinal and hip implants.

The fact that this process is so fast and common allows significant improvements in the fields where it is applied, both by saving time and in terms of production of multiple models, ensuring a rapid response to the numerous demands [29] [39].

Furthermore, because of the high level of personalization needed in prosthetic medicine, prostheses are notoriously expensive and time demanding to construct. This is due in large part to the significance of achieving a flawless fit in order to make a functioning and pleasant prosthesis for the patient, as the devices and their sockets are subjected to hard use. 3D printed prostheses are transforming the business for these and other reasons [42].

Typically, the prosthesis-fitting procedure includes many casts and follow-up consultations to fine-tune the fit. For patients, this is frequently more than simply an inconvenience: having a cast created is unpleasant, and the several fitting appointments can be intrusive to patients who are sensitive about their condition. Not to mention that all of the time spent fitting and re-fitting equates to time lost without a well fitted prosthesis [42].

Patients no longer need to sit for a physical cast thanks to 3D printing. Instead, technicians may swiftly generate an accurate 3D model of the patient's remaining limb using a 3D scanner. This 3D scan is then used to create a precise and cost-effective 3D printed socket that often only requires a single fitting session [42].

This is a key point in neurosurgery, considering that they work with the bones of the skull and skull replacements have to be perfectly designed, in every detail. An example of skull protheses can be seen in figure 23.

Figure 23 – 3D printed skull protheses [42]

Patient-specific equipment (such as hearing aids) and implants (such as prosthetic joints, cranial plates, and even heart valves) are quickly switching to 3D printing due to its ease of customization and speedy manufacture. Creating a hearing aid before 3D printing required nine processes, from casting to fitting. Hearing aids may now be 3D scanned and produced in one day. A 3D printed hearing aid can be seen in figure 24 [42].

Figure 24 - 3D printed hearing aid [42]

Dental implants and orthodontic devices, like prostheses, need substantial customisation with a high degree of precision. Dentures, crowns, implants, and retainers must be robust, accurate, and pleasant since we rely on our teeth to withstand severe use on a daily basis. Furthermore, they must be composed of biocompatible materials such as cobalt chrome and porcelain.

3D printing enables dental and orthodontic practitioners to complete these tasks more quickly and at a lower cost than traditional methods like as milling. High-quality dental equipment may be created using a mix of 3D scans and x-rays without the need for casting or setup time [42].

Products produced with 3D technology can also be created to be used as crowns for teeth. Having these products have a slightly rough surface is beneficial as the roughness promotes the formation of microfilm which could attract bacteria and other harmful products to an implant. [42]

Recently, researchers and doctors were successful in trying to implant a tooth in a patient. This new tooth brought the advantage of being customized to the customer's mouth and low cost with great efficiency. [42]

Even for devices that do not require 3D printed components, such as braces or expanders, as it can be seen in figure 25, 3D printed models made of sterilizable polymers can be used to assess form and fit, reducing the need for long patient fits or numerous visits [44].

Figure 25 - 3D printed braces [43]

7.2.1 Osseointegration

Osseointegration, defined as a direct structural and functional link between live bone and the surface of a load-bearing implant, is crucial for implant stability and is regarded as a requirement for implant loading and long-term clinical success of final bone implants. The implant-tissue interface is a highly dynamic interaction zone. This intricate relationship encompasses not just biomaterials and biocompatibility concerns, but also the changing mechanical environment. The osseointegration processes entail an initial interlock between the bone and the implant body, followed by biological fixation by continual bone apposition and remodeling toward the implant. The process is highly complicated, and numerous variables impact the creation and preservation of bone on the implant site [45] [44].

7.3 Anatomical Models for Surgical Preparation

Besides the approaches mentioned above, another application of this technology is the production of molds and models for surgical preparation. With this, it is possible to better prepare for any surgery, being able to perform simulations with objects very similar to reality, both in shape and texture. This procedure promotes several advantages, one of the main ones being the fact that it allows avoiding the constant use of X-rays, which do not even allow such a realistic analysis [28].

Besides this, in the past (and still today in some circumstances) the use of cadavers for this type of study was very common, involving high costs of maintenance and time, since a cadaver was not always available for a given research. Nowadays, it is more common to find cadavers as an aid to an anatomy class for example, with 3D printing being the big focus to produce models for experimentation [29][45].

Again, this is a very relevant concept in the field of neurosurgery, where a small mistake can lead to very serious consequences. Thus, having models like the neural network to simulate a treatment before effecting it becomes a key point for this type of therapy [28].

The process of 3D printing patient-specific organ models begins with the acquisition of anatomical information about the patient's organ of interest using various imaging modalities such as CT or MRI scans. These photos are often in digital imaging and communications in medicine (DICOM) format, which 3D printers cannot directly use. As a result, the captured pictures must be postprocessed in order to first identify the organ's region of interest by accurate segmentation of its volumetric data set and then build a stereolithography (STL) file for the 3D printing process. In certain circumstances, this STL file must be improved further using CAD software programs to correct defects in the STL model (such as closing gaps between model segments) and optimize its 3D printing. The completed STL model is then divided into horizontal layers with 3D slicing software to generate the G-code, which describes the printing routes for the 3D printed organ model. All of the phases of this process can be checked in the figure below [29] [46].

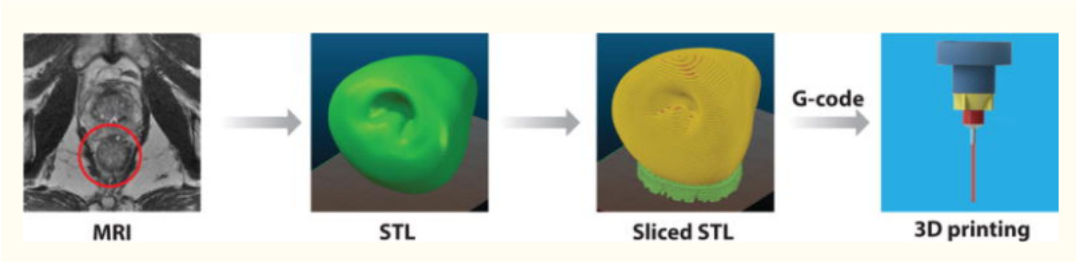

Figure 26 - Phases of 3D printing patient specific organ model [46]

7.3.1 3D printed organ models using rigid plastic materials

Initially, 3D printed organ models were mainly fabricated from a limited range of materials, as it was an under-explored field. Today, despite the wide range of materials available, these types of models are still commonly used, as they are quite accurate in representation and relatively inexpensive. These materials are characterized by their high impact strength and hardness. However, these characteristics do not always prove to be the best, as they do not allow the actual representation of an organ's texture. In this sense, the discrepancy of the elastic properties of these materials to the organs limits their application. Still, these models are widely used in cardiology, urology, neurology and hepatology [46].

In the field of cardiology, using mainly FDM process, it is possible to replicate healthy hearts and hearts with congenital diseases in order to study the correction of defects. In urology these materials are typically used to print kidney models, with different colors to identify the different sections and details of the organ, using the binder jetting technology. During surgery, it was proven that the models can be utilized to assist surgeons in performing minimally invasive off-clamp partial nephrectomy since the 3D printed model gave tactile feeling and assisted in efficiently establishing the incision line and angle [46].

In relation to neurology, besides what has been previously discussed, it is important to emphasize that these models serve not only for the simulation and planning of surgeries but also for the information of the patients themselves, since with 3D models it becomes easier to visualize and understand them. However, owing to the stiff nature of the material used for 3D printing, the models were found to be less effective for cutting and dissecting activities [46]. In this field it is also most used the FDM process with filament of PLA.

In hepatology the models were discovered to aid understanding of the spatial link between the vascular and biliary anatomies, as well as enabling hands-on surgical planning and training with the goal of lowering intraoperative problems [48] [28] [38]. Once again, this process commonly uses binder jetting technology.

All the examples above can be seen in figure 27.

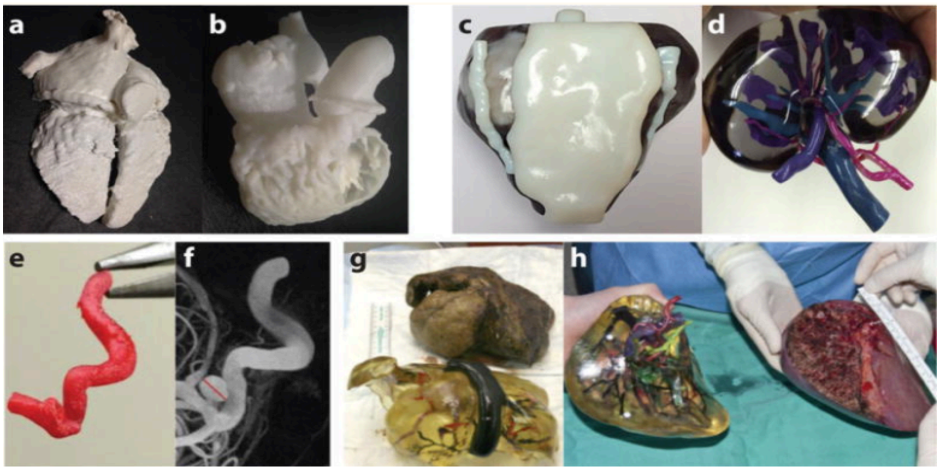

Figure 27 - 3D printed organ models using rigid plastic materials. (a) Printed cardiac model without disease, (b) Printed cardiac model after procedure for correcting disease, (c) 3D printed prostate, (d) 3D printed kidney, (e) 3D printed intracranial aneurysm, (f) digital subtraction angiography imatge, (g) 3D printed liver model, (h) liver lobe model and corresponding actual òrgan [46]

7.3.2 3D printed organ models using elastomeric materials

With the advancement of 3D technology associated with medicine, the palette of materials used for these applications has increased significantly. This includes elastic and flexible materials, which allow a tactile sensation closer to that of an organ. As such, these are primarily used for pressure and cut simulations [46].

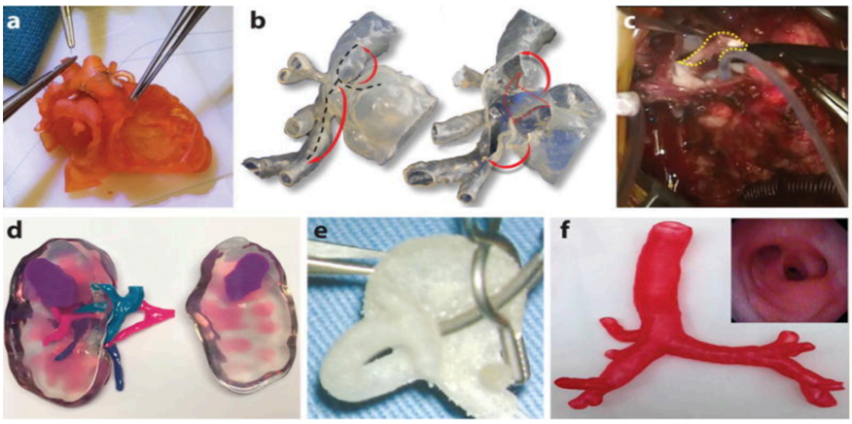

Figure 28 - 3D printed organ models using elastomeric materials [46]

As can be seen in the figure 28, there are numerous applications for this type of material associated with the creation of models for surgical preparation. Thus, in (a) you can see a model of a heart with a congenital defect for training, produced by binder jetting. In b) is the example of the impression of an aorta artery, where the red and black lines represent the proposed incision lines, and in c) the actual incision based on the model mentioned above, also produced by binder jetting technology. In d) a model of a kidney with a tumor, represented with various colors for analysis and simulation of its removal, once again with binder jetting. In e) a model of a brain bifurcation with an aneurysm for removal testing. And finally, in f) a model of a tracheobronchial tree for analysis. All of these last, also produced by binder jetting technology, letting know that this technology is commonly associated to this type of materials [46].

7.3.3 3D printed organ models using powder-based materials

Powder-based materials such as starch, cellulose, and plaster powder have also been studied for the production of diverse organ models for surgical purposes using inkjet 3D printing and solidified with binding agents. Despite the fact that their mechanical characteristics differ from those of genuine organs, such models give exact anatomical features while being easy to fabricate at a reasonable cost [48].

7.3.4 3D printed organ models using tissue-mimicking materials

Tissue-mimicking materials have been used for simulation purposes in a variety of areas of medicine, including medical imaging modalities, heart strain assessment, thermal treatment, and surgical simulation and training. Depending on the application, the composition of these materials can be modified to mimic the unique qualities of soft tissue [46].

The composition of the selected material should be modified to closely match the mechanical properties (including elastic modulus, viscoelastic behavior, hardness, ultimate strength, and so on) of the biological soft tissue when developing organ models with implications in surgical planning and training. Models made of such materials give more precise haptic sensation and mechanical behavior, similar to that of the genuine organ [42].

A typical method for adding tissue-mimicking materials into organ models is to first construct a mold with 3D printing and then cast it with tissue-mimicking materials. These molds may be made using one of two methods: (a) 3D printing a negative mold of the organ and infusing it with the tissue-mimicking material, or (b) a method analogous to lost-wax casting, i.e. directly 3D printing the organ model using commercially available materials.

This 3D printed model is then used to create a mold (for example, using silicone molding processes), and the mold cavity is then filled with the tissue-mimicking material to manufacture the final organ model [48] [45].

7.4 Pharmaceutical Application

Another application of this technology directly involved with medicine is its use in pharmaceutical manufacturing. The 3D printing technique allows better control of droplet size, high reproducibility, and the ability to produce complex pharmaceutical profiles [28].

7.4.1 Personalized Drug Dosing

The objective of drug development should be to maximize efficacy while decreasing the risk of adverse responses, which might be accomplished by using 3D printing to create tailored drugs [28].

Because of their ease of production, pain avoidance, accurate dosing, and high patient compliance, oral tablets are the most often used pharmacological dosage type. However, no feasible approach exists that could be employed on a regular basis to create individualized solid dose forms, such as tablets. Oral tablets are now made using well-established procedures such as mixing, milling, and dry and wet granulation of powdered components, which are then compressed or molded into tablets. Each of these production procedures can pose complications, such as drug degradation and form change, which can lead to formulation or batch failure issues. Furthermore, typical manufacturing procedures are inadequate for developing individualized medications and limit the potential to develop customized dosage forms with very complicated geometries [29] [48].

Patients who are known to have a pharmacogenetic polymorphism or who take medicines with restricted therapeutic indices may benefit the most from personalized 3D-printed meds. To establish an appropriate medicine dose, pharmacists might examine a patient's pharmacogenetic profile as well as other factors such as age, race, or gender. A pharmacist may then use an automated 3D printing technology to create and distribute the tailored medicine. The dose might be modified further based on clinical response if necessary [48].

3D printing offers the ability to create tailored medications in completely new formulations, such as pills containing numerous active chemicals, either as a single mix or as complicated multilayer or multireservoir printed tablets. Patients with numerous chronic conditions may be able to have their drugs printed in a single multidose form that is made at the point of treatment. Giving patients an appropriate, tailored dosage of various drugs in a single tablet may increase patient compliance. Compounding pharmacies might ideally deliver 3D-printed pharmaceuticals because their consumers are already accustomed to obtaining personalized prescriptions [28].

7.5 Safety Equipment

The COVID 19 pandemic brought great concern and demand for protective medical equipment such as masks and gloves. This sharp rise in need brought supply shortages in some regions. The ability of 3D printing to produce parts quickly, cheaply, and efficiently has also brought a new area for the application of this technology.

Not only can masks be produced, but a recent study shows a reusable, easy-to-clean, and applicable to different filtration units respirator that was made up of~

A team using 3D printing has also produced a helmet that is able to absorb large amounts of energy on impact, limiting the chance of head injuries. Using functionally graded materials, the energy absorption capabilities can be adjusted. Architected helmet liners are well-suited to the multi-impact impact that is frequent such accidents. Helmet testing has shown that the liners meet the mandatory impact testing criteria, and some design changes might allow for customization for maximum efficiency [42].

8. Advantages and Disadvantages of 3D Printing on Medical Application

Having analyzed the main medical applications associated with 3D printing technology, the main advantages and disadvantages associated with this application are now presented in table 2.

Table 2 - Advantages and disadvantages of 3D printing on medical application

Advantages	Disadvantages
Enable the preparation of complicated and thorough operations	Unrealistic expectations
Use of advanced technology	Safety and security
Low cost care compared to other processes	Patent and Copyright Concerns
Reduced costs and time	Regulatory Concerns
Customization	

The main **advantages** of this type of process are:

- Enable the preparation of complicated and thorough operations

3D printing is useful in teaching future doctors and preparing for actual procedures. Although 2D graphics are valuable, they do not give much imagery and do not depict an actual human portion. 3D printing, on the other hand, produces models that appear lifelike and closely resemble actual human parts. This improves the operating process's accuracy and effectiveness [39].

- Use of advanced technology

Future physicians will be able to practice on 3D printed organs. This is far more precise than, say, training on animal organs. Training on human-like, 3D printed components improves the level of skills doctors learn throughout training and in patient care [39].

- Low cost care compared to other processes

3D printers provide low-cost prostheses where they are needed, such as in war-torn nations. They are a cost-effective alternative for folks who cannot afford to purchase a prosthesis. Low-cost medical equipment is especially essential in impoverished nations and rural places. There are certain regions where the road infrastructure is inadequate to convey medical supplies. 3D printing makes it possible to produce the essential equipment in such areas without having to move it on a regular basis [39].

- Reduced costs and time

Medical and laboratory equipment may be 3D printed via 3D printing. Plastic pieces of the equipment can be 3D printed. This significantly decreases expenses and time spent waiting for a new medical gadget from a third-party provider. Furthermore, the production process and subsequent applications are simplified. This increases the availability of equipment and makes it easier for low-income or difficult-to-access places to obtain 3D printed medical equipment [39].

- Customization

Making prosthetics the usual method is prohibitively expensive since they must be tailored to the individual. Users of 3D printers have the ability to select numerous designs, shapes, sizes, and colors for their prostheses. This personalizes each 3D printed object. Prosthetics can also be made more readily available at a lesser cost thanks to 3D printers [39].

Regarding the main **barriers and controversies**, some of them can be identified:

- Unrealistic expectations

Despite the numerous potential benefits of 3D printing, expectations of the technology are sometimes overblown by the media, governments, and even researchers. 3 This encourages exaggerated assumptions, particularly regarding how quickly some of the most exciting possibilities, such as organ printing, will become a reality. Although progress is being made toward these and other objectives, they are not likely to be met anytime soon. While it is obvious that the biomedical industry will be one of the most fruitful arenas for 3D printing advancements, it is critical to recognize what has already been accomplished rather than expecting quick improvements toward the most advanced applications to emerge overnight [28].

- Safety and security

Safety and security concerns have arisen as a result of 3D printing. 3D printers have already been used for criminal reasons, such as the fabrication of unlawful products such as firearms and ammunition magazines, master keys, and ATM skimmers. These incidents have brought to light the absence of regulation around 3D printing technology. In principle, 3D printing may be used to create counterfeit medical devices or pharmaceuticals. Although 3D printing should not be prohibited, its long-term safety must be monitored [28].

- Patent and Copyright Concerns

For decades, 3D printing manufacturing applications have been subject to patent, industrial design, copyright, and trademark law. However, there is little precedent for how these laws should apply to individuals using 3D printing to create items for personal use, nonprofit distribution, or commercial sale. Patents having a limited lifespan often give legal protection for exclusive production techniques, substance compositions, and machinery. To sell or distribute a 3D-printed replica of a protected object, a person would need to negotiate a license with the patent owner, as doing so would be a violation of patent law [28].

- Regulatory Concerns

Obtaining regulatory permission is another key obstacle that may hamper the widespread use of 3D printing in medicine. For example, the requirement for large randomized controlled studies, which take time and money, might be a barrier to the availability of 3D-printed medicinal dosage forms. Furthermore, manufacturing rules and state legal requirements may present barriers to the delivery of 3D-printed drugs. 3D drug printers must also be legally classified as manufacturing or compounding equipment in order to identify which regulations apply to them [28].

9. Practical Case 1

Pioneering low-cost 3D-printed transtibial prosthetics to serve a rural population in Sierra Leone

9.1 Contextualization

According to the International Society for Prosthetics and Orthotics and the World Health Organization, 0.5 percent of the population in low and medium income countries (LMICs) need prosthetics or orthotics [51]. Amputees have a lower quality of life compared with the general population and the access to prothesis is restrict because producing or buying one is too expensive for lower income classes [52]. The lack of access to proper prothesis can also lead to people aggravating an injury or developing a new problem [51].

Sierra Leone, being ranked number 184th out of 187 nations on the UN development index [54], is considered an LMIC. Amputations usually happen in this country due to several situations: serious infections, complex wounds, traffic accidents, delayed patient presentation to the hospital (with time, a small problem can lead to an irreversible situation) [53].

As it happens in many countries, the number of amputees in Sierra Leone is not known to a full extent. The most recent available data, performed by the Population and Housing Census (PHC), says that there are 8305 amputees out of a population of 7 million people [53]. However, there are cases of hospitals without all the numbers registered in the system and reports of amputations that aren't even done in an hospital. Thus, the number of people needing prothesis in this country might be higher than the one registered in the PHC.

The cost of a prothesis in this country is around 200 USD, compared with the average income of 490 USD it's understandable that it is not affordable for most of the people there [56].

9.1.1. Prior Investigation

A 3D lab was established in Sierra Leone's Masanga Hospital in partnership with the Radboud University Medical Centre's 3D laboratory. A feasibility study was conducted in 2018 and 2019 to evaluate the usage of a 3D printer in a resource-limited healthcare context. Low-cost 3D printed arm prosthesis and other medical aids were developed in a short period of time using this very basic technology. The study found that design and aesthetics offered value in terms of both utility and confidence restoration. However, in that time, production of leg prothesis was not possible yet [55].

9.1.2. Material Testing

The strength of such low-cost 3D-printed transtibial prosthetic sockets was explored and assessed in a previous work. Because of the strong layer-on-layer binding, tough polylactic acid (tough PLA) was selected as the best print material. This material was used to build powerful transtibial prostheses that virtually meet the International Standard for Structural Testing of Lower Limb Prostheses (ISO 10328). During the endurance test, the socket performed 2.27 million steps with a maximum compressive force of 1200N, to pass the test 3 million steps were required. For the maximum load endured test, the socket reached a value of 6700N without fracture [57].

9.2. Investigation Conducted

Researchers hypothesized that these 3D printed prosthetic sockets would have great functionality in practical life. They developed a study to understand its impact and durability in a rural area in Sierra Leone. During two months, from February until March of 2020, participants received a prothesis in the Masanga Hospital. The satisfaction of the participants was measured by questionnaires, during interviews. These were conducted before the obtaining of the prothesis, after a period of six weeks of having them and some more are planned for follow-ups of six months and beyond (these interviews were probably already conducted but no information was published yet about the state of the investigation) [55].

9.2.1. Production of the prosthetic sockets

The sockets were made via an Ultimaker S5 printer that was installed in the Masanga hospital. Using the FDM technique, the print material PLA was used to create the final models. For the design of the socket, the stump was scanned with a 3D scanner but, before that, it was wrapped around with tight plastic to bring all the soft tissue together. The models were then created in a 3D software tool and uploaded to the printer. The socket was printed with a 0.8 mm print core, 100% infill, 0.2 mm layer thickness, and a print speed of 45 mm/sec [55].

9.2.2. Final aesthetic appearance

At the end of the process, a coverage is added to the prosthetic socket. For protection against moisture, dust and ultraviolet light the prothesis was coated with Epoxy. To provide the final aesthetics, the final color of the model must be close to the skin color of the participant, so the Epoxy was mixed with ultraviolet resistant color pigment. The final result as a closer appearance to the one of an actual human leg and it's protected against environmental threats [55].

9.3 Results

For this study, 12 participants were supposed to enter the program but, before the program was put on hold because of the COVID-19 pandemic, only 8 prosthetic sockets were completely installed so the results are only related to 8 subjects. Adding on that, one of them deceased during short-term follow up so there is no information on the evolution of the well-being of this person, the death was unrelated to the prothesis [55].

At the short-term follow up, the results of the questionnaire revealed that 6 out of the 7 subjects reached their goals in regard to walking or working with no pain. Analyzing the responses registered with those first questionnaires, it can be said that the only person that didn't reach the goal was the one that had the most ambitious one. All of the participants reported that they switched completely from the crutches to the prothesis even though some of them still used one crutch [55].

Out of all of them, three said that the distance they could walk without taking a break and the total distance they would walk in a day doubled from before and after the introduction of the prothesis, other three stated that the distances remained the same. All these six people used the prothesis more than 5 days a week and for almost 10h a day. The one subject that seemed to have opposite results to the rest of the observed group reported some pain but, according to the researchers, it was related with still getting used to the socket [55].

At the end of the follow-up, everybody felt that the aesthetic part was just as important as the functionality of the prothesis.

The weight of the manufactured parts was at an average of 1560 grams, less than the usual weight of the local prothesis of 1945 grams. The applicants that had already used the conventional model referred that the lower weight had an important influence in the increase in comfort [55].

9.4. Next step for prothesis in LMICs

Similar examples of FDM printed prosthetic legs have been set up in recent years. However, due to the limited research and follow-up performed on these projects, it is difficult to assess the quality of the medical aids. This shows that there is a need for a follow-up study to investigate this technology [55].

Conventional patellar-tendon-bearing (PTB) transtibial prosthetic sockets are widely-used in LMICs. Prosthetics produced by the International Committee of the Red Cross (ICRC) use this technique. Their workflow is considered as the standard for lower and medium income countries (LMICs). The data recovered and the production of the sockets are done manually, leading to lower acceptance levels from what has been discovered in prior researches [55].

With CAD-CAM procedures, the entire process of the production of sockets can be optimized. There is also the chance to automate the entire process of the design of the prosthetic socket. This will make the production less dependent on the skill of the operator, increasing the number of successful prostheses and making them more consistent. This automation of the process can prothesis more widely available for LMICs [55].

For the future of this investigations, there is the need to develop the automation of the entire process. This development can provide effective information on the behavior of digital produced prosthetic sockets compared to the manufactured ones [55].

10. Practical Case 2

The role of 3D printing in the fight against COVID-19 outbreak

10.1 Contextualization

Along with the COVID-19 epidemic, there has been an excessive demand for medical and specialist items, particularly personal protective equipment. The traditional medical device manufacturing line has been challenged by excessive worldwide demand, and the need for a simple, low-cost, and speedy fabrication process is felt more than ever. In order to cover the gap and improve the production line of medical equipment, manufacturers turned to additive manufacturing or 3D printing [56].

10.2 Role of 3D printing in pandemics

The accessibility and rapid prototyping capabilities of 3D printing have been critical in alleviating global shortages of medical and protective equipment. People with access to 3D printers aided in the fight against the COVID-19 outbreak by creating and manufacturing preventative, diagnostic, and therapeutic equipment in real time, from brainstorming to execution. People from all around the world are meeting in online forums to share and trade ideas and concepts for this purpose. In figure 29 it can be seen some examples of the proposed ideas [56].

Figure 29 – Proposed ideas of 3D printed devices [56]

Face shields, which create a physical barrier between the user's face and the surroundings, were one of the most popular preventative options among designers as part of the worldwide reaction. Face shields are one of the items of airborne precautionary equipment suggested by the WHO as part of PPE to prevent the spread of COVID-19 and other related infectious illnesses. Several 3D-printing businesses, including Formlabs, Prusa, and Stratasys, are offering design protocols for the production of face shields and releasing their designs online. The bulk of current face shield designs have a 3D-

printed headband that fits the user's head and is intended to carry a visor/front plate made of any laser cuttable transparent plastic [56].
Furthermore, due to a global shortage of masks, designers have looked at other means of supplying this need. Converting diving and snorkel masks to face masks took a significant amount of time and effort. This converter can maintain and connect a filter to a mask that is small in size and can be rapidly and cheaply 3D-printed. However, in order for the mask and filter sheets to fit within the holder, the user must have access to them. This mask, like face shields, is reusable, however it must be sterilized after each use [56].
Masks and other physical barriers are not the only types of protective gear. Keeping away from potentially contaminated surfaces can help to prevent the spread of COVID-19. As a result, many gadgets/tools have been created to reduce direct surface contact. One of the gadgets that can allow opening doors using elbows/feet and can simply be 3D printed to prevent direct contact with the door handle as a potential site of contamination is the hands-free door handle attachment. Small devices can also be 3D printed to be used for pressing buttons in public places or holding small things. Other designs focus on improving the ergonomics for healthcare personnel and other continuous mask users with a simple clip that secures the mask bands at the back of the head and decreases stress on the ears. Some examples can be seen in figure 30 [58].

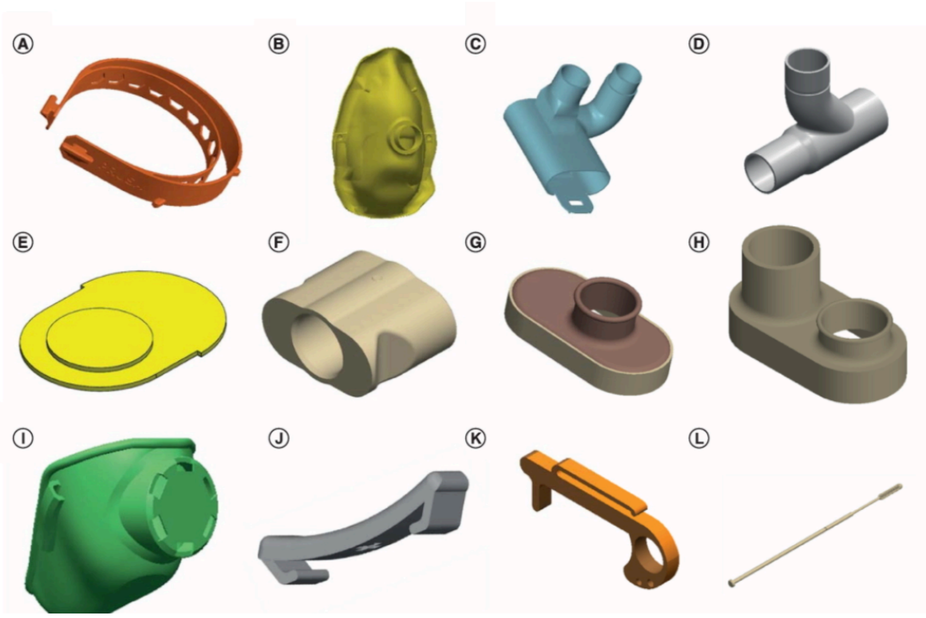

Figure 30 - Applications of 3D printing fighting COVID-19 [57]

11. Assumptions

11.1 Staff Costs

Regarding staff costs, in this particular project, the concept does not apply, since it is a theoretical research project, without any kind of experimentation and, therefore, without staff involvement.

11.2 License Costs

Regarding license costs, in this particular project, the concept does not apply, since it is a theoretical research project, without any kind of experimentation and, therefore, without license involvement to nothing.

11.3 Material Costs

Regarding material costs, in this particular project, the concept does not apply, since it is a theoretical research project, without any kind of experimentation and, therefore, without material involvement.

11.4 Energetic Costs

Regarding energy costs, these were the only ones considered in this project, considering that all the research was supported by energy-consuming technological support. The energy price considered was of 0.15 €/kWh, as it is in Spain.

11.5 Total Costs

In order to perform the calculations of the costs associated with the emissions related to the use of the computer for research we considered:

- Approximately one and a half months of continuous work on the project (40 days, i.e. 960 hours);
- Electricity price in Spain 0.15€/kWh;
- Computer power: 0.35 kW;
- Use of two computers during the project.

Having this said, the total value associated with the project developed, is:

$$0.35 * 960 * 0.15 = 50.4\ €$$

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12. Impacte ambiental

All activities, whether industrial or, as in this case, research-focused, have various associated elements that can interact with the environment and, to a greater or lesser degree, have a possible impact on it.

The environment is defined as the environment in which an organization operates, including air, water, land, natural resources, flora, fauna, humans, and their interrelationships.

Thus, the environmental impact study is an essential requirement whenever a project is undertaken. This study is considered fundamental in order to minimize unnecessary impacts.

As this is a research project, the biggest environmental impact will be the one that can be caused by the research developed, which is mostly due to the energy used during the research.

Future Trends

Through its usage in designing nutritional goods, organs, and medications, 3D printing is projected to play a major part in the movement toward personalized medicine. 3D printing is predicted to become increasingly popular in pharmaceutical settings. Pharmaceutical corporations' manufacture and delivery of pharmaceuticals might be replaced by sending databases of prescription formulas to pharmacies for on-demand pill printing. Existing medicine production and distribution processes would alter dramatically and become more cost-effective as a result. If the majority of popular prescriptions are made available in this manner, patients may be able to decrease their medication load to one polypill each day, promoting patient adherence.

The bioprinting of complex organs is the most advanced 3D printing application that is expected. It is estimated that we are fewer than 20 years away from having a completely functional printed heart. 8 Although the reality of printed organs is still some time away due to difficulties in printing vascular networks, the progress that has been achieved is encouraging. Complex heterogeneous tissues, like as liver and renal tissues, are predicted to be effectively produced as technology develops. This will pave the way for the development of viable living implants, as well as printed tissue and organ models for drug discovery. It may also be feasible to print a patient's tissue into a strip that may be used in testing to identify which treatment is most effective. In the future, stem cells from a child's newborn teeth might be harvested for lifelong use as a toolkit for growing and producing replacement tissues and organs.

Another projected future trend is in situ printing, in which implants or living organs are printed in the human body during surgeries. Cells, growth factors, and biomaterial scaffolding may be placed with exact digital control using 3D bioprinting to heal lesions of various sorts and thicknesses. In situ bioprinting has previously been used to heal exterior organs such as the skin. In one example, keratinocytes and fibroblasts were employed to fill a skin lesion in stratified zones throughout the wound bed using a 3D printer. This method might eventually be used for in-situ repair of partially damaged, sick, or dysfunctional internal organs. A portable 3D printer for in-situ direct tissue restoration is a much-anticipated advancement in this field. Robotic bioprinters and robot-assisted surgical advancements may also play a role in the growth of this technology.

Conclusions

With this monograph, it was possible to develop a better understanding and knowledge about additive manufacturing in composite and polymeric materials.

The great design freedom and the ability to print highly complex parts with minimal waste are the main advantages of this process.

As far as the methods mentioned in this paper are concerned, FDM is the most common since it is a simple, low-cost and high-speed process, and its use is directed to filaments polymeric material filaments, but it can be adapted to other materials. This process is mainly used for rapid prototyping processes, however, the mechanical properties and print quality are lower when compared to processes involving the use of powders (Powder-Bed Fusion), such as SLS and 3DP. In these methods finer resolution parts are obtained, and the associated costs and processing time are higher.

Finally, SLA is one of the pioneering processes in 3D printing and is mainly used to produce very fine resolution parts from photopolymers.

In a medical point of view, 3D printing has emerged as a helpful and possibly transformational technology in a variety of sectors, including medicine. Applications have grown in number as printer performance, resolution, and available materials have improved. Researchers are working to enhance existing medical applications that employ 3D printing technology as well as to develop new ones. The medical breakthroughs made possible by 3D printing are big and exciting, but some of the most revolutionary uses, such as organ printing, will take years to develop.

When it comes to surgical preparation, research into 3D printed organ models is an essential topic that might improve surgical results, eliminate medical mistakes, and increase patient safety.

Over the last decade, there has been a significant increase in effort in this field. Indeed, the creation of 3D printed patient-specific organ models with tissue-specific physical qualities and integrated capabilities has the potential to revolutionize preoperative planning and surgical rehearsal.

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