Faculdade de Engenharia da Universidade do Porto

Polylactic Acid-based Stent Manufacturing using Fused Deposition Modeling from a Biomedical Perspective

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Abstract

In recent times, there has been an increasing demand for customized products, arising the need for an alternative manufacturing technique. Thus, the additive manufacturing was developed, which is a faster and eco-friendly method. This technology is based on material layer-by-layer deposition from a digital model. Several techniques have emerged from this, including the fused deposition modeling. It is an extrusion process, which implies that the material is extruded by an extruder nozzle. This method, including the equipment and software involved, have been increasing the biomedical engineering applications, including the production of customized and functional medical devices, such as stents. In this sequence, the present work aims to present the three-dimensional printing and additive manufacturing concepts, particularly fused deposition modeling. Thus, different types of polylactic acid-based stent were designed and numerically tested using the finite element method. The numerical analyses performed allowed to achieve structurally and geometrically efficient solutions. In the end, the stent solutions were printed in order to show the capability of the full design process.

Resumo

Nos últimos anos tem havido um aumento da procura de produtos customizados, surgindo a necessidade de um metodo de fabrico alternativo aos existentes. Assim, surgiu o fabrico aditivo, que é também um método mais rápido e amigo do ambiente. Esta tecnologia baseia-se na deposição camada-a-camada de um de material a partir de um modelo digital. A partir deste método surgiram várias técnicas, entre as quais o fabrico com filamento fundido. Este é um processo de extrusão, o que implica que o material seja extrudido por um bico extrusor. Este método, assim como o seu equipamento e software, têm alargado a sua gama de aplicação na área biomédica, entre as quais a produção de dispositivos médicos personalizados e funcionais, como é o caso dos stents. Assim, diferentes tipos de stents construídos com ácido polilático foram projetados e numericamente testados usando o método dos elementos finitos. As análises numéricas realizadas permitiram obter soluções estruturalmente e geometricamente eficientes. No final, as soluções foram impressas de modo a demonstrar o potencial do processo completo de projeto-construção.

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Abbreviations

3D	Three-dimensional
3DP	Three-dimensional Printing
4D	Four-dimensional
ABS	Acrylonitrile Butadiene Styrene
AC	Alternating Current
AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CDLP	Direct Light Processing
CT	Computed Tomography
DC	Direct Current
DLD	Direct Laser Deposition
DLP	Direct Light Processing
DMD	Direct Metal Deposition
DMLD	Direct Metal Laser Deposition
DOD	Drop-On-Demand
EBAM	Electron Beam Additive Manufacturing
EBM	Electron Beam Melting
etc	Et Cetera
FDA	US Food and Drug Administration
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
FFM	Fused Filament Modeling
FS	Formative Shaping
LENS	Laser Engineered Net Shaping
LMD	Laser Metal Deposition
LOM	Laminated Object Manufacturing
LPD	Laser Powder Deposition
HDPE	High Density Polyethylene
HIPS	High Impact Polystyrene
HSS	High-Speed Sintering
ie	That Is
MJF	Multiple Jet Fusion

MJM	MultiJet Modeling
MRI	Magnetic Resonance Imaging
NPJ	Nanoparticle Jetting
PC	Polycarbonate
PET	Polyethylene Terephthalate
PJP	Plastic Jet Printing
PLA	Polylactic Acid
PP	Polypropylene
PTFE	Polytetrafluoroethylene
PVA	Polyvinylic Acid
RP	Rapid Prototyping
RT	Rapid Tooling
SD	Secure Digital
SGC	Solid Ground Curing
SHS	Selective Heat Sintering
SIS	Selective Inhibition of Sintering
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SM	Subtractive Manufacturing
STL	Standard Tessellation
UAM	Ultrasonic Additive Manufacturing
USB	Universal Serial Bus
UV	Ultraviolet
vs	Versus

List of Units

€	Euro
US $	United State of America Dollar

Chapter 1

Introduction

In recent years, consumer demand is shifting from standardized to customized products, so the evolution of the additive manufacturing has become essential. In comparison to the traditional ones, additive manufacturing consists of layer-by-layer material addiction and provide several advantages, including the development of complex geometries. This technology presents reduced printing time and waste of material. In addition, it enables to personalize the products, adapting them to the consumer. The recent concept of low-cost is increasing its popularity, so it has also emerged in three-dimensional (3D) printing. Currently, the most popular 3D printing technique is the fused deposition modeling (FDM) technology, which commonly use a renewable thermoplastic, the polylactic acid (PLA), due to its reduced cost and facility to be used. The FDM is one of the most popular techniques because of its low cost and the possibility to fabricate parts with locally controlled properties by changing deposition orientation and density. Thus, there are a few studies in the literature that analyse the mechanical properties of models printed by low-cost 3D printers. In the last century, biomedical area has been increasingly studied in order to try to solve the problems related to the human health. Therefore, AM has rapidly expanded to medical applications, including the development of customized and functional medical devices (as stents).

In this project, it is proposed to study the use additive manufacturing for the development of some biodevices, named stents. In order to develop these biostructures, it is essential to build different CAD models representing the real device in order to test which one suits better. For that, it might be necessary to perform some numerical simulation, in which it is generated a tetrahedral mesh and the relevant variable fields (displacement/force/stress fields) will be obtained and analysed. After this structural validation, the implant is printed by FDM using different types of PLA to analyse their performance and obtain relevant practical conclusions. Thus, it is expected with this work to demonstrate that additive manufacturing is an alternative and efficient manufacturing technique to produce stent, as it is low-cost, and it provides customization for each patient.

1. Motivation

Nowadays, cardiovascular complications are one of the major causes of death in the world. Most of the complications are due to the formation of atherosclerotic plaques in vessels. As one of the most common solution, it was developed the stents, which are endovascular biodevices that expand the vessels for an increase of blood flow. Although some studies are developing stents fabrication by 3D printing, the traditional manufacturing methods are still the only commercial techniques used to produce stents. However, with the evolution of technology, there has been an increasing demand for customized products, which has intensified the need for alternative manufacturing techniques, such as additive manufacturing. Nowadays, there are several AM techniques available, including fused deposition modelling, which is the most popular extrusion technique and commonly use a renewable thermoplastic, the polylactic acid, due to its reduced cost and facility to be used. FDM has been growing, as well as the equipment and software involved, to broad applications in the field of biomedical engineering, such as the development of personalized and functional medical devices, including stents as a possibility. Additive manufacturing technologies, in particular FDM, offer several advantages over the traditional manufacturing techniques, such as customization and almost complete freedom in the fabrication. Also, the traditional techniques are very expensive, so AM can appear as a low-cost solution. In order to evaluate the performance of biodevices, including stents, it is necessary to analyse their mechanical behaviour. One of the most effective methods is the finite element method. Compared to traditional methods used in hospitals and laboratories, numerical simulations performed by computers are more flexible, faster, low-cost and less invasive.

In addition, Figure 1 represents the data obtained through a research on SCOPUS database (www.scopus.com) about the articles published with the keywords Stent plus 3D Printing and also Stent plus Fused Deposition Modeling between 2013 and 2018, in order to analyse the development of studies in this area. As an output of this research, the interest in such topics is increasing over the years, as it started in only 1 study in 2013 and last year it was the highest number of articles published. Also, it can be concluded that stents produced by FDM are a very recent topic, when compared to stents in general AM, so the studies in this area are still pioneering.

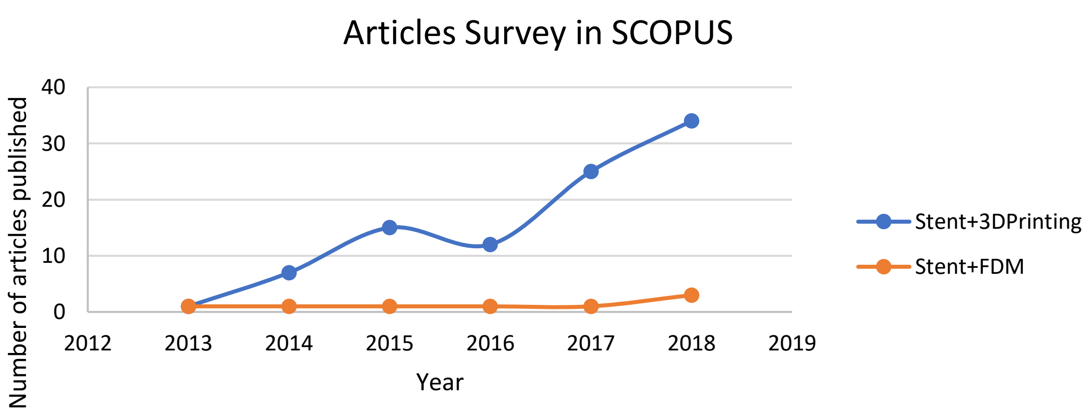

Figure 1. Number of articles published through the years, in the subjects indicated. The data was obtained through a research on SCOPUS database (www.scopus.com) assuming as keywords the subjects indicated in the graph.

2. Goals

Biopolymeric stents have received increased attention due to the high efficiency in interventional therapy and their fabrication methods still present significant challenges, including the high-cost and the non-possibility to customize. Therefore, this work seeks to complete these gaps by proposing the production of stents in an alternative manufacturing method, known as additive manufacturing, in particular fused deposition modeling. The present work was developed for Biomedical Engineering master's degree in Faculty of Engineering, University of Porto. It aims to present the state of art of the additive manufacturing, as well as their techniques, obstacles and innovations. Furthermore, this thesis aims to develop and test numerically biodevices, such as arterial stents, to be produced with the FDM technique. In the end, it is intended to produce such biodevices in order to prove the complete cycle of the process. To achieve these main goals, other secondary objectives have been established:

- Development of different geometries in order to find out which one is the most effective;
- Perform numerical analysis to test the structural behaviour of the stents;
- About PLA, test different low-cost types to analyse which has better performance;
- Use different types of printing parameters to conclude which combination has the best results;
- Assembly the stent parts and analyse the whole stent behaviour when completed.

3. Document Outline

The dissertation was organized in several chapters, beginning with Chapter 1 in which the motivation that led to the development of this work and the main goals are presented. In Chapter 2, the state of art is described in different subchapters: the first topic is about 3D printing, including the 3D printers, techniques and materials; the second one is the areas of application, with special emphasis on biomedical applications; the third presents the innovations and which is expected to be the future trend of AM; the fourth focuses on cardiovascular system, some complications and nowadays solutions; finally, the fifth and last subchapter is about stents, specifying the most common types and materials used. Chapter 3 presents the practical component of this work, focusing on the design component, the numerical simulation and the 3D printing. In the design subchapter, it is showed the developed models, as well as their main dimensions. The numerical simulation topic presents the structural analysis of one of the models to define the best geometry and its main results (displacement, stress and force), and the 3D printing one introduces the procedure of models printing and demonstrates the printed results. In Chapter 4, several conclusions are exposed, such as the expected main achievements of the work and the planning of future works.

Chapter 2

State of the Art

1. 3D Printing

3D printing is usually used to describe the additive manufacturing processes which, as will be explained later, consists of technological processes that lead to the production of 3D physical model, in a fast and autonomous way from a Computer-Aid Design (CAD) model. Notice that the CAD modulation is the use of any computer technique possible to be applied to the design process [1-3]. 3D printing came in 1984 by Chuck Hull, cofounder of the American company 3D Systems and author of the first 3D printing [4, 5]. Initially, 3D printing was mostly used to test new concepts before its production and, consequently, to identify errors [6]. Afterwards, the production of final products became broadly employed, achieving customized designs and competitive prices in market [6]. Then the consumer himself appears as a 3D printer owner, producing his own objects [6].

This concept has become quite popular thanks to its cheap and fast capacity of producing, along with the possibility of customizing models. Therefore, the model can be produced at once and with different materials. In 3D printing, the only possibility to stock is the material used, which reduces the manufactured products not sold [6]. In opposition to traditional manufacturing, which can obtain material waste up to 96%, additive manufacturing can reduce this expense by 40% [6]. Therefore, the additive manufacture is economically favourable for small series [6]. Furthermore, it does not require the use of molds or extra tools, it is a highly automated process and it can produce its own replacement parts [6].

1.1. 3D Printers

For 3D printing, it is used an equipment named 3D printers. In 1987, the first 3D printer, named SLA1, was launched by the company 3D Systems Inc, and since then many more have been developed. In Portugal, the first 3D printer, titled BeeTheFirst, was developed and produced in September 2013 by the company BeeVeryCreative (Figure 2). This printer has an extruder diameter of 0,40 mm and a build volume of 190x135x125 mm and it only works with polylactic acid (PLA) thermoplastic [7]. The connection is done via a USB cable and requires the specific use of BEESOFT software [7]. Currently, it is possible to purchase this equipment online and in physical stores, including Worten.

Figure 2. The first Portuguese 3D printer - BeeTheFirst. Cited from [7].

Typically, 3D printers, especially those that use FDM, are composed of five units responsible for their structure and operation: the extrusion unit; structural and movement unit; control and communication unit; power unit; and print bed unit [8]. Furthermore, it is used filament-type material.

The extrusion unit is responsible for a sequence of tasks, which start at the filament supply and its conduction to the extruder, which is cooling at its entrance [9]. Then, it enables the extruder to be assembled into the effector, it also extrudes the material and isolates the parts adjacent to the extruder [9]. Thus, this unit is composed by filament driving bearing and feeders with a material driving gear associated with step motors [9]. The rotation speed of the engaging regulates the speed of filament conduction to the extruder [9].

For these components assembly, it is commonly used the Bowden configuration, which use Bowden tubes (flexible cables based on polytetrafluoroethylene (PTFE)) for connecting the extruder to the feeder, resulting in higher driving speeds [9, 10]. Even though its filament changing is difficult and friction may occurs between the Bowden tube and the material, this configuration enables, if necessary, filament retraction, which is a technique that allows the molten material to be drawn back to the hot-end, during the printing, reducing the "stringing" effect [10]. This effect results from the fact that the extruded materials are not in complete liquid state, creating thin mouldable wires [10].

The 3D printer also possesses extruders (also known as material feeder), which are responsible for filament feeding in the hot-end and they have the filament driver and the hot-end [5]. This last component is generally composed by a block of aluminium (with temperatures up to 250°C to extrude the material), a nozzle extruder and a temperature sensor [5]. Figure

3 shows an example of an extruder and its components. The extruder nozzle, which works as a resistor, has three heat sinks, which enable the filament to be solid when it enters the heated nozzle [5, 9]. Its aperture diameter can range from 0,20 to 0,50 mm and it regulates the printing resolution: the smaller the nozzle, the higher the resolution, but the longer it takes to print [10]. The extruder is further associated with an effector whose function is mentioned below [9]. Moreover, there is a cooling structure, consisting on a fan, which works through forced convection to cool the heat sinks [9]. In this unit, it is mandatory to make a regular monitoring of material residues that remain between the gear teeth during printing, because it can result in filament slip instead of driving at a controlled speed [9].

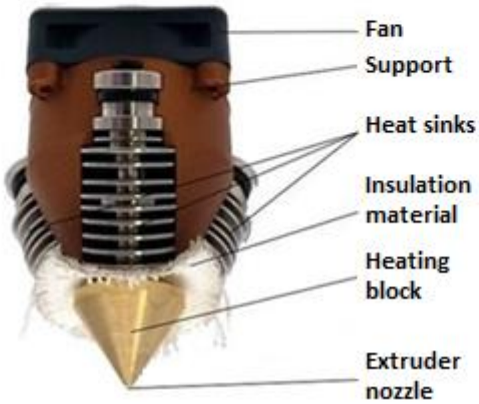

Figure 3. Extruder example and its components. Adapted from [9].

On the other hand, the structural and drive unit provides a linear delta drive system, enables the movement transmission between components and also allows the connection of the rails to the transmission systems. In addition, it enables the rails to slide off, the assembly and protection of the fixed components, and provides stability to the entire printer. Therefore, the linear movement system is achieved through the arms, rails and effector assembly, which has magnetic pieces that connect the extruder to the arms [9]. The sliding of the rails is carried out along the chassis towers by the linear bearings [9]. The transmission is based on pulleys and straps connected by step motors.

The control and communication unit enables the movement control of the step motors (related to the transmission of rail movements and the feeding of the filament) and the cooling fans operation. It also provides heat to the extruder and the printing platform, along with their temperatures measurement [9]. Additionally, it allows the position detection of the rails and their limits, the connection to a computer by USB for control and monitoring. This unit allows to print models from a SD card and also to control, to monitor and edit the operating parameters from a control panel or from a computer. More, this unit can be powered by low voltage DC and it may provide an emergency command, which stops the printer operation through the reset button [9]. Thus, this component possesses the Arduino, which consists of an electronic board that uses microcontrollers and enables microcontrollers programming through a firmware, while programming the boards is done from a software called Arduino Integrated Development Environment, available for free [9]. The microcontrollers are responsible for calculating the conversion of the rail position according to the desired position of the effector, and the number of controllers used is based on the sum of step motors for the three Cartesian axes and for the existing filament feeders [9]. The firmware is the program installed on the microcontroller that reads the G-code instructions and also manage and control all peripheral components (including step motors, temperature sensors, fans, etc.) [9]. Currently there are several available firmware, such as Marlin firmware and Repetier [9].

The power unit is responsible for converting high voltage AC into low voltage DC to supply power to microcontrollers and has a general power cut and protection system for situations that need it.

Finally, the print bed unit enables the model fixation and the manual adjustment of the print bed position and it has thermal insulation [9]. The print bed is the place on which the model is printed and it is usually composed of Plexiglass (acrylic), aluminium or glass [10]. Thus, a correct manual calibration of the print bed is essential in order to all its points be at the same distance from the extruder nozzle, which promotes the first layer adhesion and consequent good surface finishing [9]. Sometimes, it may be necessary to cover it with Kapton tape (high heat resistance) or glue, hair spray, among others to facilitate the initial adhesion [9, 11]. In Figure 4, it shows a schematic of some FDM printer components.

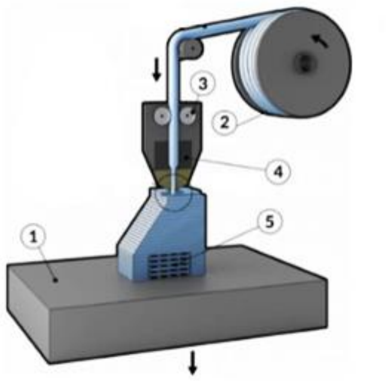

Figure 4. Schematic of FDM components: (1) print bed; (2) filament coil; (3) filament feeder; (4) extruder; (5) structural component. Adapted from [12].

1.1.1. The Categorization

Nowadays, there are several 3D printers using FDM, available both in Portugal and in the rest of the world. Therefore, it becomes necessary to categorize the different types FDM printer and the most common are price-based and those related to the extruder's translational movement.

In terms of costs, the 3D printers can be professional (or industrial) or desktop (or personal) printers. Professionals printers have acquisition costs higher than 4500€, while the desktop printers costs up to 4500€ [13]. The professional 3D printers have a wide range of applications and are commonly used for molds and prototypes design and production, so it is essential to have high quality [13]. Thus, they typically have high size and weight (ranging from 30 up to thousands of pounds), depending on the degree of resolution, precision and print speed desired [13]. About the technologies used, these vary according to the manufacturer, being able to adapt/use different technologies and materials. Furthermore, most of manufacturers have their own software [13]. Therefore, they have high costs, which limits their target clients [13].

On the other hand, desktop 3D printers are economically more affordable and their cost has been decreasing in recent years, for example the printer MakiBox A6 LT (John Buford) whose price is about 180€ and the Buccaneer printer (Pirate3D Inc) costing about 300€ [13]. In addition, the cost of the materials used, particularly the filaments, has also decreased and the actual coil price is between 20€ and 45€ [13]. Since these printers are for home use, they are small and rarely exceed 254 x 254 x 254 mm in volume, which limits their range of applications [13]. Additionally, most of them are based on FDM technology, which requires thermoplastic materials [13]. About their software, it needs to be simple because the target users will be amateurs [13]. Therefore, these printers have low print speeds, frequent printing errors, and reduced accuracy compared to professionals [13]. However, they have better aesthetics and design. An example of each type of 3D printer can be seen in Figure 5.

(a) (b)

Figure 5. Example of a 3D printer: (a) desktop (The MakerBot Replicator MINI+); and (b) professional (Stratasys Objet1000 plus). Adapted from [14, 15].

Most 3D printers have three degrees of freedom. Thus, the positioning mode of the extruder varies with the kinematic chain of the printer, so the extruders can be in series or parallel [16]. The in series extruders include an open kinematic chain, so the degrees of freedom movements are performed independently, unlike the parallel extruders [16]. The last ones have a closed kinematic chain, which makes them composed of several mechanical elements connected to each other and driven synchronously [16].

To print a 3D object, it is necessary for a 3D printer to move on three Cartesian axes [6]. Thus, the categorization is based on the extruder spatial translation mode, and the printers can be divided into Cartesian or linear delta configuration [6, 16, 17] (Figure 6). The main difference consists in its movement, and to make a horizontal movement: in Cartesian it is possible to move a single axis, while in the delta there is always the combined movement of the three axes [16, 17]. The Cartesian printers have the arms parallel to each of the three orthogonal planes and its principle consists on its three main axes being linear, and the coordinate origin is on the print bed border [6, 16, 17]. The movement of the axes takes place in a straight line (does not spin) and is independent, not influencing the resolution of the other axes [6, 16, 17]. Therefore, these printers have three degrees of freedom, in series extruders and their printing area is rectangular [6, 16, 17]. Although these printers have a reduced printing speed, precision and uniformity of the components, they enable a high volume printing and have an easy calibration [16, 17].

On the other hand, linear delta printers were developed, possessing parallel extruders that move in the three Cartesian axes through a set of arms connected to linear joints [16, 17]. The three axes movement occurs simultaneously to define a position [16, 17]. These printers have a fixed platform connected by a few arms to the effector, which have also connected three pairs of arms (aluminium tubes or carbon fiber) that limit the rotation of the effector [16, 17].

The chassis, effector and arms form the moving part and must be light and rigid enough to have a low inertia [16, 17]. The coordinates origin is in the print bed centre [16, 17]. These printers have a higher print height, which enables higher printing precision, so it has emerged to civil engineering and architecture applications [16, 17]. In addition, component uniformity and print speed are higher thanks to the connection between the three axes [16, 17]. However, they only allow a reduced volume printing and have a hard calibration [16, 17]. Today, there are several linear delta FDM 3D printers on the market, such as DeltaWASP 2040 (WASP), which feeder is suspended by three elastics on the rails, and Pollen PAM Series P (Pollen), which has a movable base and a fixed feed and extrusion unit.

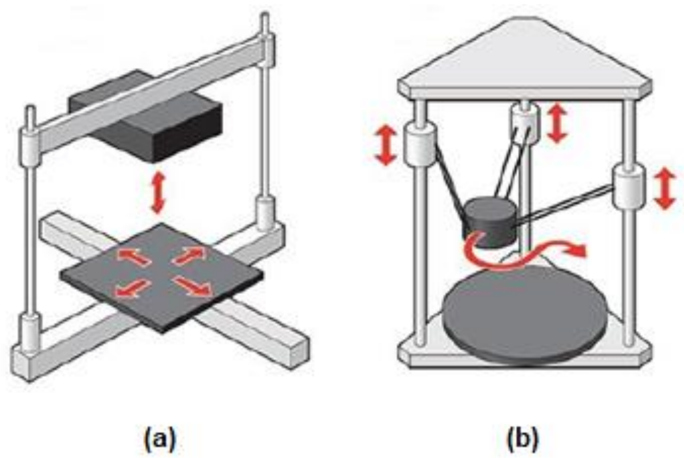

Figure 6. 3D printer configuration: (a) cartesian; e (b) linear delta. Adapted from [9].

To compare the existing 3D printers, benchmarking was developed as a continuous and systematic process that enables the performance comparison between different systems (processes, organizations, machines), establishing standards [13]. Thus, this concept allows the identification of strengths and improvements in the practices and processes of an application [13]. Therefore, there are several benchmarks, but the most common are the geometric, mechanical and process ones [13]. The geometric benchmark is common to verify the dimensional and geometric model accuracy, including tolerance, repeatability and roughness [13]. The mechanical benchmark is used to characterize the model mechanical properties such as hardness, tensile strength, compression, bending, impact and heat resistance [13]. Finally, the process benchmark provides the establishment of the process characteristics, specially the construction direction, STL resolution, speed, layer thickness and filling [13].

1.1.2. Brands

Since the 1980s, there has been an exponential increase in companies demand to develop products related to 3D printing [18]. Although there are already several companies in this area, the most popular manufacturers are the Makerbot, Stratasys, Ultimaker, Afinia and 3D Systems [18]. Another examples are FelixPrinters, FabTotum (Startup) and Type A Machines [18].

Makerbot is one of the most popular American companies of 3D printers and it was created in 2009 by Bre Pettis, Adam Mayer and Zach Smith [19]. Initially, it only produced low-cost printers, but in 2013 it was acquired by Stratasys, which led to its expansion, because it has a wide range of products of different costs [19]. Therefore, Stratasys was founded in 1989 by S.

Scott Crump and Lisa Crump [19]. This American company focuses on several areas such as aerospace, industrial, electronic, medical, among others, which makes it one of the market leaders [19].

In 2009, Afinia emerged from Mircoboards Technology, a company related to the printing and scanning hardware [19]. On the other hand, Ultimaker is one of the biggest European manufacturers and it was developed in 2011 by Martin Esperma, Erik Brain and Sire Mijina [19]. This company has the Cura software patent and focuses on the production of equipment with the best quality possible [19].

Last but not least, 3D Systems is one of the oldest 3D printing companies and it was developed in 1983 by Chuck Hull [19]. It was focused on 3D printing for professional use with high-cost ranges. In order to expand its market, it has created the Cubify in 2011, producing low-cost printers for home use [19]. Currently, it has several products besides printers, such as scanner, material and software.

1.1.3. Open-Sourced Concept

In recent years, the open-source concept has been under strong development. Its goal is to promote and distribute the products design for free use, in other words, its license is free to any user, which provides a vast diversity of available software [20]. In contrast to closed-source software, in open-source code, original code modification is strongly encouraged in order to adapt it to the user's needs and to correct errors [20]. With the extension of open-source application, it was developed the open-source hardware, in which the machine or component design is freely available, and changes can be made freely [20]. Briefly, the open-source provides the free sharing of knowledge that enables users to complete their needs [20]. The 3D printers development and expansion enabled models and components replication with few or no marketing restrictions [20].

This movement provided the creation of several companies derived from this same concept, and over the years some have remained open-source, such as Ultimaker, selling the same products, but providing the possibility of technological evolution [19]. In contrast, there were others that became closed-source, which no longer allows the free sharing of designs, including Makerbot. Currently, there are several open-source projects and the most popular are Fab @ Home and RepRap [19, 20].

Fab @ home was developed in 2005 and its main goal is to develop and distribute a platform of personal low-cost manufacturing [20]. Model 1 (Figure 7), which was the first version of this product, had a chassis in acrylic plates and the extrusion unit consisted of two syringes, so it was intended to extrude paste materials, including some food products, ceramic pastes or resins [20].

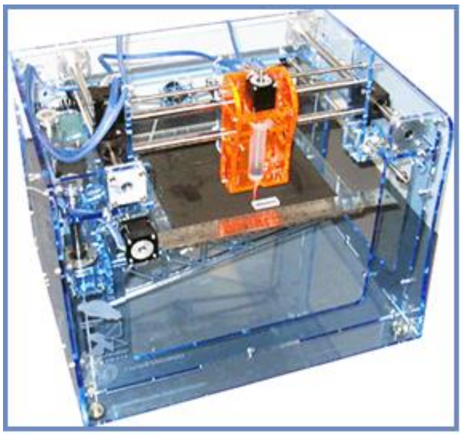

Figure 7. Fab@Home Model 1. Adapted from [21].

Over the years, some technological, economic and community defects were detected. For instance, it did not allow the use of resistive materials and had a high cost [20], so it ended in 2012. However, it led to the creation of some models by MakerBot [20]. In addition, Fab @ school was also developed to expand 3D printing concept among young people [20].

RepRap (Replicating Rapid Prototyper) was developed in 2004 by Adrian Bowyer and his students from the University of Bath and its concept consists on the first self-replicating 3D printer with the capacity to reproduce most of its own components, so later the users do not need to buy another [22]. The parts that cannot be replicated by this printer are easy to buy [20]. In 2008, the first model of the RepRap concept was developed, titled Darwin I (Figure 8), and it was produced through FDM components [20].

3D printers that emerge from the RepRap concept use FDM technology, so the most commonly materials are thermoplastics [22, 23]. Most of the prototypes are printed to analyse their performance and viability [23]. Being open-source, the software used is free and it has the possibility of free sharing its developments [13, 19]. In recent years, there has been a huge evolution of this concept and there are currently many commercial models that are based on this project [20]. Nowadays, it is the most popular 3D printer [13].

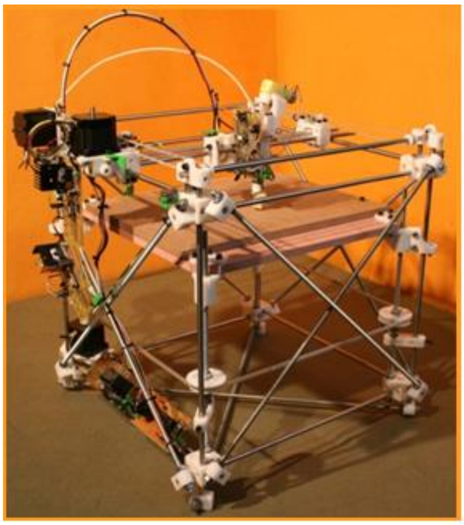

Figure 8. Darwin RepRap 3D printer. Adapted from [24].

1.2. Socioeconomic Analysis

In recent years, there have been many public and private initiatives, including research centres and consultancies, to explore opportunities for 3D printing innovation [25]. The exponential expansion of fused deposition modeling has required educational programs that address the fundamental principles of this technique [25]. Therefore, several AM educational initiatives have been developed.

Since the first 3D printers commercialization, there has been an increasing of scientific and technological impact of 3D printing [22]. In the last decade, its products and services revenue has been increasing, as shown in Figure 9 (a), mainly due to the low-cost equipment expansion [25, 26]. In 2012 this revenue was US $ 1843,20 million and increased 35,2% from 2013 to 2014, corresponding to US $ 4,10 billion [25, 26]. In 2016, the AM industry grew 17,4% (more than US $ 900 million), down from 25,9% the previous year (about US $ 2,20 billion), resulting from the failure of two largest manufacturers of the sector [27]. About materials, the highest sales percentage are for polymers (USD 350 million), while metals have a value of US $ 127 million in 2016, and there has also been a materials sales increasing in for 3D printing over the years [22], as can be seen in Figure 9(b). Furthermore, about 40% of 3D printing business is in United States of America, 10% in Germany, 10% in Japan and 8,5% in China [19]. The remaining percentage is distributed throughout the rest of the world. Nowadays, 3D printing sales are still lower than the traditional industry, which had a total production of about $ 60 billion in 2014 [28]. However, 3D printing is expected to maintain the growth rate in the future [25, 28]. According to [8], the 3D printing market is expected to reach $ 692,2 million by 2020.

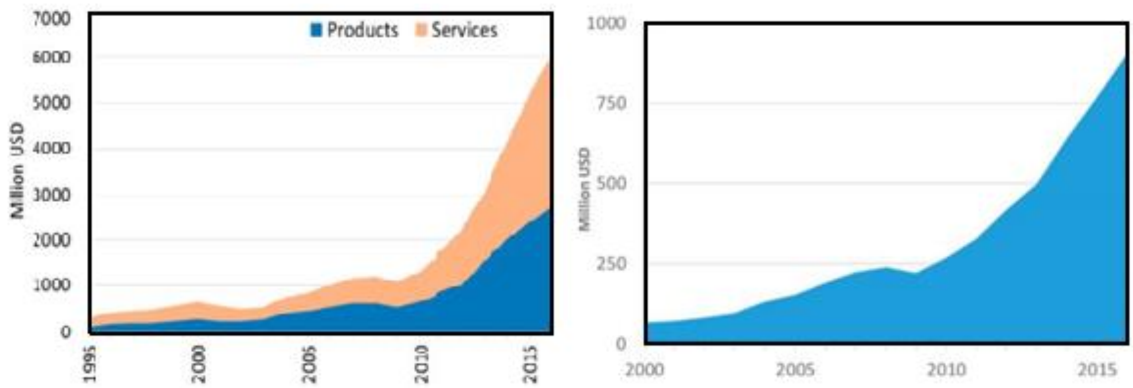

Figure 9. Worldwide revenues from 3D printing: (a) products and services between 1995 and 2016; and (b) material sales between 2000 and 2016. Adapted from [22].

1.3. Additive vs Traditional Manufacturing

According to Ferreira *et al.*, rapid prototyping technologies can be based on: material removal, which requires a process that removes material; or in material addition [29]. In Figure 10, the three main methods used in rapid prototyping are represented. The traditional method of modeling is called subtractive manufacturing, which is based on the material removal and some examples of this process are milling, grinding, drilling and rectification [4, 30]. There is another traditional conformation process, which is a compression / consolidation process called formative shaping [4]. Thus, it is used the application of pressure, including forging, pressing and folding [4]. Both the subtractive and formative methods use large amounts of energy, provide a huge waste of material and require several steps to be carried out, so it takes a significant amount of time [4]. To produce components with complex geometry, it is necessary to divide the components into several parts that are later assembled [4]. These disadvantages contribute to another: the high costs [4]. To conclude, the introduction of the new products in the market takes time [4].

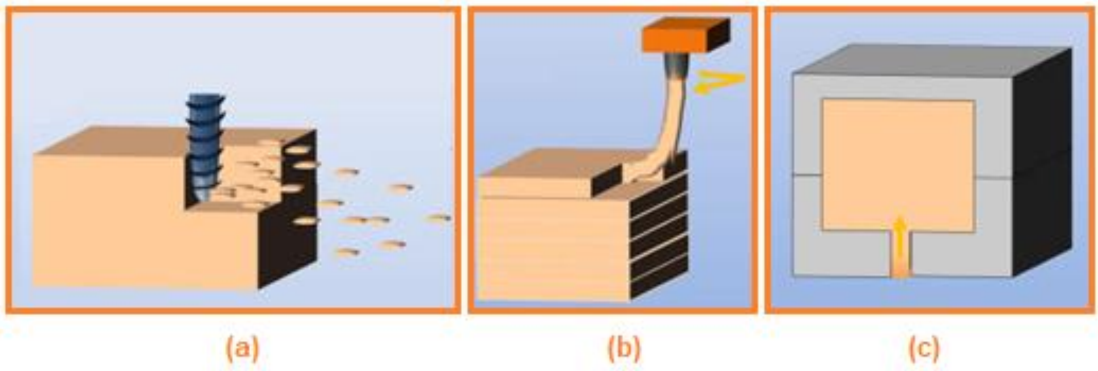

Figure 10. Representation of manufacturing techniques: (a) subtractive; (b) additive; and (c) formative shaping. Adapted from [22].

To resolve these obstacles along with the current consumer demand for customized products, it was developed the additive manufacturing process, which, as will be explained later, consists of the objects production through layer-by-layer material addition [4]. In opposition to traditional methods, the additive manufacture produces objects of limited size, because most of the current equipment enables the manufacturing of components up to 500 dm^3 in volume and its speed is limited for a large-scale production, preventing mass production [4, 5]. As a result of this layer-by-layer printing, it shows the step effect, which provides a bad surface finishing [4]. So, in the literature, it is suggested to reduce the layer thickness, but this will reduce the process speed [31]. Brajlih *et al.* has developed a method to detect the best speed and precision of the AM [31]. After printing, it usually requires post-processing, and the surface finishing can be associated with a higher roughness and lower quality, which may provide product problems [5].

In comparison to the formative and subtractive techniques for plastic use, AM is slower [22]. Thus, the current range of AM materials is limited (polymers and few ceramics, metals and alloys) and more expensive than the traditional raw material, which makes difficult the transition from conventional to the AM. However, for manufacturing a reduced number of components, AM presents the best cost [28]. Another major concern is the spatial resolution, more precisely in the z-direction, associated with the minimum layer thickness, because it depends on the motor operating precision on the printing platform [22]. Another obstacle is the fact that it requires a certain level of knowledge, particularly in the modeling and manipulation of 3D CAD files [19]. In addition, the largest concern to its globalization are due to the lack of repeatability, since there is always a variation in the model produced in equal process parameters, and to the insufficient building materials properties, including thermomechanics, porosity, long-term stability, cost, corrosion properties, creep, etc. [4, 22]. Due to the layered production process, the parts tend to be anisotropic with the space between the adjacent layers representing weak regions with maximum residual stresses [22]. Thus, one of the main research areas in AM is trying to improve the models mechanical properties produced by AM [22].

On the other hand, additive manufacturing is a simple method with form freedom, and it does not require accessories, cutting tools, refrigerants, etc. [4, 22, 32]. As it is processed from a digital drawing, it is possible to produce the model without using molds [22, 30]. In addition, it enables the structures incorporation inside the model and allows the construction of more complex geometries with multifunctional materials and complex forms and functionalities, such as biological systems [4, 5, 22, 30]. It also provides the production of hollow components and the early identification of design errors, eliminating possible costly corrections in later phases, and offers a reduction of the labour and transportation costs and process steps to a single one (and consequently of the producing time) [4, 22, 30]. It is also possible to perform several tests, reduce production changes and increase the product lifetime by excluding unnecessary details in project phase [13, 28]. This process is capable of printing different parts using different materials and has a reduction of lead time for single parts [5]. Furthermore, the cost of each part does not depend on the quantity produced, being the ideal method for the customized components manufacturing, and the equipment used requires reduced investments and almost no human supervision [20]. The components produced are lighter due to the one-step production, eliminating nuts, bolts, etc. [4]. Moreover, it enables home-based manufacturing for non-specialized individuals and it is eco-friendly, as it results in a low waste of material, it does not include environmental pollutants and it requires lower amounts of energy [4, 23, 28, 30].

1.3.1. The Concept of AM

There are currently several names for additive manufacturing, as Automated Fabrication, Solid Freeform Fabrication, Desktop Manufacturing, additive Layer Manufacturing, 3D Printing, Direct CAD Manufacturing, Additive Processes, Additive Techniques, Rapid Prototyping or Manufacturing [32]. This technique was originated from rapid prototyping (RP) in 1986 by Charles Hull [23]. Rapid prototyping is used for very fast prototypes production [4]. Over the years, this technology has undergone many improvements, and another technology emerged, called Rapid Tooling (RT) [4]. In contrast to RP, this technology is used to produce tools that will be used in other manufacturing processes [4]. In the late 1990s, AM started to be used in the manufacturing of parts for final use [4].

According to the American Society for Testing and Materials (ASTM), AM consists on the development of physical prototypes through the addition of layer-by-layer material by several physical and chemical processes, from 3D virtual models [33]. With the development of technologies, additive manufacturing is moving from rapid prototyping models to functional models for final use [23]. This technique involves all the steps to produce autonomously 3D physical models from a CAD model in a reduced time (hours, sometimes minutes) [13]. The manufacturing is achieved by the successive addition of cross-layers (Slicing), one on top of the other, forming the physical prototype [4, 23]. Thus, with AM it is possible to manufacture customized parts, including prototypes and small components in series [4, 22]. In addition, it has complete form freedom and it is normally used for a variety of applications, including concepts previsualization, surgery simulating, molds designing, and functional parts constructing for final use [4, 22].

From the model drawing to its print, the additive manufacturing includes a few steps. Firstly, a 3D digital model is obtained by drawing and manipulating it through CAD software or by a reverse engineering process, in which the object is subjected to a acquiring process through a 3D scanner system, which results in a set of points that are subsequently processed until a 3D digital copy of the physical object is reached [5]. For this, there are several commercially available softwares, including Solidworks, AutoCAD, SolidEdge. At a low-cost perspective, a number of free softwares are on the market, including: BLENDER (Blender Foundation), which is a very popular open-source one, capable of modeling surfaces; SKETCHUP (Trimble), which is a software with few errors and it allows the online model share; FREECAD (Juergen Riegel and Werner Mayer), an open-source, engineering-oriented program; the OPENSCAD (Clifford Wolf and Marius Kintel), where the modeling is done by scripting; the SCULPTRIS (Tomas Pettersson, Pixologic), in which the surfaces are modified by drag; the 123D (Autodesk), which includes several programs for different applications such as 123D Design, 123D Sculpt and 123D Creature [19]. When it comes to the human body, it is possible to use technologies to obtain the model geometry including magnetic resonance imaging (MRI), computerized tomography (CT), anthropometry, among others, which require highly sophisticated equipment and provide high resolution results of a tissue or organ [34]. An alternative is to obtain a pre-existing 3D model from a CAD file repository, such as Thingiverse, Grabcad and Myminifactory [35].

After this step, it becomes necessary to convert the 3D model into a standard format through a flat face approximation process called STL (Standard Tessellation or Triangulation Language), since it is the only format that can be used in the next step [4, 5]. This format is characterized by model surface approximation by triangles, and the smaller the triangles size, the better is the surface approximation, but the largest file's processing time [13].

In this way, the next step is to manipulate the STL file through a pre-processing program, which enables the adjustment of the model size, position and orientation, determining the printing time required: the lower is the dimension in the z axis, the smaller the number of layers and, consequently, the shorter the construction time [4]. The printer is connected to the computer through a computer-aided manufacturing (CAM) system, which constantly monitors the building commands. The CAM system controls, from a computer, the printing while it is taking place. Thus, for each layer, the coordinates or paths of extruder nozzle are generated [5, 8]. Therefore, it is used a slicing software, as they allow the "slicing" of the 3D model for layer-by-layer printing [35]. Thus, these programs create a G-code file, which is a programming language that allows the machine control, converting 3D models in text, including the parameters and instructions for the printing [8]. Currently, there is a huge variety of CAM softwares, some of which are presented in Table 1.

Table 1. Some CAM softwares and their characteristics.

Software	Developer	Accessibility	Specificity	Comments
Cura	David Braam/ Ultimaker B.V.	Free	Basic	Works great on RepRap; good interface; very complete.
Slic3r	Alessandro Ranellucci	Free	Intermediate	Versions have been improving; has enough detail.
Makerware	Makerbot	Free	Intermediate	Only works on Makerbot models.
Pronterface	Kliment Yanev	Free	Basic	Non-intuitive installation; requires Python.
OctoPrint	Gina Häußge	Free	Basic	Simple to handle and configure.
Afinia 3D	Afinia	Free	Intermediate	Connection via Wi-Fi but limited use to branded printers.
CraftWare	CraftUnique	Free	Intermediate	Ignore small details.
MatterControl	MatterHackers	Free	Intermediate	Allows to draw 3D.
Repetier-Host	Hot-World GmbH & Co. KG	Free /Paid	Intermediate	Capable of setting up to 16 extruders; telephone printing control; includes 4 Slicers; Slow updates.
KISSlicer	Jonathan Dummer	Free /Paid	Intermediate	Pro version configurable for 2 extruders.
Simplify3D	Simplify3D, Inc.	Paid	Advanced	Provides the results with the highest precision and speed; compatible with many printers.

Subsequently, the 3D printer is configured [13]. Thus, print parameters and instructions, such as print speed and temperatures, layer thickness, print bed and extruder temperature, etc. are set [19]. Next, the physical construction of the virtual model is performed through the execution of the commands indicated [19]. Although it is not necessary, human supervision is advisable, since it is the stage where more errors occur, such as lack of material, unwanted deformation, clogging of extruders, etc. After this step, the solid is created, the first layer serving as the base from which the rest of the template is printed [5]. When the printing is finished, it is transferred to post-processing, which includes curing activity, exclusion of the machine prototype, excesses and support structures, cleaning, painting and surface finishing [4, 5]. In Figure 11, the main steps of the additive manufacturing are summarized: the development of the object by digital software; then its pre-processing, such as slicing the virtual model in layers, adjusting the support structures, among others; and, finally, model additive printing and its post-processing to remove support structures, for example.

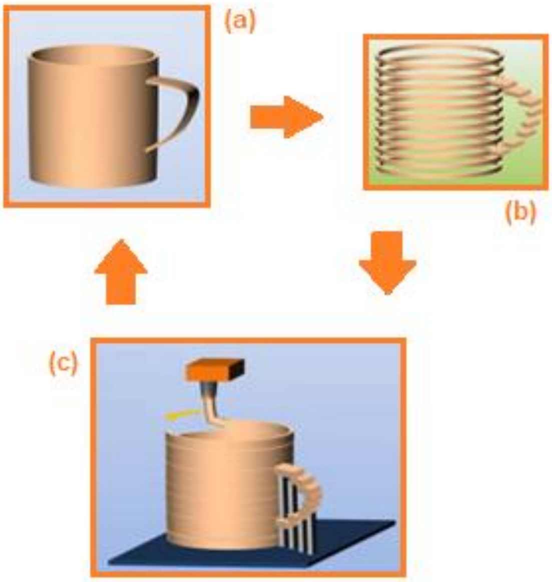

Figure 11. AM stages: (a) 3D model development; (b) pre-processing of the model; (c) printing and post-processing. Adapted from [22].

Sometimes, it is necessary to use supports, structures normally generated by slicing software that keep the model fixed and that can be removed at the end of the print [36]. For the use of supports, there are several strategies such as the 45-degree rule, which assumes that it is necessary to use them for protrusions with a slope greater than 45 degrees [36]. However, "YHT" rule was also developed, which indicates that "Y" parts do not need support, "H" depends on the length of the horizontal component, and in "T" errors will occur during printing, as there is no support for the lower layers [36]. Finally, holes can also cause printing errors if they have a diameter of 5 mm or more, and this can be avoided by the tear dropping technique, which limits the protrusions to 45 degrees, making the larger holes printable [36]. Thus, the use of supports requires more material, which increases the printing time and associated cost [36].

Normally, the models produced are widely used in prototype visualization (visual prototyping), due to the facility to be more easy to understand a real model than a virtual one, and also in the model simulation, particularly to test its geometric characteristics and function (functional prototyping) [22, 36]. Furthermore, this technique is also commonly used for error correction at an early stages, solutions analysis for design selection, optimization of functional and mechanical performance before the product manufacturing [13, 36]. Thus, the main applications of AM are shown in Figure 12.

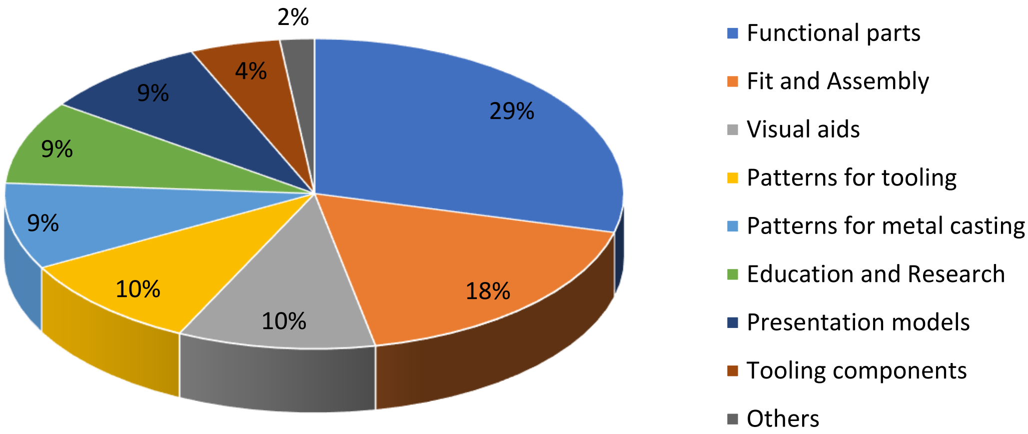

Figure 12. Most popular AM applications. Data from [22].

1.3.2. The Categorization of AM

Currently there are several strategies to classify AM processes, based on, for example, the type of material used (polymers, metals, ceramics, composites and biological materials) [22]. Another categorization consists on the raw material initial state (liquid, powder and solid) [22]. According to the American Society of Testing and Materials, AM processes can be grouped into seven categories, based on the methods used for layer deposition and its way of connection - powder bed fusion, vat photopolymerization, material jetting, blinder jetting, directed energy deposition, sheet lamination and material extrusion [22].

Powder bed fusion consists of powder melting by a laser, electron beam or a heated printhead, for partially or totally fusion of the particles [22]. It is normally used for metals or polymers [22]. In this category, many technologies are introduced, including electron beam melting (EBM), selective laser sintering (SLS), selective laser melting (SLM), multiple jet fusion (MJF) and selective heat sintering (SHS) [22].

The EBM uses a electrons bundle in a powdered layer, resulting in metal particles fusion [22]. The system used produces small residual voltages, it is quite fast, and only uses a small amount of energy [22]. However, it requires a vacuum for production and it only uses conductive materials [22].

On the other hand, SLS was developed by Dr. Carl Deckard at the University of Texas, it was commercialized by DTM Corporation and later purchased by 3D Systems. This technology uses a laser in a powdered material (including metal, ceramic and plastic) [4, 30]. Specifically, it consists of a carbon dioxide laser that sinters a powdered layer, and the interaction of the laser with the powder raises the temperature to the melting point, which results in the fusion of the particles to the previous layer [4, 30, 36]. Then, a layer of powder is placed over the formed layer and the process is repeated until the model is complete [4, 30, 36]. Thus, this technology provides high stability and strength, requires neither supports nor post cure and it requires reduced post-processing. Furthermore, with this technology a high range of materials can be used and it is possible to produce components on top of pre-existing ones [4, 36]. However, the final models have high dimensions, the surface finishing depends on the powder size and the process is quite slow, expensive and not eco-friendly, because it produces toxic gases and requires a high amount of energy consumption [4, 36]. One of its most popular applications is in the footwear industry, and Adidas and New Balance have already commercialized some footwear with elastomeric midsole produced by SLS [22]. It can also be used to produce prototypes and injection molds and also in aeronautics, automobile and medicine [4, 22].

In addition, the MJF consists of a few ink jet nozzles which introduces the melting agent in the plastic powder layer by an infrared radiation source, sintering the layer until the model is completed [22].

Finally, the SHS consists of a heated print head passing through a thermoplastic powder layer, sintering it, and then adding a new layer of powder. This process is repeated until the object is finished [22]. This technique is similar to SLS, and the main difference is based on the use of a print head instead of a laser, which makes it cheaper [22].

About the vat photopolymerization, it uses a liquid photopolymer, specifically resin [22]. This material is in a vat and it is selectively cured by light activated polymerization [22]. In this category, direct light processing (DLP) is inserted, which uses a digital projection screen to create the layer images, each consisting of square pixels and the DLP projector is used for selectively solidifying a liquid polymer [30]. This technique is quite fast [22]. Furthermore, there is also the continuous direct light processing (CDLP), which consists of the same procedure as the DLP, but it has vertical continuous movement of the printing platform, so it is faster than DLP [22].

On the other hand, the main technique of this category is called stereolithography, or stereolithographic apparatus (SLA), which uses a laser that selectively scans a liquid photopolymer tank [4, 30]. This was the first rapid prototyping method developed in 1984 by Charles Hull and commercialized in 1986 by 3D systems Incorporations [4, 5]. In this method, the system has a tub with a photosensitive liquid resin (acrylic, epoxy or vinyl) and with a platform inside, that moves vertically [4, 5]. The CAD model is sliced in layers and each layer is scanned by ultraviolet (UV) light to cure the resin, whereby the computer sends the first layer information to the platform, the numerical control of the machine positions the platform in the resin surface and the galvanometric mirrors control the laser beam position in the resin portion corresponding to that first layer [5]. Thus, through the incidence of UV laser on the resin, the model cross section is solidified [5, 23, 37]. The platform descends again in order to another liquid layer can be placed on top of the formed material [23, 30, 37]. The new layer is scanned by the laser, adhering to the previous bed and this process is repeated until the model is finished [23, 30, 37]. Once completed, the model is removed from the tub, washed and the supports are removed [5]. At the end, the model is placed in a UV oven to receive the curing process [22]. Therefore, this technology has a high precision and surface finishing, several materials can be used, it is a very automatic process and the final products have transparency [36]. However, it is slow and expensive, it has curling and wrapping problem, only produces small sized-models and supports a limited range of materials. Moreover, it requires support structures, post-processing and post-curing and it involves the handling of chemicals, which may be toxic [4, 30, 36]. This technique can be used to produce prototypes, casting pattern and in medicine [4, 30].

In addition to these methods, Solid Ground Curing (SGC) was developed by Cubital Inc. of Israel and it is very similar to SLA [4]. Its machine produces the image of the model transverse section on a glass plate and the surface of the liquid photopolymer is solidified layer-by-layer by a UV light [4]. Thus, this technique has high throughput, does not require support structures or curing treatment and the production process can be interrupted and adjusted [4]. However, it needs constant control and skill, it is a noisy and expensive process [4]. Usually, it is used to produce prototype, casting patterns and in medicine [4].

The material jetting consists of the photopolymer deposition on a platform through a few nozzles, and when deposited, the droplets are cured and solidified by UV radiation, forming a model quickly and layer-by-layer [22]. Usually, support structures are required, which materials are normally dissolvable for subsequent removal [22]. Moreover, a powder bed is not required [22]. In this category, several technologies are inserted, including drop-on-demand (DOD), nanoparticle jetting (NPJ) and multijet modeling or thermojet (MJM) [5].

DOD technology has the material jetting basis procedure, but uses two printing jets, one for depositing the waxy printing material and the other for the dissoluble material which will form the supporting structures [22]. Thus, this technique is commonly used for the construction of wax-like patterns to mold production [22]. This technology is also used in jewellery, since it allows the production of small models with high detail and precision [22]. However, it is slow for higher pieces production [22].

In this category, the NPJ is also inserted, which expels a liquid with metal nanoparticles for the printing platform, layer-by-layer [22]. During the printing, high temperatures are used to provide the liquid evaporation and deposition of metallic components [22].

To conclude, MJM uses a nozzle that expels heated thermoplastic material (usually resins or waxes) while moving horizontally and the platform moves vertically and in y-axis to create a new layer [5]. Thus, this process provides high detail, high precision and smooth finishing and it also enables the use of different materials [22].

Similarly to the above category, there is also the binder jetting, which utilizes powdered material and a binding agent [22]. Functionally, the nozzles expel binder drops into a powdered layer which solidify forming one layer at one time, bonding together to form a solid pattern [22]. After finishing a layer, it descends, and a new powdered layer is deposited in the construction area, and this procedure is repeated until the model is finished [22]. Thus, although this process is fast, the final product requires post-processing and the resulting models are still very fragile due to the limited number of materials used [22].

The main technology of this category is three-dimensional printing (3DP), in which the machine used distributes a powdered layer through the printing platform and prints the binder solution into the powder, giving rise to the first cross-section [4, 36, 38]. After the first layer is complete, a new layer of powder is placed on the surface and the procedures are repeated until the object is finalized [36]. This technology is versatile, simple, fast, it has high resolution, it is able to incorporate different colours and materials (plastic, wax, plaster and bronze) and it does not loose material. However, it is associated with limited functionality of the model and it is a slow and noisy process [4, 36]. It is commonly used to produce prototypes, model and casting patterns [4].

On the other hand, there is also the directed energy deposition, which consists on melting the powdered material (usually metallic) as it is deposited [22]. In this category, it is included the conformation close to the final laser format, which uses a laser, powder distribution nozzles and tubes with inert gas to fuse the powder as it is expelled, with subsequent solidification, resulting in layer-by-layer model production [22]. This process is usually used to add a missing part to a pre-existing part [22].

In addition, laser metal deposition (LMD), also known as direct metal laser deposition (DMLD), direct laser deposition (DLD), direct metal deposition (DMD) or laser powder deposition (LPD) , which uses a laser for the metal models manufacturing [4]. This technique can be used to repair parts and the fact that it is possible to use multimaterial simultaneously enables the production of functional materials [4]. In addition, it exhibits models with minimal physical distortion, better surface quality, almost liquid form and totally dense [4].

The Engineered Net Shaping Laser (LENS), which was developed by Sandia National Laboratory in the 1990s, uses high-power laser to melt the metal powder by focusing the laser through one or more lenses [4]. The powdered material is fed by the nozzle through the direct material deposition process [4]. After melting the material, it solidifies rapidly, which results in very dense pieces, eliminating the need for post-processing [4]. In this technique, the composition of the material can be changed dynamically, allowing to produce highly dense parts with good grain structure and it does not require post-processing. However, this technique needs a finishing machining [22]. With this, near net shape objects can be produced [4].

Alternatively, there is also the electron beam additive manufacturing (EBAM), similar to LENS, but it is used an electron beam [22]. This process is more efficient than LENS due to the use of an electron beam instead of a laser, but it needs a vacuum, which is an obstacle to its popularity [22].

Recently, Infrared and masking systems have also emerged, which uses infrared radiation to fuse a powdered layer through the negative masks printed under glass plate [4]. In comparison with other laser based methods, infrared light has higher processing velocity and lower operating cost [4]. In this group, some techniques were developed such as selective inhibition of sintering (SIS) and high-speed sintering (HSS) [4]. Although the absorption of radiation depends on the colour of the material (dark absorbs more), this innovation appears as a faster and low-cost process and it enables the use of different types of materials (polymer, metal and ceramic) [4]. It is used for prototypes production and molds injection in aeronautics, automobile and medicine [4].

Sheet lamination emerges as a process that connect thin and solid layers of material with alternating layers of adhesive to produce a model [4, 22]. In this group, it is included the Laminated Object Manufacturing (LOM), which was developed in 1986 by Helisys of Torrance [4]. In this technique, the printing consists of laminating each material layer (paper, plastic, ceramic or metal) and also its contour through a carbon dioxide laser [4, 36]. After the first layer is finished, the platform descends and the next layer is then laminated and deposited on top of the laser cutting layer [4, 36]. Therefore, this technology does not require post-cure and it is very fast and inexpensive, enabling the use of different materials and the construction of large volumes of self-supporting parts. Thus, this technology does not need the use of support structures [4, 36]. However, precise adjustment of the machine energy is required and sometimes it provides instability of the material [36]. Moreover, it does not allow the production of models with holes and its strength depends on bonding strength [4]. In his study, Kotlinski analysed the mechanical properties of materials and commercial techniques of AM and concluded that LOM anisotropy is the worst [39]. This technique allows the production of prototype and models patterns for injection moulding [4].

In recent years, it was also developed the ultrasonic additive manufacturing (UAM), which uses metal foils (typically titanium, stainless steel, copper and aluminium) to produce objects, layer by layer [22]. The layers are connected by ultrasonic welding and compression, which implies no need for melting and uses less energy than the others [22].

Finally, material extrusion consists of the extruded material layer-by-layer deposition (usually thermoplastic) using a extruder nozzle along a predetermined path [8, 22]. In this category, there are several techniques, including 3D microextrusion, 3D microfiber extrusion and fused deposition modeling (FDM), which is currently the most popular 3D printing technology [22].

In [5], the authors provide detailed comparative study between MJM, SLA and FDM, in which they analysed the equipment acquisition costs, annual operating costs, annual prototyping volume, hourly rate for equipment operation, average cost of a prototype, average time of prototype construction and total average processing time. In this mentioned study, it was verified that the FDM presents the longest average time of prototype construction and it is the second providing the highest average time of processing [5]. However, it presents better results in the other relevant features, so it was concluded that it is the best cost-effective technology [5]. Additionally, since it has low noise and low material waste, this technology can be easily used in non-industrial research environments [5]. Thus, this is the technology presented in the present work.

1.4. Fused Deposition Modeling

In 1989, FDM was developed by S. Scott Crump, the cofounder of the company Stratasys, and it was commercialized in 1990 [22, 23, 30]. To date, this technique has increased, along with the equipment and software involved, the number of applications in biomedical engineering and is one of the simplest and most popular technologies used in 3D printing [4, 40, 41]. In Figure 13, the number of low-cost FDM type printers produced between 2009 and 2015 is presented. With the technology development, analogous terms have been developed including the fused filament fabrication (FFF), plastic jet printing (PJP), fused filament modeling (FFM) and thermoplastic extrusion [30]. Since it is inserted into the material extrusion group, it implies that the material is extruded by an extruder nozzle [30, 38]. Thus, its operation is based on the layer-by-layer deposition of fused thermoplastic filaments, adding a layer of material for the construction of the desired physical model [4, 8, 18, 41, 42].

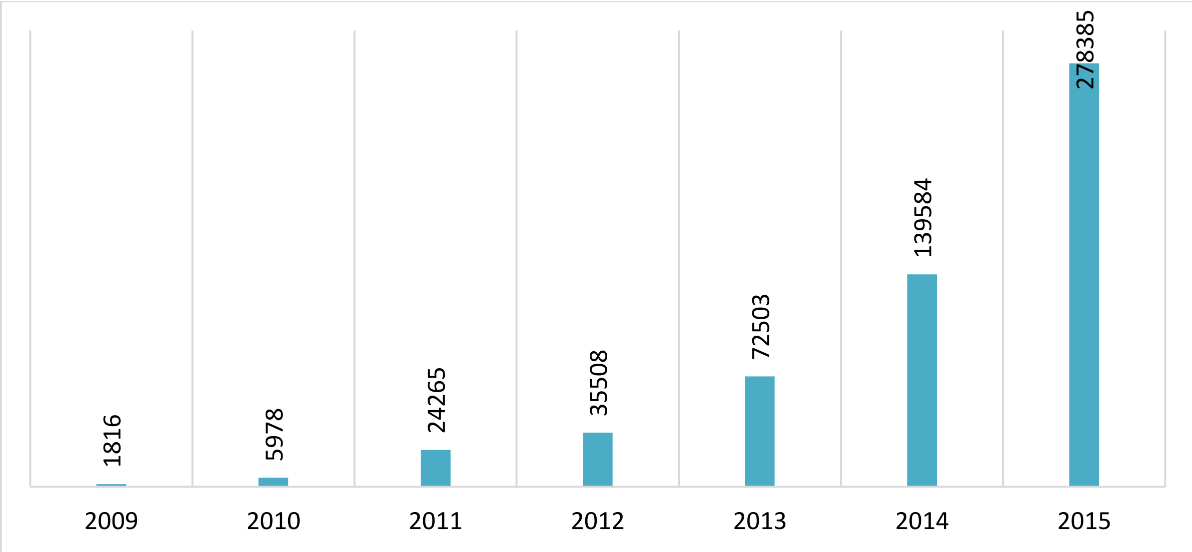

Figure 13. Low-cost FDM 3D printers' sales per year. Data from [29].

Thereby, the extrusion nozzle, which is computer controlled, has a heat source with temperature management, making it responsible for heating and modifying the physical state of the filament [8, 22, 30]. The extruder is maintained at a temperature above the material melting temperature to ensure its extrusion and high surface adhesion [22, 41]. Thus, the material, fed by a coil, is extruded to the construction platform through the heated extruder, which moves in a predetermined direction. The extruded material is melted with the adjacent material before solidifying [8, 18, 23, 30, 36, 38, 43]. The platform is kept at a temperature lower than the material, so that it cools quickly and consequently solidifies, serving as the basis for the subsequent layer of material [4, 36]. After deposition, the fused material may be referred to as fiber, and the connection between the fibers is due to heat and mass transfer phenomena, thermal and mechanical stress accumulation, and phase changes [8, 23]. After the first layer is completed, the extruder nozzle moves up or the platform down and the extrusion nozzle places a second layer, and this procedure is repeated until the model is finished [5, 22]. In Figure 14, a schematic with the main steps of this process is presented.

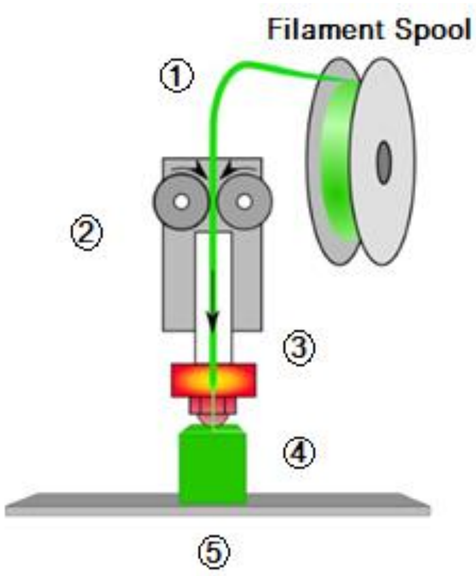

Figure 14. FDM stages: (1) Filament is led to the extruder; (2) The extruder uses torque and a pinch system to feed and retract the filament precise amounts; (3) A heater block melts the filament to a useable temperature and the result filament is forced out the heated nozzle at a smaller diameter; (4) The extruded material is laid down on the model where it is needed; and (5) The print bed is moved to the correct X/Y/Z position for placing the material. Adapted from [10].

This is similar to conventional polymers extruders, but it has the extruder mounted vertically instead of horizontally as in the conventional technologies [8]. If necessary, this technology enables the use of a multiple extruder nozzles system, which provides the inclusion of different materials in the printing [10].

In this process, material deposition failures can occur due to the process itself (problems with printing, hardware or software parameters) and / or material characteristics surface defects or internal defects [35]. About the surface problems, these usually result from the ladder effect type originated by slicing, and can be reduced through the use of lower layer heights [35]. On the other hand, the internal ones are usually due to the inconsistency of the filaments deposition, which causes deposition failures [35]. During the solidification, the extruder material cooling of the different sections takes place at different speeds, which causes a change in its dimensions (shrinkage) and it may lead to the lifting of the upper layer borders resulting in warping [35], as shown in Figure 15. To avoid these defects, it is necessary to monitor the temperature of the print bed and the printing chamber and promote adhesion between the material and the print bed. Therefore, specific glues or tapes and hot printing surfaces must be used [44].

Figure 15. Warping effect resulted from extruded layers solidification.

Currently, there are several studies that use FDM and in SCOPUS database, using the keyword "Fused Deposition Modeling", it was found 3007 FDM articles since 1986. From 1986 to 1990, only 3 articles on this area were published and in the last 3 years 1811 articles were published. Thereby, some of these studies sought to analyse the effects of extrusion process parameters, such as filament feed rates, extrusion viscosity, etc., to improve surface acclimation, dimensional accuracy, mechanical properties and process efficiency [22]. For example, near the extruder nozzle, the fused material is under tension and the stored elastic deformation energy provides its radial expansion after extrusion. Then, after materials deposition, it occurs heat exchanges between layers and with the environment by convection and radiation [8]. The printing parameters define the entire construction process, influencing the result of the models obtained by FDM. Thus, the FDM printing parameters correspond to the variables involved in the process, such as the pressure velocity and the extrusion temperature.

Print speed is based on the extruder speed during material deposition and it is controlled in CAM software, depending on the printing phase (first layer, perimeter or fill velocity) [35]. Typically, the speeds used are usually around 60 mm/s, but some equipment is already reaching higher speeds [20]. On the other hand, the extrusion temperature is the temperature that the extruder nozzle uses during printing and it depends on the material used, but the most common is 200°C or more [20, 35]. Bellini, in his study, concluded that extrusion temperature influences inter and intralayer connection [45] and Sun *et al.* found a direct relationship between the extrusion temperature and the mechanical strength [46].

Regarding the models printing preparation, it is the user who controls the parameters including the layer height, the printing angle and orientation, the percentage of infill, the possibility of adding supports, among others [20, 35]. There is also the flow of material, which consists of the material amount that is extruded, and it is controlled by the extrusion multiplier, influencing the dimensional quality of the produced model [20].

In turn, the height of the layer consists of the height of the filaments deposited in the layers and it is related to the printer characteristics, including filament thickness, extrusion nozzle diameter and printing speed [20, 35]. Thus, lower height provides better finishing and higher resolution, but a higher value provides a lower printing time [20, 35]. Normally, the minimum layer height for this technology is between 20μm and 300μm, and most equipment use heights around 100μm [20]. Sood *et al.* concluded that tensile strength firstly decreases and then increases with the increasing layer height [47]. About layers, it has also the width of the layer consisting of the filament width in the layer and its value is multiple of the width of the extruder nozzle [35].

The printing angle and orientation are important for the definition of the model structural properties and it consists of how and in what direction the filaments are placed on the printing platform [42]. Specifically, the printing angle consists of the path that the extruder nozzle does along the print bed. Normally, it makes rectilinear movements (Figure 16(a)) and its possible values are usually 0º, 45º, 90º or -45º / 45º (cross type) [42]. The use of cross-type, which consists of fiber overlap, reduces void density and increases the contact area between the fibers, resulting in stronger connections. However, the excessive material at the layer perimeter affects the dimensional accuracy in horizontal plane [8]. Alternatively, it can also use other types of trajectories such as those shown in Figure 16(b) and (c). On the other hand, the orientation identifies the angle between the model and the print bed [35]. In the FDM, once the printing components are anisotropic, this parameter influences the mechanical strength of the printed model [48].

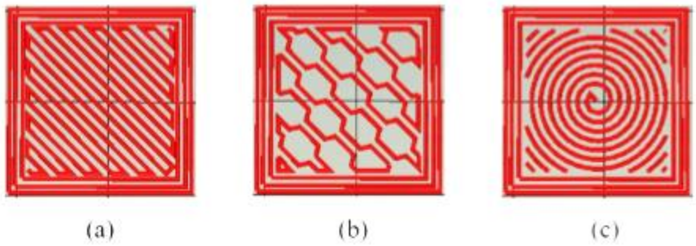

Figure 16. Example of a model using printing angle: (a) rectilinear movement (b) honeycomb (c) Archimedes. Adapted from [35].

On the other hand, the infill corresponds to the material density inside the model, being used as percentage and its value depends on the stiffness desired, quantity of material, weight and printing time [20]. A higher value increases the components mechanical strength, but it takes higher printing times and material expenditure [35]. If this value is reduced, the model becomes mechanically fragile (low resistance), and if the percentage is total, the object becomes massive [19]. Currently, several infill patterns are available, and they are associated with different mechanical behaviours [20]. In Figure 17, the aspects of a few different infill values can be visualized.

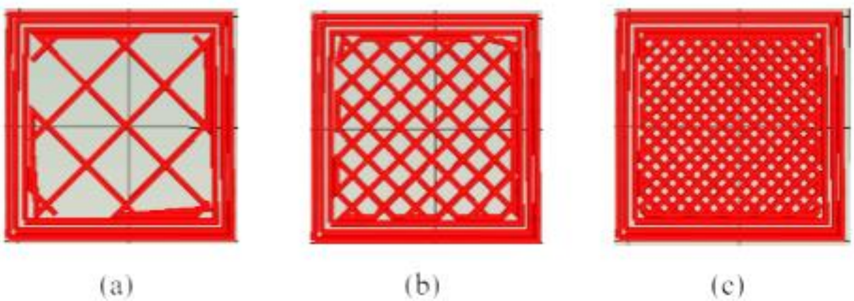

Figure 17. Printing infill of: (a) 20 % (b) 50 % e (c) 100 %. Adapted from [35].

In addition, support structures may be required, which are formed during the model printing, in order to support the model structure [18]. These usually have a high area of contact with the component and the print bed, guaranteeing printing stability [18]. Nevertheless, the supporting structures printing requires the use of a significant material amount and an increase the printing time [18]. Typically, it is used a weaker material or a water-soluble material, which makes its removal easier [4, 18, 22]. Usually, there are support generation algorithms that automatically detect the surfaces that need support and there are currently numerous approaches such as those found in [18, 49-51]. After identification of the surfaces that need support, it is determined its geometry, for which there are also several approaches, including the presented in [49, 51-55]. Furthermore, Autodesk has developed the MeshMixer that creates a thin, tree-like support structure that limits the number of dots and the print time [18]. Alternatively, Adobe Photoshop CC was released, enabling the automatic generation of support structures for 3D printing [18].

Also, it may be necessary to include other external elements such as "skirts", consisting of material extrusion in print bed around the perimeter of the model, in order to verify if the extruder is working properly (before printing starts); the brims, which constitute an extruded layer of a higher area than the model contact surface, providing adhesion to the print bed, and it is easily eliminated; and the Raft, which consists of grid support structures used to support the model during its printing [20, 35].

About the process itself, FDM is a slow and precision-restricted process, since the material used must be in a filament form and its diameter controls the model printing resolution [36, 37]. During the printing, the filament can only be deposited over an existing surface, whereby the projections of the mold require a disposable structure, i.e., support structures [18]. These increase the amount of material required and the time of printing [18]. In addition, it has poor transparency and delamination problems due to the poor temperature control [4]. Moreover, it is exposed to unpredictable contractions, since the extruded material is exposed to a fast cooling, which can cause distortions in the final model. Additionally, it possesses a low vertical resolution (and limited layer thickness), which increases the roughness of the surface [4, 22, 36, 41]. The reduction of the filament diameter provides a reduction of the printing speed [22]. Thereby, the printing volume also appears as a limitation, since the print bed has a maximum dimension of 250 mm and the height of the machine goes up to 200 mm [19].

On the other hand, this process is simple and low-cost, it enables the construction of functional parts and the simultaneous use of different materials (and consequently colours), which must be compatible with each other, and it requires just a few post-processing (clean-up) [4, 5, 8, 18, 22, 37, 38, 43]. There is also a minimum waste of materials and it is easy to remove the supporting structures and the exchange of material [4, 5, 8, 36]. In addition, the processes are quite automated, there is a high availability of printers for purchase and it is possible to use them in non-industrial environments [5, 18].

Thereby, FDM has evolved into an available consumer technology. Thus, it can be used to produce functional models with complex geometries, assembly testing, investment casting and injection moulding [37, 42]. Recently, this technology has also been used for microfabrication, particularly in the development of microfluids, and in the manufacturing of biological materials [37].

1.5. Materials

With the development of FDM, a higher materials diversity has been verified, and there are no limitations in the choice of materials to be used [23]. However, metals and ceramics have high melting points, so it is difficult to achieve their fusion [13]. Therefore, low melting (between 68ºC and 270°C) and low thermal conductivity materials are commonly used in FDM, particularly waxes, elastomers and thermoplastic materials, including acrylonitrile butadiene styrene (ABS), polyvinylic acid (PVA), polycarbonate (PC), high density polyethylene (HDPE), high impact polystyrene (HIPS), polyethylene terephthalate (PET), nylon, polypropylene (PP) and polylactic acid (PLA), but the most common are PLA and ABS [4, 22, 23, 42]. However, there are other non-conventional materials, including flexible materials, composites and fluorescent, thermovariable, transparent and electric conductors, some of which try to replicate the behaviour of materials used daily, such as metals and wood. In recent years, it has become possible to use edible materials such as chocolate [30], as will be explained later.

As previously mentioned, the materials are used in the filament form with diameters of 1,75 mm or 3,0 mm and they are sold in filament coils by weight or by meter [20]. The next illustration presents a summary of some features of the materials used in FDM, and the ease of printing consists of some aspects related to the materials printing, including adhesion to the print bed, maximum speed, errors frequency, extrusion ease, etc.

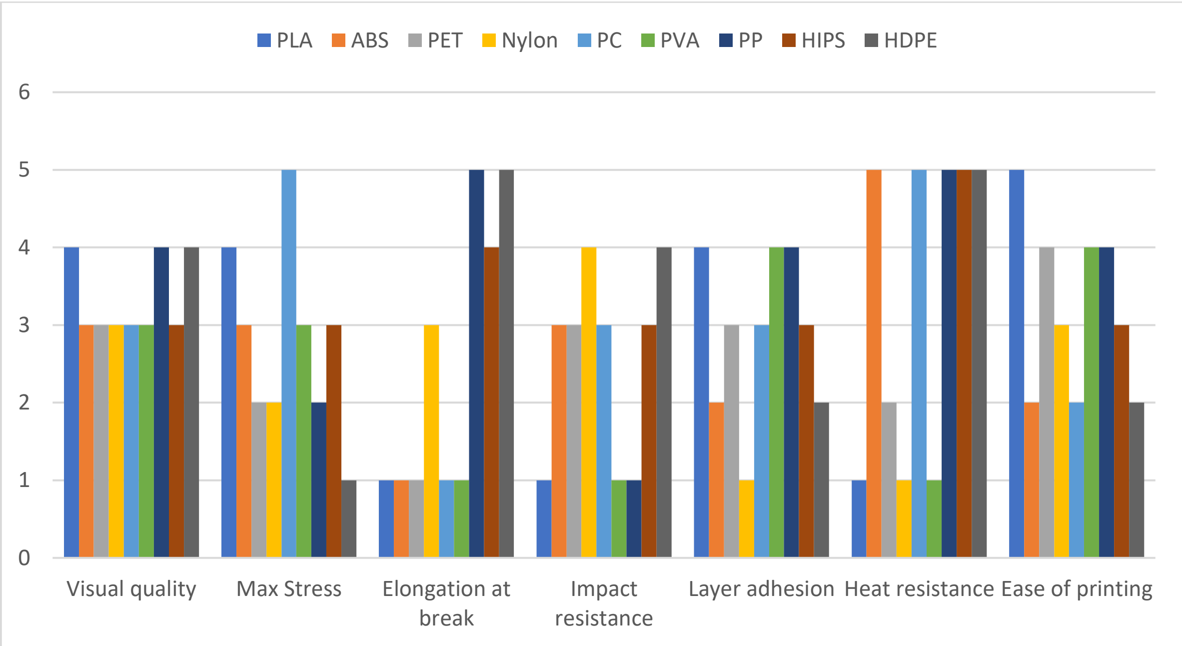

Figure 18. Comparison of some materials characteristics (minimum quality = 0; maximum quality = 5).

Acrylonitrile butadiene styrene is a non-biodegradable thermoplastic material that comes from fossil fuels [19]. It is characterized by its high abrasion and chemical resistance and it is degraded by UV radiation [56]. This thermoplastic has bed temperatures ranging from 90°C to 103°C and extrusion temperatures from 215ºC to 250°C. For printing it, you need a glass printing surface with tape and Kapton (made of PTFE and possessing high temperature resistance). Due to its good mechanical properties (such as high strength and flexibility) and easy to extrude and mold, it is widely used in 3D printing, especially for toys production, sports equipment, kitchen utensils and in the automobile and medicine [19]. However, its fusion causes the emission of noxious gases, so it is necessary to have a controlled printing chamber or a forced ventilation system [56].

On the other hand, polyvinylic acid is a water-soluble biodegradable polymeric material, which can be used to produce substrates in 3D printing [57]. It has the bed temperatures up to 50°C and the extrusion ones from 180ºC to 200°C and it requires a lacquered glass printing surface and a blue painter tape [57].

Alternatively, the polycarbonate consists of a non-biodegradable thermoplastic with good mechanical properties, such as high rigidity, transparency, stability and impact and temperature resistance [58]. Furthermore, it has the range of 85ºC to 95°C for bed temperatures and from 280ºC to 305°C for the extrusion temperature [19]. For use it in FDM, you need a glass printing substrate with Kapton lacquer and tape, but it is not quite used due to the high temperatures required for its extrusion [19]. However, a new material is being developed combining PC and ABS, which makes the extrusion easier [19]. Currently, the PC is used for bulletproof glass production [19].

High-impact polystyrene is a thermoplastic material whose mechanical and thermal resistance are equivalent to ABS, but it is degraded when exposed to UV radiation [35]. Its extrusion temperature ranges from 220ºC to 235°C and the bed temperature corresponds to 115°C. In 3D printing, HIPS is used as a support structure material because it is easily dissolved, and it requires a Kapton tape surface [35].

In addition, high density polyethylene is a low-cost thermoplastic material which is not used in 3D printing due to its tendency to contract after extrusion, so it may occurs deformation [19]. The bed temperature equals room temperature and the extrusion temperature is between 225ºC and 230°C , requiring the use of a polypropylene plate with Kapton tape [19]. Additionally, it is not a biodegradable material and it is chemical resistant [19]. Thus, it is commonly used to produce water bottles and tubing [19].

Polyethylene terephthalate is a high crystalline recyclable thermoplastic that has high chemical resistance and also high impact and corrosion resistance [58]. The bed temperature range used is between 20ºC and 65°C and the extrusion one varies from 210ºC to 220°C. This material requires the use of a glass printing surface with Kapton tape [58]. It shows a higher weight than the other materials and it needs refrigeration after printing, to maintain its transparency [58]. This material is commonly used for the manufacturing of bottles, food packaging, cosmetic bottles, microwave containers, among others [13].

Nylon, which is a polyamide, consists of a synthetic fiber of high strength and elasticity and low friction [59]. Its extrusion can occur at temperatures from 225ºC to 240ºC and the bed temperature is at room temperature, requiring a Garolite printing surface [59]. However, it has low surface adhesion and involves its drying before its use [59]. This material is predominantly used in the manufacturing of clothing, but it is also common in the food industry, for the manufacturing of food packaging, and also in the automobile industry to produce machine screws, gears, etc. [13].

Polypropylene is a low-cost recyclable semi-crystalline thermoplastic material with high chemical, fatigue and impact resistance and high thermal stability and it is easy to mold it. Extrusion temperatures range from 230ºC to 300°C and the bed ones are between 85ºC and 100°C, whereby a printing surface with Kapton tape is used [13]. Thus, it is widely used in engineering, especially for the manufacturing of components with hinges [13]. However, it has a high UV rays sensitivity [13]. In the table below, it is possible to consult the summarized characteristics of each material presented so far.

Table 2. AM materials and corresponding characteristics.

Material	Extrusion temperature (°C)	Bed temperature (°C)	Printing surface	Price (EUR/kg)	Comments
ABS	185 – 235	90 – 110	Kapton	20	Flexible, easy to mold.
PVA	180 – 220	50	Kapton	40	Dissolve in hot water. Used as support material.
PC	280 – 305	85 – 95	Kapton	60	Impact resistant. Transparent.
HIPS	220 – 235	115	Kapton	25	Similar to ABS, but it can be dissolved. Usually used as a carrier.
HDPE	225 – 230	Room	PP and Kapton	30	High chemical resistance.
PET	210 – 220	20 – 65	Glass and Kapton	30	Completely recyclable.
NYLON	225 - 240	Room	Garolite	35	Low friction.
PP	230 – 300	85 – 100	Kapton	50	Easy to mold. High thermal resistance.

Finally, the polylactic acid is a thermoplastic material that is not sensitive to temperature changes, which makes it easier to work with, so it is the present work focus.

1.5.1. Polylactic Acid

Polylactic acid was synthesized in 1932 by Carothers, through heating lactic acid under vacuum [60]. Currently there are several ways to produce PLA (fermentation, polycondensation, ring-opening polymerization, azeotropic distillation and enzymatic polymerization). However none of them is simple to perform because it requires a strict control of the temperature, pressure and pH, use of catalysts and high polymerization times [8, 60].

Therefore, polylactic acid has characteristics very similar to ABS, but it is a bioplastic that comes from corn flour [8, 41]. Further, it is included in the aliphatic polyesters group, which are produced from α-hydroxy acids [13]. Currently, PLA is one of the most popular materials in FDM, and its cost is around 20€/Kg. Typically, the bed temperature is around 60°C and the extrusion temperature can be between 160°C and 220°C [19]. During its use in FDM, it is necessary a lacquered glass printing surface and Kapton tape to avoid adhesion and model removal problems [61]. The mechanical properties of PLA depend on the molecular weight, which is controlled by the addition of hydroxyl components, and also depend on their stereochemistry, that can be d-lactic, lactic, d-l-lactic or meso-lactic polymerization [13].

Thereby, the PLA has low thermal stability and thermal resistance, and it is distorted when in contact with high temperatures [8]. However, in the printing process, it does not need high temperatures. It is also biodegradable, recyclable, biocompatible, inexhaustible and low-cost and does not emit toxic vapours [8]. In addition, it is easy to use and does not require a heated environment, which makes it possible to print at room temperature [35].

In the last decades, several studies have analysed PLA, especially its possible applications, behaviours and properties, in 3D printing. Ningetal *et al.*[62] concluded that, as the filament feed rate increases, there is a reduction in PLA tensile and flexural strengths. In [42], the authors concluded that the PLA exhibits a high anisotropy, that consists on the variation of a certain physical property with the direction.

1.5.1.1. Types

There are several new types of PLA, resulting from some materials combination. One of them is the soft PLA, which has a higher level of flexibility, and can be used for the fabrication of support structures, as it is easy to be removed [19]. The bed temperature is the room one and the extrusion temperature is between 200°C and 220°C, using glass printing surface with lacquer [19]. It is also biodegradable and recyclable [19]. In addition, there are other types of PLA, for example resulting from the combination of PLA with Lignin, PLA with metal alloys, conductive PLA, PLA with carbon fibers, PLA with stainless steel, magnetic and ferromagnetic PLA, incandescent PLA and thermovariable PLA.

Lignin is an aromatic biopolymer present in the fibrous part of several plants and it is extreated by pulpwood industries [8]. Therefore, the use of lignin increases the thermal stability and the resistance to organic decomposition, but also the flammability [8].

On the other hand, the PLA can be combined with bronze, brass or copper, resulting from the blend of PLA with metal component powder [63]. The addition of the powder raises the resistance and provides the metal appearance and density, but usually the portions present are not enough to be electricity conductive. Its various features are detailed in [63]. All these combinations of PLA with metals can be used in 3D FDM printers for the manufacturing of metal-looking parts, handles, buttons, sculptures, emblems, trophies, jewellery, game pieces, among others [63].

In turn, the conductive PLA is composed of PLA and dispersant and conductive carbon and it is very flexible [63]. This is ideal for use in low-voltage circuits, digital keyboards, air-conditioners, tactile sensors, robotics and electronics, especially to control any element through a resistance of 1 kOhm [63]. This enables the conductors printing that integrate switches, potentiometers, LEDs, capacitive touch sensors, among others, and their properties are detailed in [63]. Thus, this material presents high electrical conductivity and print quality, but limited stiffness and lower layers adhesion compared to normal PLA [63].

On the other hand, PLA can be combined with carbon fibers, which includes parts of carbon fibers (15%), providing more rigidity and higher structural strength and layer adhesion [63]. Thus, it can be used in the manufacturing of parts that will not be folded like supports, tools, propellers, etc. [63].

The PLA with stainless steel is composed of PLA and powdered stainless steel, looking as stainless steel [63]. This material is as resistant as the simple PLA and it does not contain enough steel powder to make it electrically conductive [63].

Additionally, the magnetic PLA was commercialized and it consists of PLA with powdered iron [63]. It behaves similarly to pure iron, especially in the oxidation and response to magnets, having a wide range of applications such as fashion accessories and metal parts simulation [63]. The printed components do not work as magnets, but these can be attracted by them [63]. In comparison to the normal PLA, this combination has lower resistance and higher density, and also it is not an electricity conductor [63]. Similarly, PLA ferromagnetic was developed, consisting of PLA with iron that attracts the magnetic fields, being strongly attracted to the magnets [63]. Its purpose is to produce ferromagnetic components, such as magnetic sensors and actuators, magnetic stirrers and it has limited oxidative behaviour [63]. Contrary to the magnetic PLA that produces parts with a greyish finishing, those printed with ferromagnetic PLA are black, have the same resistance as simple PLA and are not electricity conductors [63].

Recently, the PLA reflector was also developed, which uses PLA with small reflective particles and it can be used in FDM 3D printers [63]. This semi-flexible material can reflect light intensely, even after printing, and it has a natural grey finishing, but when it is on darkness or specific light, it turns bright white [63]. In addition, it is easily washable and easy to clean [63]. Thus, this material is being used in the automobile industry in passive signage, in safety devices to increase visibility and in fashion to produce functional accessories, such as reflective vests, sunglasses, necklaces for mascots, among others [63].

The thermovariable PLA consists of PLA with thermochromic additives and it presents the ability to cause thermochromism (colour change according to temperature). Usually, the colour change occurs above 29°C and it can be used in FDM [64]. In contrast to the normal PLA, this biodegradable material is more impact resistant, less rigid, easy to print and has better flow behaviour and adhesion between layers [64].

Nowadays, there is also the incandescent or phosphorescent PLA, which results from PLA with zinc sulphide, calcium sulphide or estradium aluminate pigments, which are phosphorescent (it glows when exposed to a light source such as the sun or a flashlight) [10]. This type of material can be used in FDM and it has an extrusion temperature between 180ºC and 220°C. More detailed information can be found in [10].

2. Areas of Application

The total market for 3D printing can be divided into components (technology, materials and services), raw materials, geographic regions, and areas/applications, but only this last one will be presented in this study [3]. Over the years, 3D printing has been expanding its range of areas and applications. Hence, its principal acting areas are presented in Figure 19, including the industrial, governmental and military, academic, automotive, aeronautics and aerospace industries, consumer products, etc. [3, 22]. In these areas, 3D printing is used to manufacture different components, such as structural components, turbine blades, snowboards, aerospace components, toys, cylinder heads and brake rotors [28]. There are also other sectors, that are also increasing their popularity, for example the electronics industry, in which AM allows a faster production of micro-systems than the traditional techniques [28].

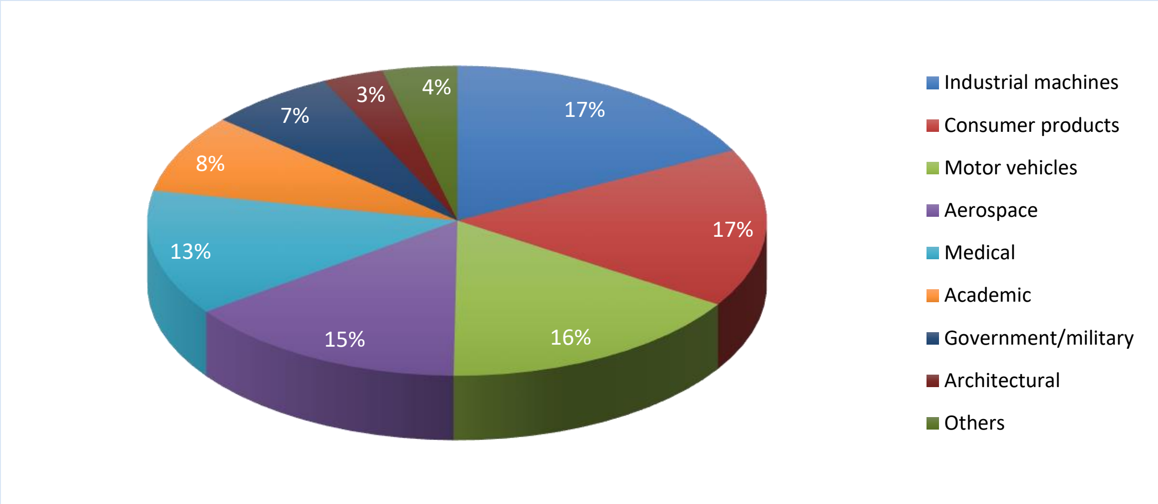

Figure 19. Use of AM in the different areas. Data from [22].

In architecture and civil construction, this technology has been widely used due to its reduced production time, in opposition to manual production and also thanks to the possibility of showing real projects to the customers, for example by printing models [22]. On the other hand, in fashion, it has been used by designers, and one example is Michael Schmidt and Francis Bitonti who printed a dress in polyamide in 2013 [22]. In this area, there are some obstacles to its global use, including the printing time and cost and the mechanical rigidity of plastics [22]. However, the company Nervous Systems has developed a 3D dress, which consists of multiples interlaced polygons that provided some flexibility [22]. In addition, this technology is already being used by countless popular footwear brands, such as Nike, which offers customized footwear for elite athletes, and Adidas and New Balance which offer footwear with some components printed by AM, as previously presented [22].

Although not very popular, 3D printing has also been used in the food industry, and the first experiment was based on the sugar selective sintering by the CandyFab project in 2008 [22]. In the last decade, there has been an increasing interest in AM for food production, with the production of cakes, processed cheese, peanut butter and chocolate already being made [22]. This increase is mainly due to the recent popularity of personalized nutrition, professional cooking and food customization [22]. Figure 20 shows an example of an edible component printed with AM.

Figure 20. Edible model based on a paste with insect proteins. Adapted from [22].

2.1. Biomedical Area

In recent years, 3D printing has been increasing its application in the medical and dental industry due to the precision increase and time decrease in the surgeries, resulting from the capacity of preoperative planning and the possibility of producing functional structures with complex geometries for each patient [22, 26, 65]. Particularly, PLA is approved by the FDA for human implantation, being the FDM one of the methods used for medicine [22, 26]. On the other hand, there have been some limitations such as implant precision, composition, mechanical characteristics and biocompatibility of the material, among others [66]. However, the additive manufacturing technologies are in continuous progress, so the costs are being reduced and the models properties are improving [26].

For biomedical applications, there is a set of steps to be performed for the implant manufacturing, as shown in Figure 21: diagnosis; imaging and scanning; data transformation; design and customization; biomechanical simulation; regulatory approval; rapid manufacturing; post-processing, sterilization and surgery [65, 67]. Firstly, it is essential to evaluate the patients' condition and their eligibility to receive a customized implant. Subsequently, solid biomodels are obtained to reproduce the anatomical parts involved through computed tomography or magnetic resonance imaging [65, 67]. Then, it is necessary to convert the obtained images into a 3D model. So, it is necessary to perform the model design and customization [65, 67]. When completed, its biomechanical simulation is performed to predict and analyse its behaviour in the patient, and usually it is used the finite element method (FEM), whose basis and formulation is explained with detail in [67, 68]. Once these steps are completed, regulatory approval is needed, so the model must fulfil the performance and safety standards [67, 68]. Thereby, the materials need to be simple to use and non-toxic, and the implanted material mechanical properties should be the same or similar to those that are being replaced [22, 65]. Particularly in orthopaedics, materials require high mechanical strength, low degradation rates and high toughness. That is why metals such as pure titanium and its alloys are the most popular [65]. Implant degradation should be avoided within the human body, because it may affect the implant function and may damage some organs [65]. Thus, firstly the materials must be biocompatible [65]. If it is approved, the implant is printed by additive manufacturing and the following steps are the post-processing, sterilization and implantation [67].

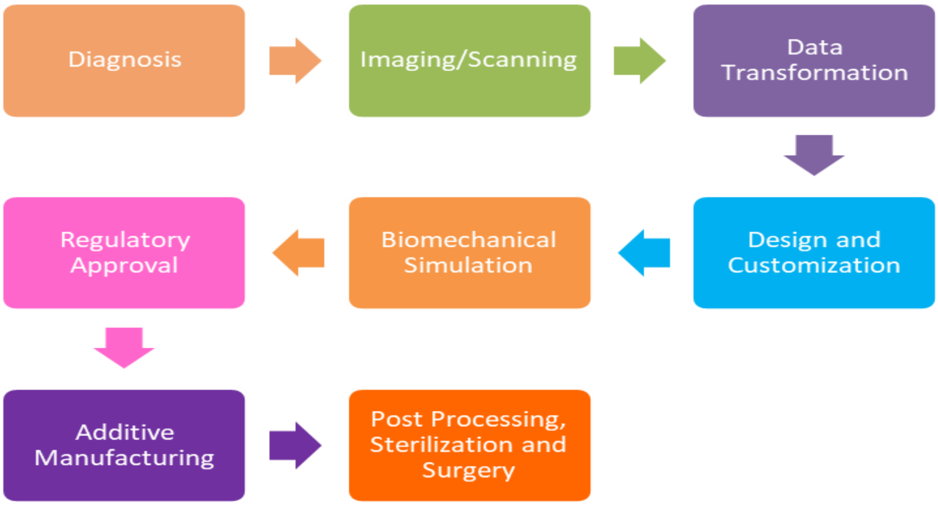

Figure 21. Procedural steps for the manufacture of customized implants.

Thereby, the 3D printing technological advances are inciting several innovations in the medical industry. In turn, this technology enables the manufacturing of surgical equipment, medical tools and customized implants that are suitable for the patient [26, 32, 65, 68]. Therefore, it has been used in many biomedical applications, such as orthopaedics (prostheses such as transtibial), dentistry (dental bridges, crowns, alignment devices, etc.), neurosurgery, maxillofacial surgery, craniofacial and bone reconstruction (artificial bone), tissue engineering (scaffolds, cell structures, etc.), traumatology, veterinary medicine (anatomic molds), oncology, pharmacology (drug delivery devices) among others [26, 28, 40, 65, 69]. In addition, it is also possible to produce body aids such as hearing aids and preoperative models to plan and / or simulate surgical operations [28, 40, 43, 65]. In [66], the authors analysed in detail a wide range of medical applications of 3D printing and predictions for the future, with the introduction of 'smart implants' that function as substitute tissues.

In recent years, the term bioprinting has been developed, consisting of all printing methods that use biological components (especially viable cells), tissue and functional organs [22]. It enables the fabrication of functional 3D tissue, including bones, blood vessels and organs, and there are currently several entities trying to use this concept, including EnvisionTEC, Organovo, 3Dynamic Systems, Bio3D and Aspect Biosystems [22]. However, this is still at an early stage due to the difficulty of producing and designing this materials to incorporate vascularization into the structures [22, 28].

3. Current Innovations and Future Trends

In recent years, several innovations have emerged to resolve some limitations related to applications, mechanical properties, time of printing, fidelity to the virtual model and multimaterial printing. To improve mechanical properties, researchers at Yale University developed the Fill Compositing Technique, which elevates the strength of the printed models by FDM through the addition of high strength resins [70], and the steps can be checked in Figure 22. A low filling value is defined, but in the end the voids are filled with liquid resin, increasing its stiffness and tensile strength [70].

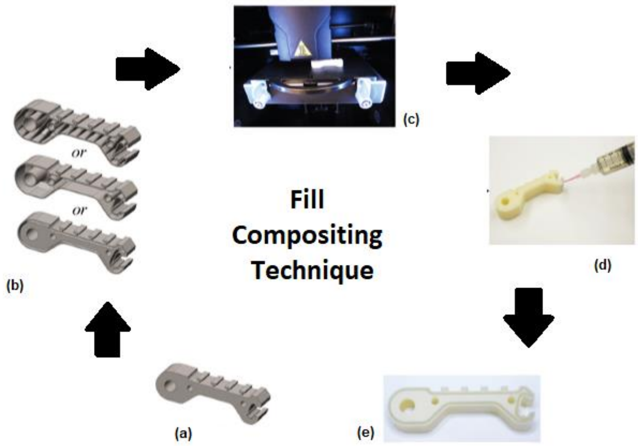

Figure 22. Fill compositing technique and its steps: (a) original part model; (b) modify part with internal voids; (c) print part using FDM; (d) inject resin into internal voids; and (e) section view of final model. Adapted from [70].

In addition, the Curved Layer Fused Deposition Modeling technique (Figure 23) was developed, which is based on material deposition in non-planar layers without thickness uniformity, improving its vertical mechanical behaviour [71, 72]. This layers inclination variation enables the reduction of the layers perpendicular stresses and the surfaces roughness, which brings its geometry closer to the virtual model one [71, 72]. However, the geometry of the nozzle extruder influences the maximum inclination and the printing time is higher [71, 72].

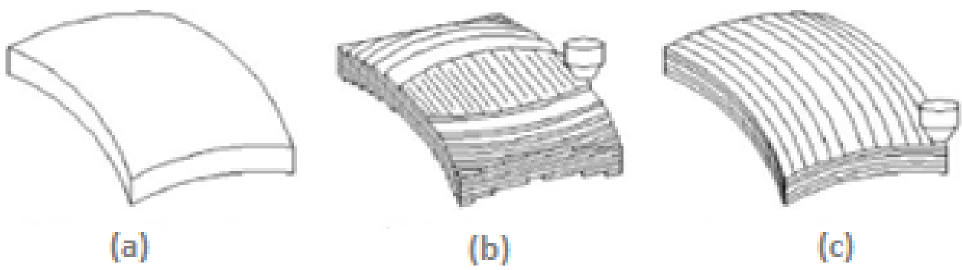

Figure 23. Curved Layer Fused Deposition Modelling: (a) curved model; (b) flat layers; and (c) curved layers. Adapted from [71].

Furthermore, a new method was developed that consists of the model reinforcement with continuous fibers (Figure 24) and its extrusion system enables the long fibers introduction during the printing [73]. In this process, it is possible to use these fibers up to 50% of the model and it can double the mechanical resistance [73]. An example of its application is the MarkForged company, which produces printers based on this concept [73].

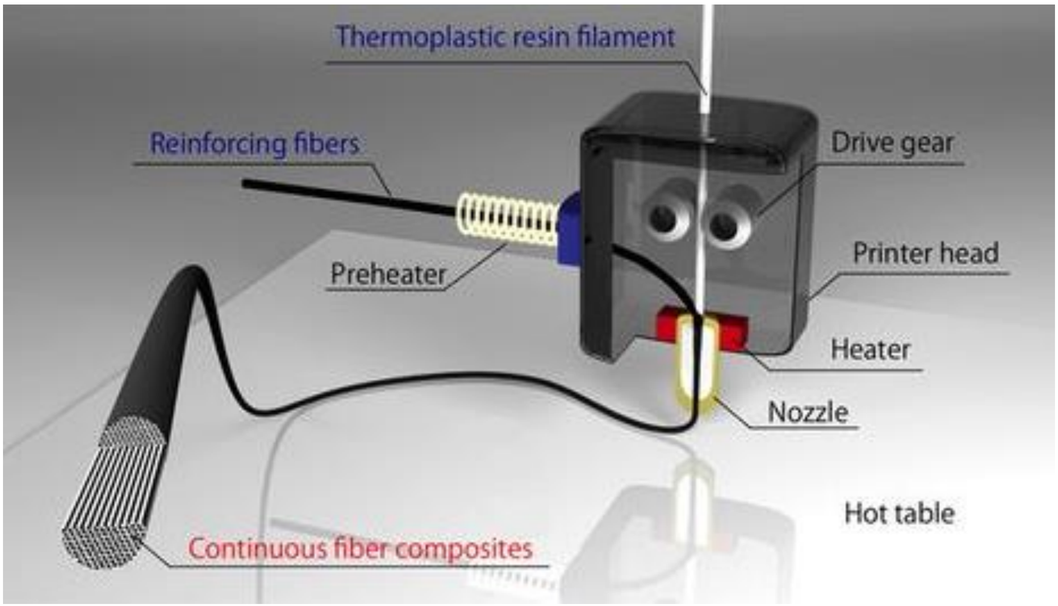

Figure 24. Schematic of the components present to produce continuous-fiber composites by in-nozzle impregnation. Adapted from [73].

Recently, the printing with multimaterial, particularly in FDM, has been developed, which consists of using different materials in a single model in order to have different mechanical and chromatic properties. For this purpose, it can be used one single multimaterial extruder nozzle or several independent extruder nozzles.

In the case of a single extruder nozzle for multimaterial printing, it is possible to use unimaterial extruder nozzle, which requires manual filament exchange during printing [22]. However, this method requires a cleaning cycle in the material change and it has higher material waste. Thereby, other types of single-nozzle extruders having multiple feeders have been developed, including Cyclops, Palette+ and Diamond [35].

The E3D Cyclops is a compact extruder, which has a single nozzle with a double feed, and the two filaments can be mixed [35]. Although there are no complications associated with misalignment as in multiple extruders, it is not possible to do different temperature controls, so it is necessary to use the same materials or with similar fusion temperature ranges [35].

The Palette+ of Mosaic Manufacturing has also appeared, consisting of a printer with just one extruder that allows the use of up to four materials in one model, through a conduction system that enables to each filament quantity control [35]. Thereby, each filament is cut by a rotary cutting system and these pieces are then connected [35]. Thus, a filament is obtained with multiple parts of different materials, which enables its automatic printing without interruption to change filaments [35].

On the other hand, the RepRap has developed the Diamond extruder, which has a single extruder nozzle with three-filament feed [35]. As well as Cyclops, it only enables the control of one value for the extrusion temperature, whereby the filaments must be of the same material or have similar fusion temperature ranges [35]. This model comes with a reduced mixing chamber, with a faster filament exchange, but requires filament retraction cycles during filament swapping to avoid mixing [35]. In addition, it provides non material waste and it produces models with different colours [35]. In opposition to multiple extruders, this has an easier calibration and better accuracy [35].

Otherwise, the use of multiple independent extruder nozzles does not require a cleaning cycle and it provides the control of multiple extrusion temperatures and the use of different materials [35]. However, it is necessary a correct offset calibration between the nozzles so that the filaments alignment is guaranteed, which can be difficult and uses more energy [35]. Typically, a double extruder is used, which consists of two extruder nozzles with each of them extruding different materials [35]. This mechanism is presented in Figure 25. This type of extruder is often applied for the printing of models that need support. Thus, one of the nozzles is responsible for producing the model layers and another for the support structures manufacturing [5]. In [74], the authors analysed the mechanical properties of multimaterial model printed (with PLA and ABS) resulting from a double extruder and obtained complications in the connection between materials.

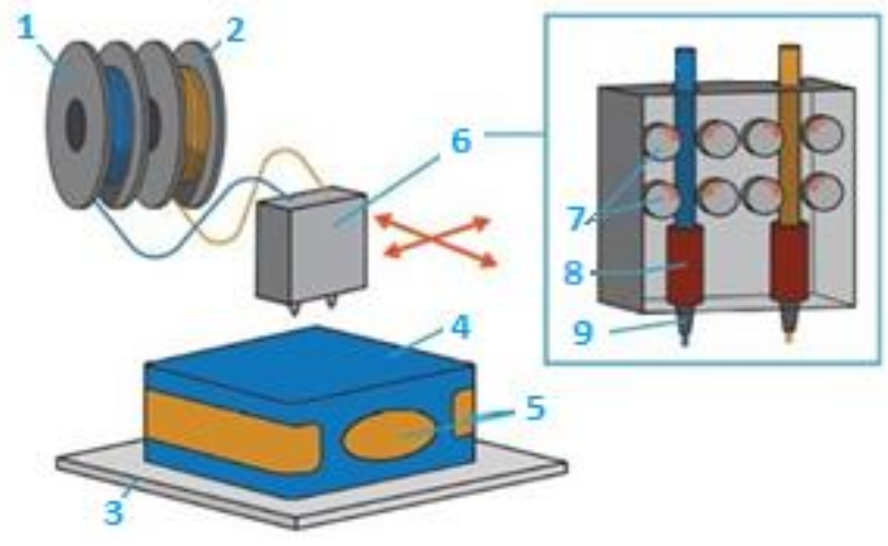

Figure 25. Elements present in double extruder nozzle FDM: (1) material coil for model printing; (2) support material coil; (3) printing base; (4) model; (5) support structures; (6) extruder; (7) gears; (8) blenders; and (9) extruder nozzles. Adapted from [35].

In the last decades, it was developed a simpler FDM method for domestic use, denominated 3D Pens [22], and it can be visualized in the next illustration. These equipments are simple to use and low-cost and they use FDM [22]. Therefore, these pens enable 3D drawing during printing, and can be used by children or adults in several areas such as architecture [22].

Figure 26. 3D pen application example (Sunlu 3D). Adapted from [22].

On the other hand, 3D Systems has recently developed a wood composite, which has 30% wood fiber and PLA, for FDM use [22]. This innovation provides the texture and smell of wood, along with the possibility of different treatments as applied to wood, such as drilling, sanding, staining and lacquering the printed components [22]. The use of this material requires an extruder nozzle with larger diameter and the printed models present lower fragility [22].

Recently, Skylar Tibbits in collaboration with Stratasys developed the four-dimensional (4D) printing, which uses time as the fourth dimension [22]. Thus, these intelligent structures are produced in three dimensions, but they have shape changing over time in response to external stimuli, including water, temperature, pH, light, among others [22]. This method extends the range of materials used, as well as applications, such as robotics, smart textiles, drug administration and regenerative medicine, for example, in the production of hydrogels [22]. In [22], the authors discuss in detail this technique and its different applications.

The evolution of 3D printing has been expanding its applications and reducing its limitations. Studies of the 3D printing market conclude that this area will grow significantly in the coming years due to the growth of users, increased manufacturing facility and research activities. Thus, 3D printing can be part of the next industrial revolution [4] (or catalyse it). Higher accuracy, customization of products, printing with multiple materials, reduced production time and financial cost, are the principal consumer factors of the market. However, it is impossible to guarantee the materials properties, some materials are high-cost (such as metallic ones) and sometimes are unavailable, the models have poor quality and there is a lack of access and know-how to use this technology [4]. Thereby, further research is important to remove these barriers. Therefore, it may be performed an extensive characterization of the printed material, a higher scale printing and also reduced it to the microscopic scale [4]. In addition, this area needs to be extended to new industries, which can be encouraged by the combination of formative, subtraction and additives techniques and by reducing environmental impact [28].

In recent years, there has been an increasing demand to reduce the environmental impact of the industry so, in the future, this demand will probably be increased, especially for the energy, material consumption and greenhouse gas emissions reduction [28]. This need may increase the 3D printing use if some advances would be made in this area [28]. Sometimes the amount of energy consumed for an AM printing can be higher than for traditional processes and there are potential health risks such as eye and skin irritation [28]. In addition, it is difficult to eliminate some materials used that have low biodegradability, including epoxy resins, polycarbonates, acrylates, among others [28]. Thus, it is necessary the promotion of new innovations that resolve these environmental weaknesses, in order to make it the most eco-friendly option [28].

4. Cardiovascular System

The human body has a sophisticated system, called the cardiovascular system, which carries the metabolic components between cells and the environment [75]. Thus, it consists of the heart, blood vessels and blood, and also lymphatic vessels and lymph, and all of them are very important in the distribution of the metabolite compounds [75]. Inside the blood vessels, there are mainly veins that collect blood and carry it to the heart, the arteries that are responsible for the blood's transport from the heart to the target organ, and the capillaries, which are small vessels that provide the components changes [75].

Therefore, these distributions can be divided into pulmonary and systemic circulation [75]. Deoxygenated blood (i.e., abundant in carbon dioxide) flows from the heart to the lungs. In the lungs gas is exchanged and blood is oxygenated. Then the oxygenated blood (i.e., abundant in oxygen) returns to the heart [75]. In the systemic circulation, there is the transport of oxygenated blood from the heart to the other organs, exchanging gases and other compounds, and deoxygenated blood from these organs to the heart [75].

4.1. Heart

The heart is the organ responsible for coordinating and pumping blood to the organs, whose muscle is called the myocardium, and it can be seen in the following figure. It consists of four cavities, two atriums and two ventricles [75, 76]. Therefore, the inferior and superior cavae vena carry deoxygenated blood to the right atrium, which contracts to pass it to the right ventricle, ejecting the blood into the pulmonary artery, responsible for transporting the deoxygenated blood to the lungs [75, 76]. In the other half of the heart, the pulmonary veins deliver oxygenated blood to the left atrium, it contracts and blood passes into the left ventricle, which also contracts, ejecting oxygenated blood into the aortic artery [75, 76]. This one will distribute the oxygenated blood to all the organs [75, 76].

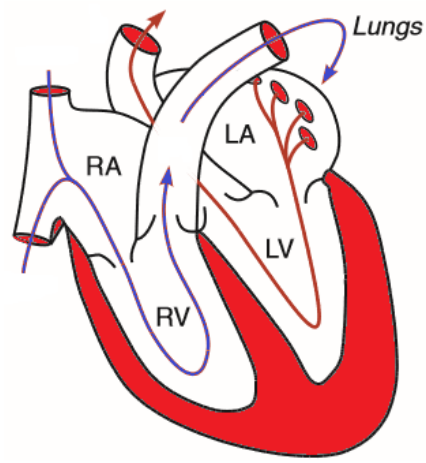

Figure 27. Heart and its mechanism. RA – right atrium; RV – right ventricle; LA – left atrium; LV – left ventricle. Adapted from [75].

4.2. Artery

As previously mentioned, the artery is the blood vessel responsible for the blood conduction from the heart to the target organs, consisting of three layers, the tunica intima, media and adventitia, as shown in Figure 28 [75-77]. The intima consists of the innermost layer of the artery, so it is in contact with the blood [77]. This is the thinnest layer and it contains collagen fibers [77]. It has the endothelium, which an antithrombogenic layer and it inhibits blood coagulation under healthy conditions [78]. On the other hand, the media is the middle layer and it is composed of elastic (connective) tissue and smooth muscle cells with different compositions, depending on the size of the artery [77, 78]. Finally, the adventitia is the outermost layer, being the main structural component [77]. In addition, it consists of collagen fibers and it has connective tissue [77]. The lumen is the cavity through which the blood circulates [77].

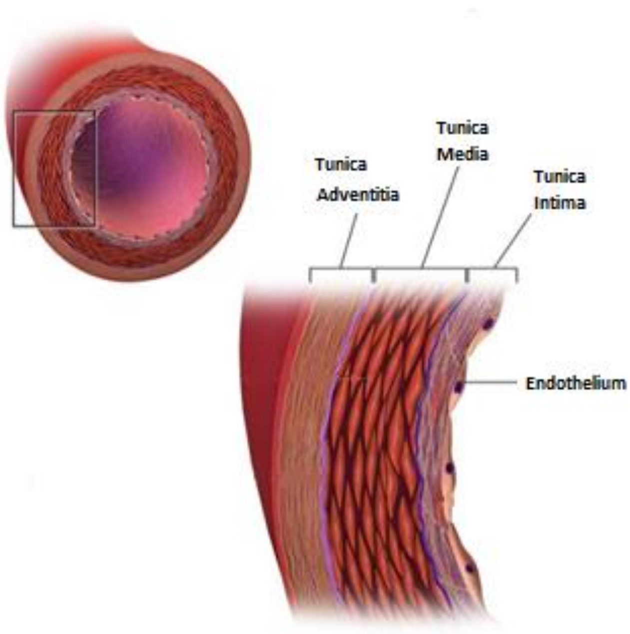

Figure 28. Structure of an artery wall. Adapted from [78].

4.3. Complications

In 2001, there were around 1 million heart attacks in the United States of America [78]. Cardiac events, such as heart attack or cerebrovascular accidents, are due to the formation of an atherosclerotic plaque in vessels which disturbs the blood flow inhibiting the supply of oxygen and nutrients to the cells [78]. Aging and bad habits, including smoking, sedentary lifestyles or fat diet, are the main factors for cardiovascular problems [78].

Over the years, it may occur some complications in arteries, such as plaque formation, which results from a progressive accumulation of fat, cholesterol, calcium and other substances [77]. Firstly, it occurs a small inflammation in the endothelium layers, where it begins to form an injury [77]. Lipids begin to accumulate progressively in the area, with plaque calcification [77]. In turn, the body's defence mechanisms promote the accumulation of smooth muscle cells in the area, with a thickening [77]. This process promotes the necrosis of the arterial cells and smooth muscle cells return to accumulate around the lesion, forming a fibrous plaque, which makes it difficult to pass blood, increasing the risk of stroke and, in extreme cases, death [76, 77, 79]. This event consists of atherosclerosis, which can be visualized in Figure 29, and may result in coronary artery disease, which is one of the deadliest diseases in the United States [76, 77]. When the fibrous plaque ruptures, a heart attack may occur. Furthermore, there are many other complications, but most ischemic heart diseases are due to atherosclerosis [76, 77, 79].

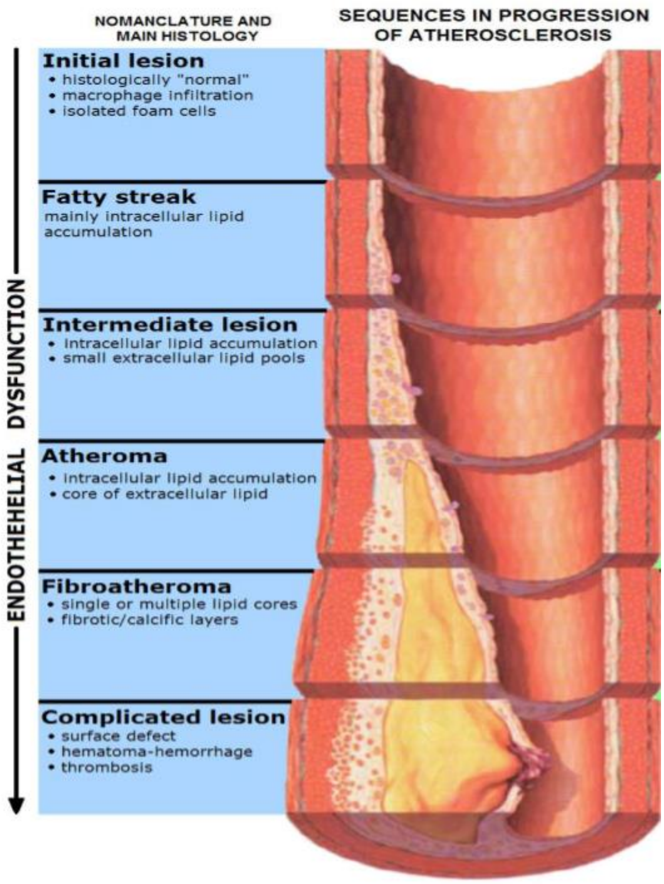

Figure 29. Atherosclerosis steps and complications. Adapted from [77].

One of the most common resulted complications is the thrombosis. This is a quick complication resulted from the rupture of endothelium, which display the collagen of tunica intima to the bloodstream [78]. Thus, platelets are activated by contact with collagen and several thrombogenic events are generated and a thrombus is developed which might block the artery or detach and block other vessels [78]. In addition, atherosclerosis can also cause stenosis, which is resulted from a slow development of the atheroma plaque, which causes a continuous narrowing and final obstruction of the vessel [78].

4.4. Treatments

After these complications occurred, it is necessary to follow a medical treatment. To fight these complications, several methods have already been developed, including vascular bypass (blood flow redirection to a region where the blood circulates correctly), thrombolytic therapy and angioplasty [77, 78, 80].

Myocardial revascularization surgery, or opened-heart surgery, aims to increase the blood flow to the coronary arteries by inserting part of a vein or artery from another part of the body into the coronary artery [77]. This method is extremely invasive and it presents a high risk of infection, rejection of grafts, among others [77].

On the other hand, thrombolytic therapy consists of the intravenous injection of anticoagulants for the fibrous plaques dissolution [77]. The main risk of this technique is haemorrhage, which may also occur in the brain [77].

Finally, angioplasty consists of using a catheter with a reduced size balloon that inflates and widens the arterial lumen, promoting blood flow [77]. This technique is quick enough to be implemented (about 90 minutes), does not require general anaesthesia and the main risk associated is restenosis (recurrence of narrowing of the blood vessels) [77]. This technique is often combined with the stents implantation, and in these cases, a stent is placed inside the artery to keep it open [77].

5. Stent

The stent is a cylindrical endovascular device that enables widening the lumen of any organ, preventing them from narrowing again (restenosis) [1, 78]. This concept was developed by Charles Stent in the 1980s, and with the technological development in health, it is currently used in several parts of the body to intervene in many conditions, such as coronary artery disease [1, 81]. These structures are expandable meshes with a length of 6 to 60 mm and a diameter of 2 to 10 mm [78].

Although stent implantation may result in failure due to fatigue, thrombosis, cholesterol accumulation, restenosis, inflammation and hyperplasia, this method is low-cost, it is easy to implant and enables a faster recovery and reduction of heart attack risk [77, 80].Thus, stent implantation is a minimally invasive method where the stent is placed into a delivery catheter, which is guided into the position by using a guidewire, typically inserted into the peripheral artery in the thigh [77, 81]. Then, it is approximately 50% by a spring-like recoil in its naturally expanded form or by plastic deformation under the influence of an inflated balloon within the stent at 8-20 atmospheres of pressure [78]. The stent expansion is represented in Figure 30 [77]. Therefore, the stent needs to be biocompatible, rigid enough to support it, resistant to corrosion and impact [82]. Furthermore, stents must allow the inclusion of therapeutic agents and to be removed at the end of the treatment without introducing toxic materials into the body [77, 79]. The US Food and Drug Administration (FDA) has guidelines for stent fatigue testing, and it should have a minimum fatigue life of 10 years at a heart rate of 72.3 beats per minute [77, 83].

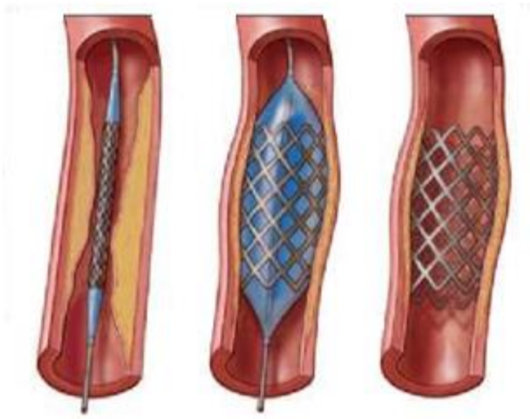

Figure 30. Stent implantation by angioplasty. Adapted from [78].

Usually, stents consist of a matrix of repeating structural elements, called struts, that are arranged around the stent circumference and that are connected in alternate ends forming "V" or "W" [1, 84]. This link is called apex, and a line of apexes that complete a 360º turn is a column [1]. In turn, the adjacent columns of struts are connected by bridges that link the apices regularly [1]. In order to be functional, the stent must be able to convert from a small diameter during insertion to a larger diameter at the target site [1].

In this sequence, the stent uses crimping (stent diameter reduction) and expansion mechanisms, which uses the material plasticity to increase radial resistance [77]. For its *in vivo* application, it is necessary to control these mechanisms, so it was developed the Adjustable Rigid Torus plugin for Abaqus software, suitable to computationally simulate the structural behaviour of stents. It uses cylindrical displacement vectors to control the expansion and the crimping of the stent and the positive vector represents the expansion and the negative one the crimping [77].

5.1. Types

Currently, there are several classifications for stents, but the most common are based on the expansion mechanism (self-expanding or balloon expandable), in their material (stainless steel, cobalt-based alloy, tantalum, nitinol, magnesium, PLA, etc.) and its design (mesh structure, coil, tube with grooves, ring, multiproject or custom design) [84].

The self-expanding stents are placed within a sheath-like stent delivery system for placement into a vessel, and when the stent is pulled back, the stent deploys radially outward against the vessel wall and the catheter is removed [85]. Therefore, the stent needs to be strong enough to be compressed without being plastically deformed or permanently bent and its modulus of elasticity needed to be high enough to enable the stent spring back to its unloaded state from the compressed one [86]. On the other hand, the balloon-expandable stent is the most used technique and consists of introducing a stent with an empty balloon into the artery vessel by a catheter system with subsequent balloon inflation, causing the stent to expand to the desired diameter [79]. Thus, the balloon is returned empty and it is eliminated with the catheter system [79].

About geometry, there are several available models, but the most popular are the Palmaz-Schatz and the Lozenge [79]. The Palmaz-Schatz is the most popular model due to its straight lines, forming a grid, which enables a uniformity of the applied loads on the inner surface of the stent [79]. On the other hand, the Lozenge presents a simple geometry similar to a diamond mesh [79, 87]. These two models are present in next figure. In addition, there are many other models with their own geometries, as presented in [11].

Figure 31. Representation of model: (a) Palmaz-Schatz; and (b) Lozenge. Adapted from [79].

Therefore, many stents, including Multilink Penta (Guidant), Express (Boston Scientific), NIR Royal (Medinol and Boston Scientific), Biodivysio (Biocompatibles) and S7 AVE (Medtronic), were developed and commercialized [84]. In [84], the authors present a survey of several commercially available stents, particularly their characteristics, performance and the studies that analyse them. In the chart below, there are some characteristics of the mentioned stents.

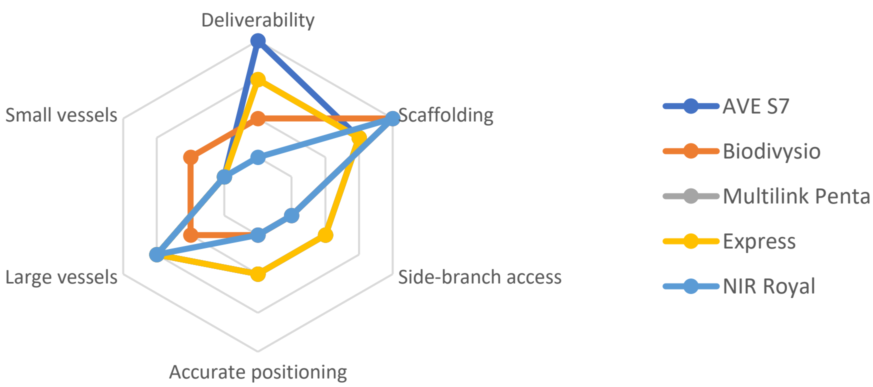

Figure 32. Stent consumer’s guide. Data from [87].

Nowadays, there are some researchers that are studying the use of 3D printing to develop stents. Kang *et al.* analysed a tubular flexible self-expanding stent for oesophageal cancer patients using 3D printing [88]. In this study, the authors developed a new 3D-printed polymeric stent with spirals using a combination of PLA and thermoplastic polyurethane (TPU) [88]. Therefore, it was concluded that this geometry provides higher self-expansion and anti-migration force compared to non-spiral stents [88].

5.2. Manufacturing Techniques

Nowadays, there are different methods for the manufacturing of stents, depending on the material, dimensions and geometry needed. For the production of metal stents, the most common methods are the Laser machining, Photo-chemical machining, Thin film technology, Electroforming and Wire bending [78].

The laser machining consists of a laser rotating and cutting a tube with the assistance of a numerical control computer that makes the desired mesh design, as can be seen in [78]. This method has several subcategories depending on the type of laser used (solid-state lasers, diode-pumped solid-state lasers, optical fiber lasers and the ultrashort-pulse lasers), and a detailed description can be found in [78].

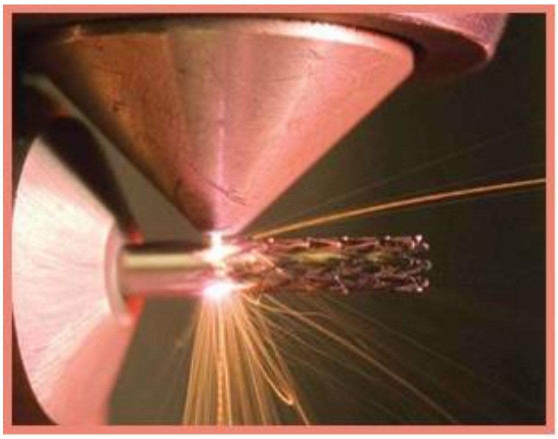

Figure 33. Laser machining use for a stent development. Adapted from [78].

The photo-chemical machining is a chemical milling method to conform thin metal sheet components using photoresists and etchants to machine away specific areas [78]. This technique provides stress-free and burr-free machining, suitability for all metallic stent materials and it is low-cost [78]. Nevertheless, it causes low aspect ratio depth/width, so it is not possible to use it to stent designs of standard coronary and peripheral stents [78].

Thin film technology consists of a sputter deposition on a rotating 3D substrate, i.e. physical vapor deposition by the ejection of material [78]. This requires a high potential differential and an ultra-high vacuum atmosphere [78]. Thus, this process is high-cost although it offers thin layers and a very pure material [78].

The electroforming involves photolithography and the process can be consulted in [78]. This process has high precision and low cost, being used in gold, silver and nickel, but not in stainless steel, CoCr alloys or Nitinol [78].

The stents developed by the shaping technique do not have junction points between the crossover yarns, thus being more flexible and adaptable [78]. This method was developed by BMV Medical [78].

About polymer stent manufacturing, the commercial polymer stents have been developed by the combination of mold injection and laser machining. The mold injection consists firstly in polymer melt into a polymer extruder and then injected into a tube mold. This technique presents some complications, including the concentricity maintenance in the mold during the tube cavity walls filling and also the polymer thermal degradation. The laser machining machines the resulted tube from the previous method with a laser cutter, which must be an ultrashort-pulse laser to convert the material directly from the solid to the vapor phase without generating any heat affected zone. However, these stent manufacturing processes are expensive. Therefore, as previously mentioned, there are a few projects to obtain stents at low price and also customized. One of the alternatives is the use of 3D printing technique, as it can be a low-cost method with the possibility of customization of the design. In Table 3, it is presented a comparison between the actual common technique and the additive manufacturing method.

Table 3. Comparison of the additive manufacturing and traditional polymer stent conformation method.

Conformation method	Additive Manufacturing	Injection Moulding + Laser Machining
Advantages	- Not a minimum economic batch size - Customizable dimensions - Fast fabrication process - Very indicated for prototype designs - Seamless (no weld lines) - More crystallinity and better mechanical properties	- More precise method - More accurate results
Disadvantages	- High filament diameter - Less accurate results	- Possible tube eccentricity - Possible weld lines - Expensive laser machining process - Big economic batch size - Possible loose of molecular weight - Lower mechanical properties (thanks to the crystallinity)

In [78], the authors developed a new stent 3D printing fabrication method based on the solvent-cast direct-write fabrication technique to produce low-cost and easily customized PLA cardiovascular stents. Therefore, stents are printed through a syringe using a PLA solution (with chloroform) as "ink" through an adapted FDM 3D printer, in order to dispense the ink produced into a laminating tube and to fabricate cylindrical PLA structures [78].

5.3. Materials

Stents are typically composed of stainless steel, cobalt and chromium alloy, tantalum, nitinol and magnesium [1, 77, 84]. The most common type is the Bare Metal Stent (BMS), which is metallic stent used to prevent artery elastic recoil and negative remodelling [78]. BMS are more efficient than balloon angioplasty due to a structure that remains in the artery decreasing restenosis [78]. Nevertheless, balloon stent expansion destroys partially the endothelium thanks to the high mechanical stress, which results in an early thrombosis and stenosis post implantation [78]. Therefore, the most popular BMS are stainless steel stents, which are usually low-cost and biocompatible [78]. However, they usually present high rates of restenosis and thrombosis [77, 79]. In the literature, there are already many studies that have developed a stainless-steel stent and analysed its mechanical behaviour to simulate its implantation [80, 89]. It is also possible to use gold, which is a biocompatible and typically inert but very expensive metal, or to use tantalum, that presents high flexibility and structural support but is not biocompatible and tends to have high levels of restenosis [77]. On the other hand, the cobalt and chromium alloys are highly biocompatible and have high yield strength and elasticity modulus [86]. Nitinol is a biocompatible nickel and titanium shape memory alloy and it has high elasticity [1, 77]. This material is widely used in biomedical applications, including stents, due to their high stability of the mechanical properties [1].

In addition, it was developed another type, named Drug Eluding Stents (DES), which are the evolved BMS, so they consist of a metallic structure coated with a polymer containing pharmacologic agents enabling a local drug supply (anti-inflammatory, anti-proliferative, anti-migratory and pro-endothelialization agents) [78]. These agents try to reduce in-stent restenosis by minimizing vascular inflammation [78]. However, it provides a negative consequence on delayed arterial healing and the increased risk of late stent thrombosis, so a continuous dual-anti-platelet therapy is required for one or more years after DES placement [78].

However, in recent years, there have been many studies that seek the use of new materials, mainly biodegradable or bioabsorbable, in order to have a temporary stent that bioabsorbs over time enabling the vessel to regain its natural shape and function while improving rates of stent thrombosis and restenosis [78]. Thus, these biodegradable materials must also be biocompatible and capable of not be degraded while the stent performs its function and it must have the finest struts possible [79]. According to [90], the mechanical flexibility of these stents can maintain the original vessel geometry better than rigid metal stents. One of these materials used are magnesium alloys, which are currently the most popular choice [79]. Magnesium is one of the essential elements of the human body, it does not provide carcinogenic risks and it has high mechanical resistance [79]. The most recent stents of this material can be used for 9 to 12 months and its degradation takes between 2 and 12 months [79]. In [79], the authors developed a magnesium stent and analysed their mechanical behaviour in order to evaluate the influence of geometry.

Alternatively, biopolymer stents were also developed, and the most popular are the PLA-based stents, that exhibits a viscoelastic nature [77]. The first biodegradable PLA-based stent used in humans is called Igaki-Tamai and was developed by Kyoto Medical Planning Co [90]. This stent was self-expanding, so it expanded at body temperature. In 2000, Tamai *et al.* [91] published results of its implantation in 15 patients in whom 25 stents were successfully implanted. The use of this material enables mechanical support of the vessel for several months (usually 6 months) and a lower incidence of thrombosis [90, 92]. In addition, it has similar radial strength to metal stents [90].

As previously said, Kang *et al.* developed a polymeric stent, using 3D printing, which was made of TPU, which provides the necessary toughness, durability, and biostability, and also made of PLA that enables higher mechanical strength and biodegradable properties [88]. In [92], the authors give an overview of the use of biodegradable stents, specially their applications and the involved studies that are being carried out. Furthermore, they have also performed an analysis of the PLA-based stents studies that are being developed [90].

Zhao *et al.* have performed an experimental study about fabrication of polymeric stent using homemade 3D printers [93]. In this study, it was used a rotating shaft with controllable temperature and rotating speed in an FDM 3D printer to support the printed stents and the authors investigated the effects of operating conditions (such as rotating speed, printing temperature, printing speed, and step distance) on the dimensions of the printed stents [93]. As a result, they concluded that it is possible to print polymeric stents using the homemade 3D printing system [93].

Chapter 3

Design Procedure

To achieve the proposed objectives, the practical component was initialized by the model design. For that, four different geometries were developed and printed. For one of the geometries, it was necessary to perform a biomechanical simulation to analyse the best bandwidth/force correlation to print the stent. Finally, all the models were differently printed, and the main conclusions were highlighted.

1. Design

The first experimental step of this study was the creation of the stent model. Therefore, the software used was Solidworks (version 2018) and four different geometries were developed. Firstly, it was developed Model 1, whose dimensions are presented in Figure 34.

This model is characterized by ten wires, each formed in twenty-one zigzags and the wires were connected at the crown points to complete the stent (Figure 35). This geometry is very popular and it is commonly used in medical industry, so there are a few studies that have been analysing it [77, 87].

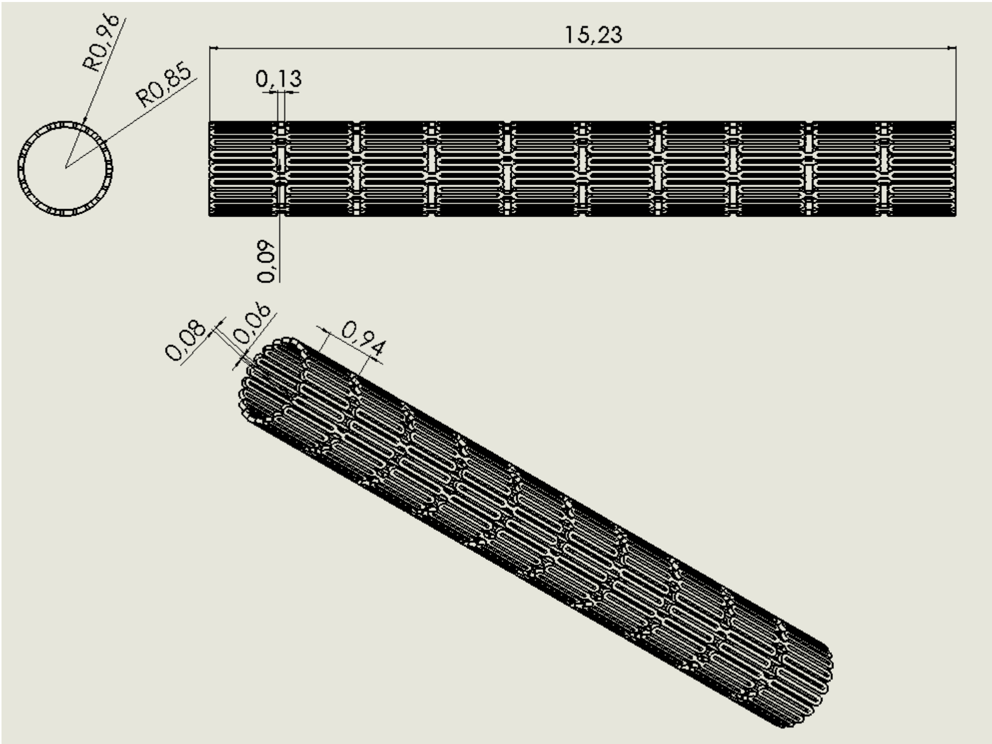

Figure 34. Drawing model of the Model 1 with some dimensions.

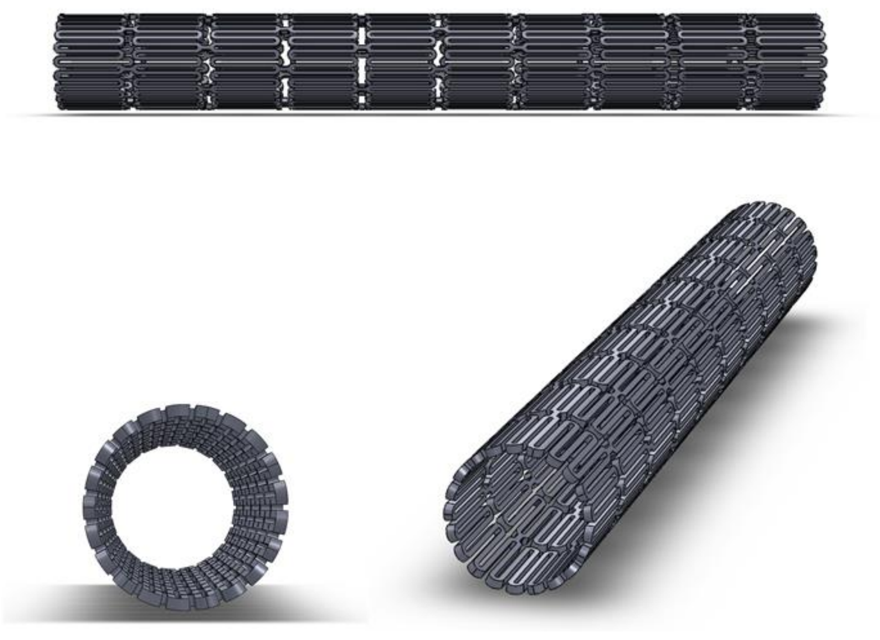

Figure 35. CAD model of the Model 1.

Then, it was developed the Model 2, similar to the previous one, but it was composed by ten wires, each one formed in six zigzags, and its main dimensions are shown in Figure 36.

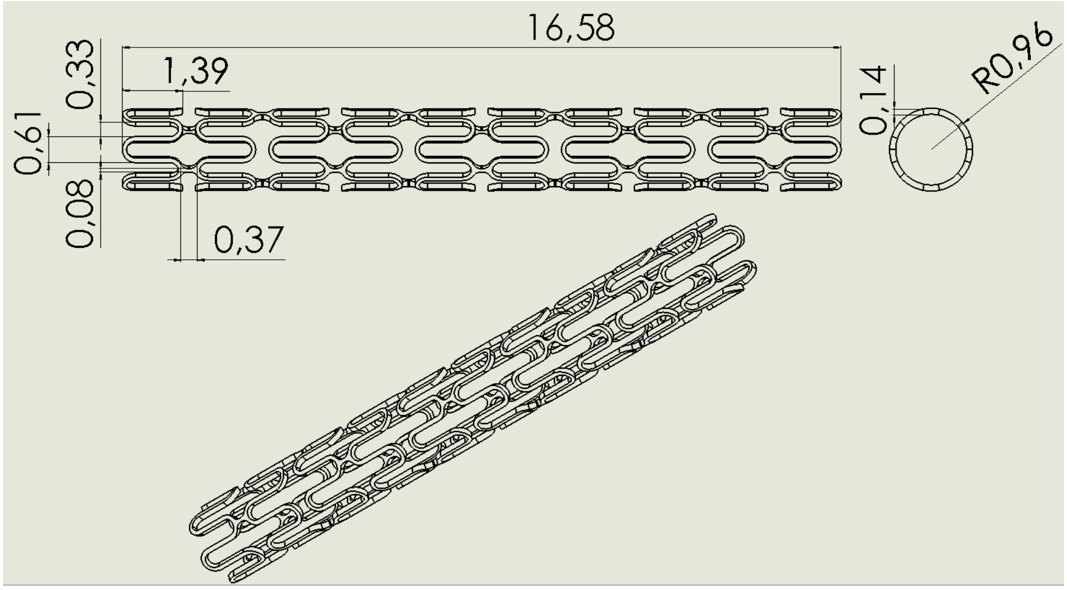

Figure 36. Drawing model of the Model 2 with some dimensions.

This model is less compacted than the previous one, as it can be seen in its CAD representation in Figure 37. This geometry is also frequently used for medical use, so there are some research groups studying it [11, 79-81].

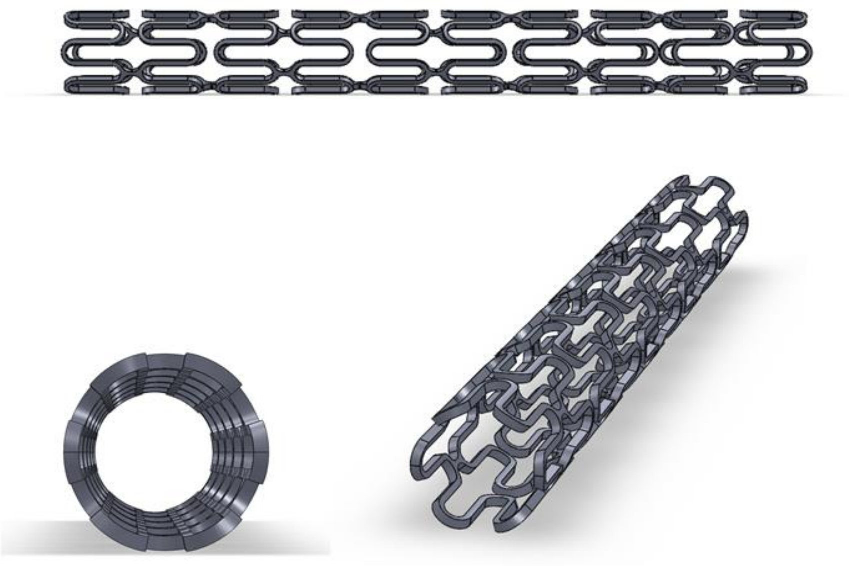

Figure 37. CAD model of the Model 2.

After these geometries, it was developed the Model 3, whose dimensions can be visualized in Figure 38. It is an indent connection model, which consisted of wires formed in six zigzags bonded at their indent connectors.

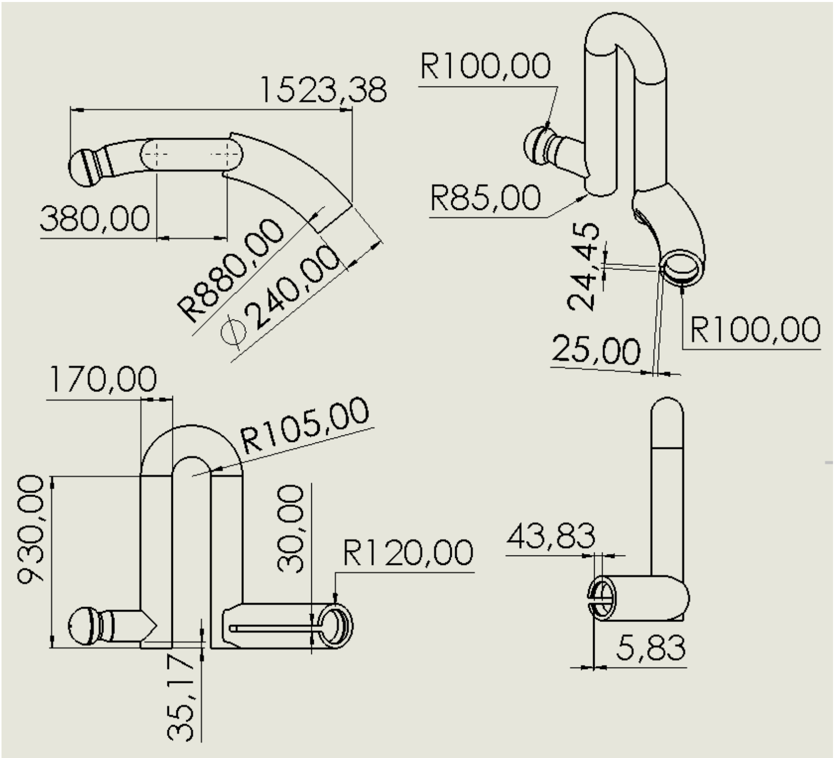

Figure 38. Drawing model of the Model 3 with some dimensions.

To bond each wire, it was developed a hook and its measures are presented in Figure 39.

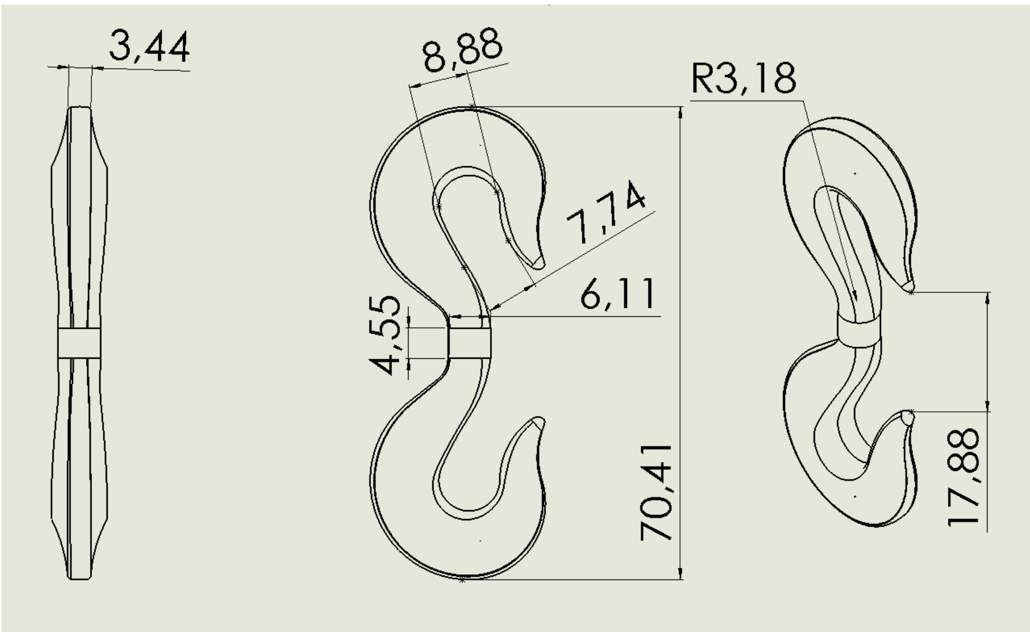

Figure 39. Drawing model of the hook geometry with some dimensions.

This model geometry was developed in order to be more resistant to the 3D printing and it is shown in Figure 40, as well as its hook in Figure 41.

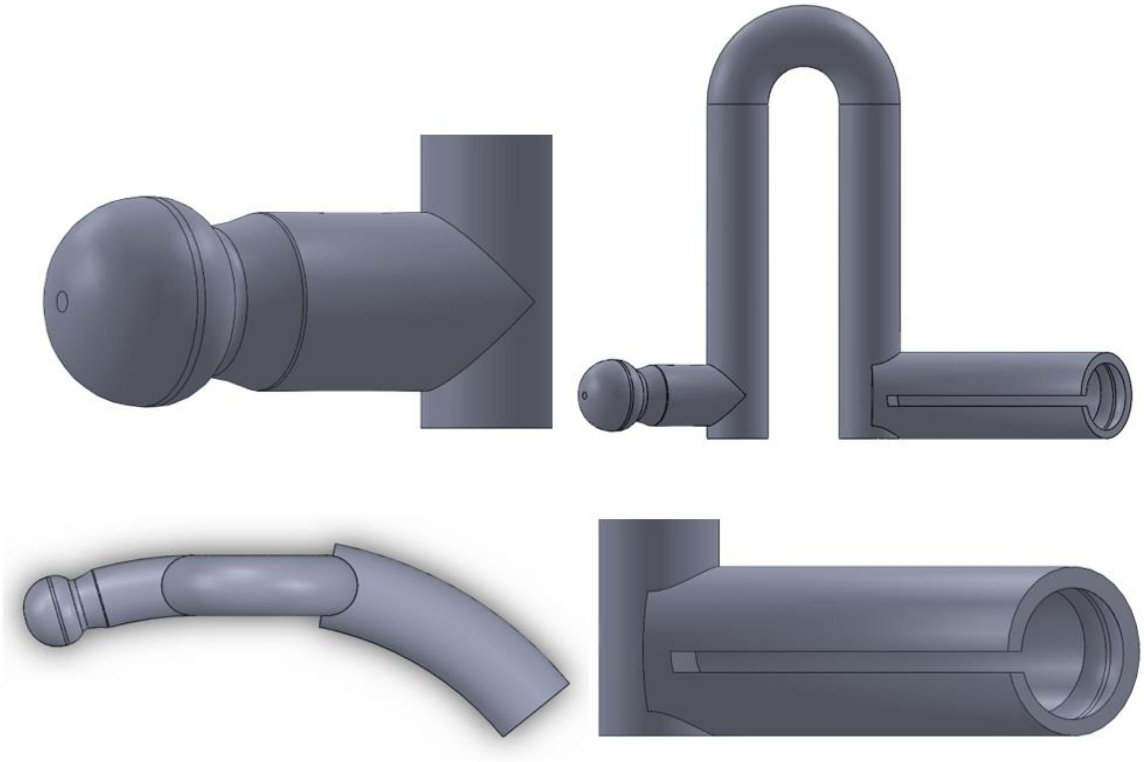

Figure 40. CAD model of the Model 3.

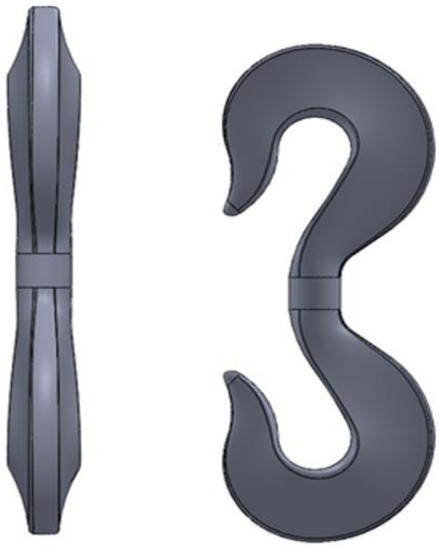

Figure 41. CAD model of the hook.

Finally, it was developed the model 4, a cylindrical grip model, which consisted of wires formed in five zigzag that are bonded by cylindric connectors. The dimensions are presented in Figure 42.

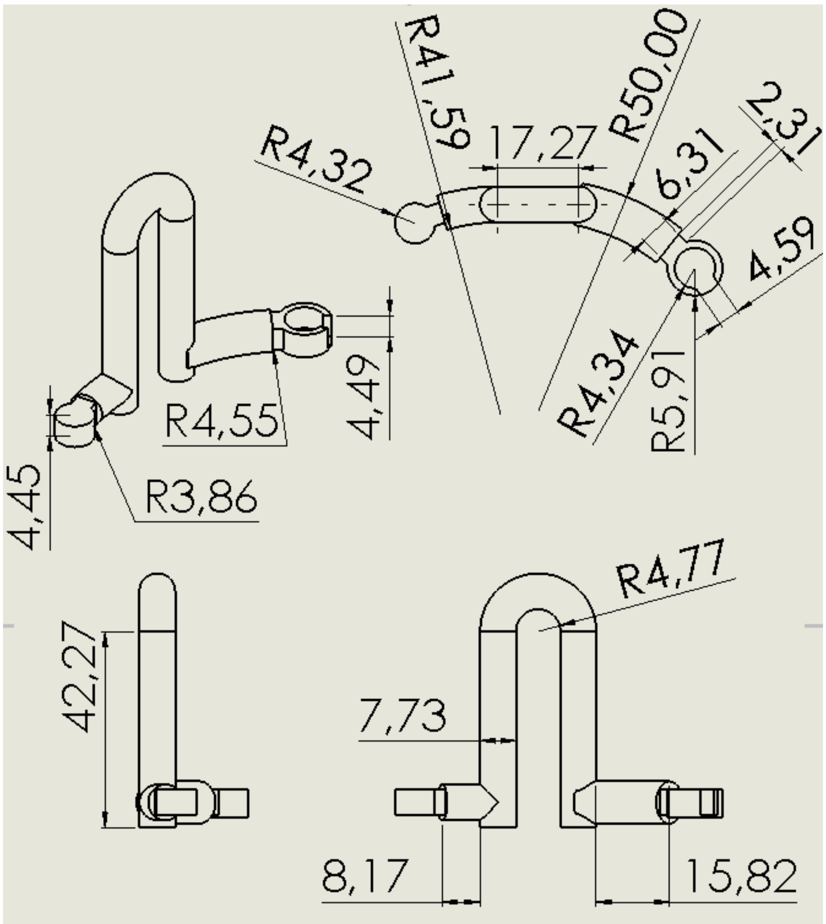

Figure 42. Drawing model of the Model 4 with some dimensions.

To connect each wire, it was used the hook previous developed. This model was developed in order to be more easily fixed and stable to the printing and to the assembly and it is shown in Figure 43.

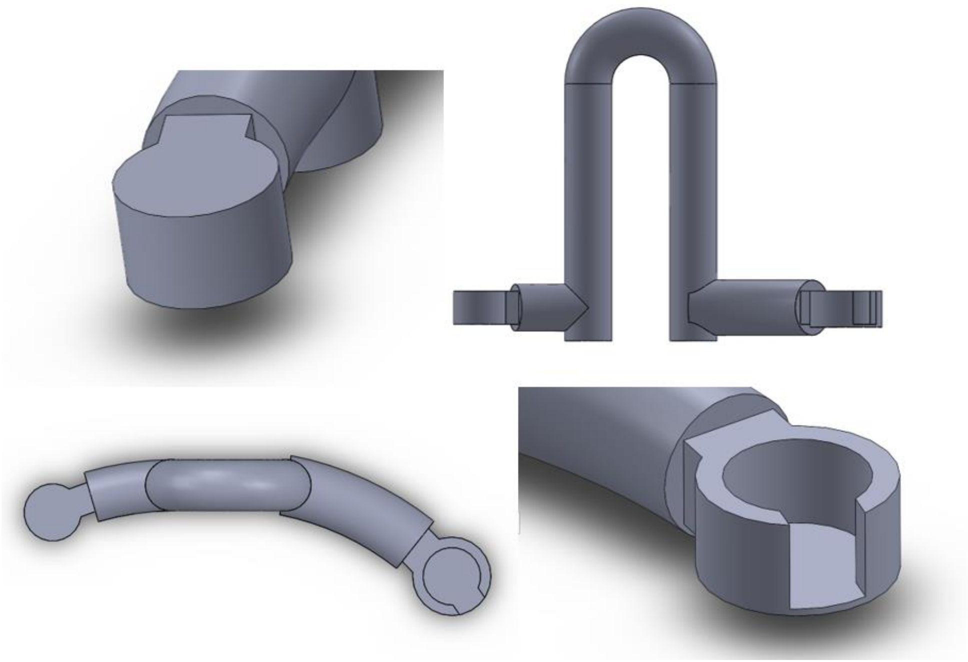

Figure 43. CAD model of the Model 4.

2. Numerical Simulation

To analyse the mechanical behaviour of the Model 3, it was performed a numerical structural simulation using Finite Element Method (FEM) in Solidworks (version 2018), whose basis and formulation can be consulted in [81]. Once the scale of this model is too large when compared to the real stents, it was done a scale adaption to 0,045. The mode of the zigzag component was discretized with 14166 nodes and 8344 elements and the mode of the hook with 41301 nodes and 25018 elements. Both types used were blended curvature-based mesh. The 3D elements used were the constant strain tetrahedral elements. The element mesh is shown in Figure 44.

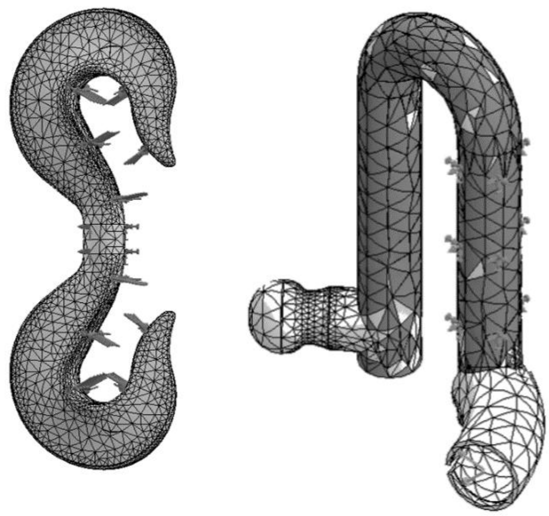

Figure 44. Mesh representation of Model 3: (right) hook; (left) zigzag.

Firstly, it was measured the opening dimension required for the wire to fit into the hook, which value is 0,2864 mm. The opening dimension is represented in Figure 45 for a better understanding.

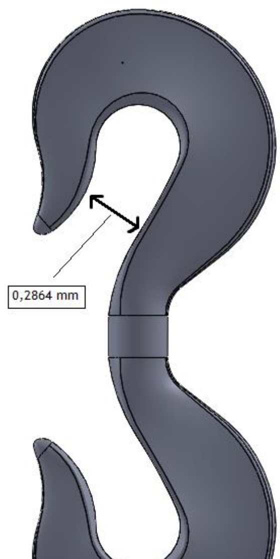

Figure 45. Schema of required opening dimension of the hook.

Then, it was applied a distributed force on the inner surface of the hook, with a total magnitude of 1,00 N, as it can be seen in Figure 46. In the end of the analysis, it was measured how much the hook has opened due to the application of the force, as shown in Figure 47. The magnitude of such displacement is shown in Table 4. Furthermore, the application of pressure on the inner surface of the hook led to stresses, as represented in Figure 48. The maximum stress obtained is also shown in Table 4. This procedure was repeated with different force values in order to confirm the linear correlation between the applied force and the obtained displacement and also between the maximum stress and the opening displacement (Figure 49 and Figure 50). The necessary force to obtain the desired opening displacement and the resulted maximum stress were then calculated from the obtained functions. As a result, the force necessary is 73,05 N and the maximum stress obtained (26,64 MPa) was compared to the ultimate stress of the used PLA to find out if the hook would resist to the connection, and it was concluded that the hook would resist to the needed forces to connect with the rest of the stent, as shown in Figure 51.

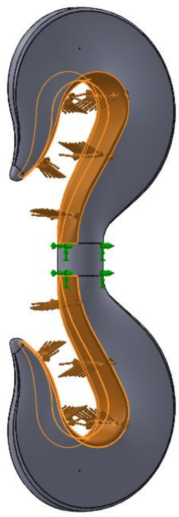

Figure 46. Representation of the applied forces in hook.

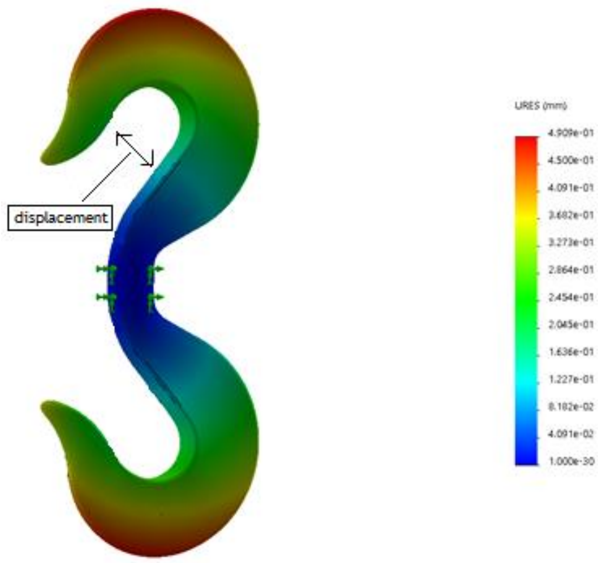

Figure 47. Example of the opening displacement of hook resulted from the applied force.

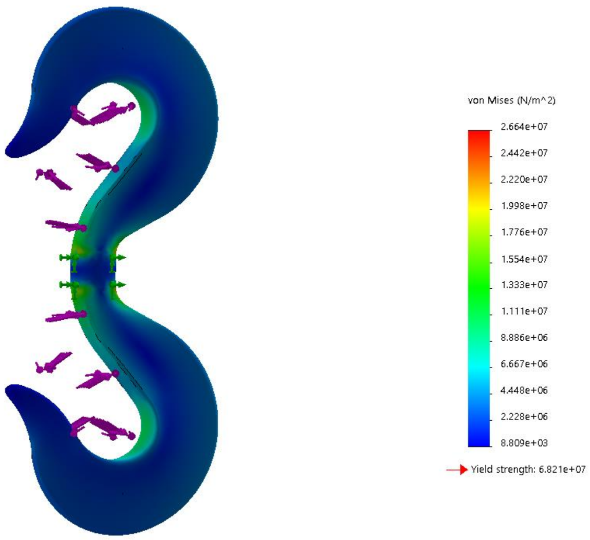

Figure 48. Example of the stress gradient of hook resulted from the applied force.

Table 4. Hook: applied forces and the displacement and maximum stress resulted.

Displacement (mm)	**Force (N)**	**Maximum Stress (MPa)**
0,00392	1,00	0,3647
0,00784	2,00	0,7294
0,196	50,00	18,24
0,274	70,00	25,53
0,2864	73,05	26,64
0,292	74,00	26,99
0,352	90,00	32,82
0,392	100,00	36,47

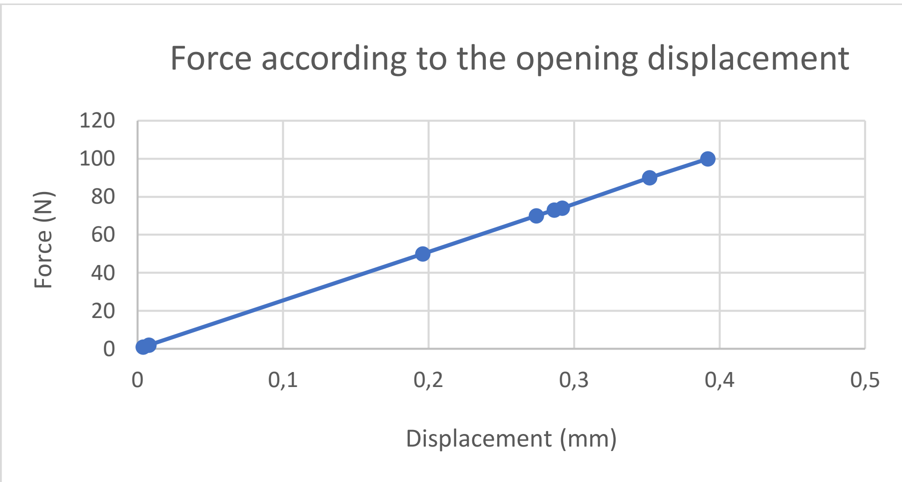

Figure 49. Force as a function of the opening displacement resulted from the hook simulation.

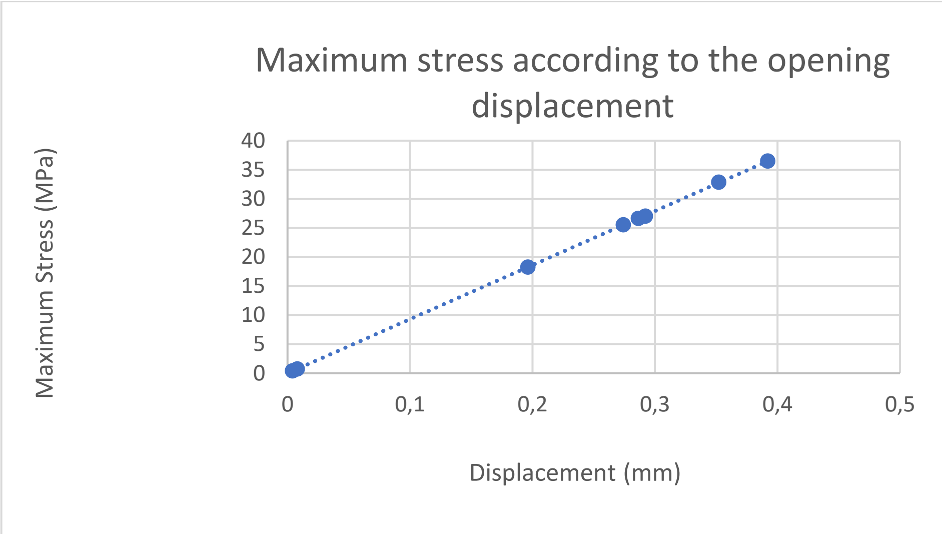

Figure 50. Maximum stress as a function of the opening displacement resulted from the hook simulation.

Figure 51. Assembly of hook with the zigzag component.

From these results, it was concluded that the force necessary to connect the stent zigzag with the hook is 73,05 N. Therefore, it is possible to visualize that the maximum stress obtained (26,64 MPa) is lower than the tensile strength of PLA (105 MPa), which allows to conclude that the model resists to the application of the necessary forces.

Posteriorly, it was measured the opening required for the spherical component to fit into the cylinder of the wire, and this opening is represented in Figure 52. Then, the necessary force was analysed as a function of the bandwidth of the spherical component. In Figure 53, it is represented what was considered to be the bandwidth, in which the minimum bandwidth is related to the middle plan of the sphere.

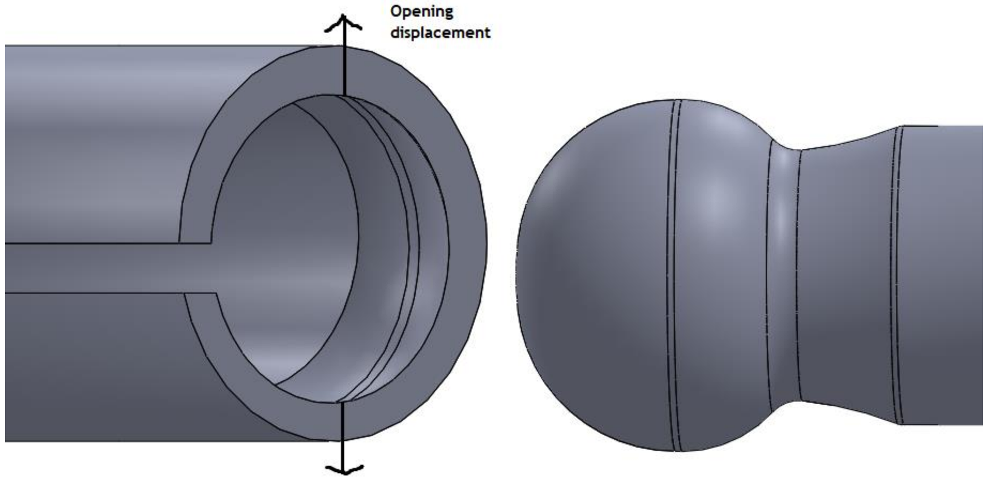

Figure 52. Representation of opening displacement of the cylinder.

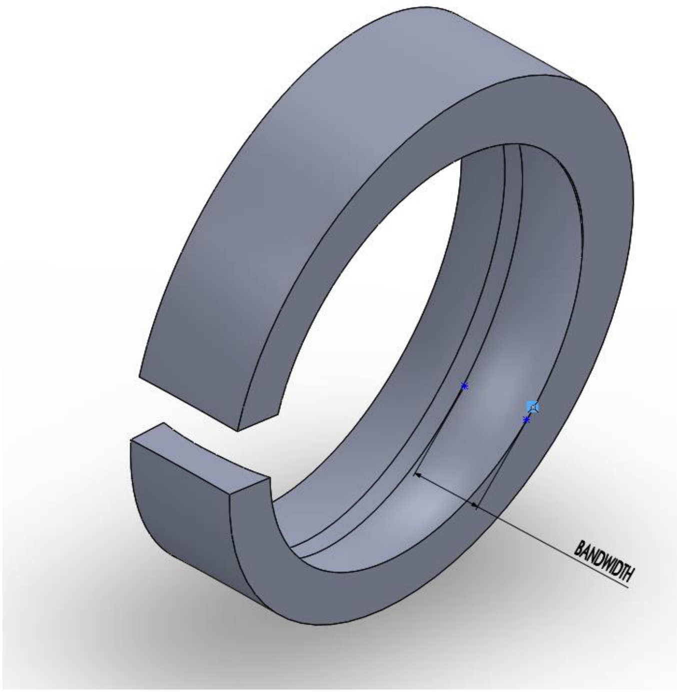

Figure 53. An example of a bandwidth.

Thus, it was applied a uniformly distributed force on the bandwidth face, totalizing 1,00 N, as it can be seen in Figure 54. The other parts of the model were fixed, and the opening displacement obtained was analysed. Once again, the opening displacement was obtained by subtracting the final diameter (after applying the pressure in the bandwidth face) to the initial diameter. With this value, it was possible to determine the necessary force for the desired displacement as shown in Equation 1 (notice that the force of the simulation is known and it is 1,00 N).

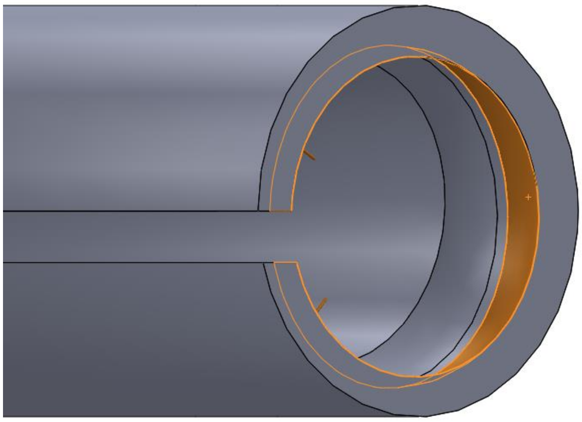

Figure 54. Representation of the applied forces in bandwidth of the cylinder.

Equation 1. The calculus of the necessary force to open the cylinder.

$$\frac{Force_{needed}}{Displacement_{needed}} = \frac{Force_{simulation}}{Displacement_{simulation}}$$

The diameter of the minimum circle resulted from bandwidth was measured and this value was used as the diameter of the hollow component inside the cylinder, as represented in Figure 55. Then, this procedure was repeated with different bandwidth values in order to obtain the minimum force necessary to connect the components, as it can be seen in Table 5. Correlations between the needed force and the bandwidth/sphere radius and also the maximum stress and the bandwidth/sphere radius are demonstrated in Figure 56 and Figure 57, respectively. As a result, the minimum force necessary was visualized and the maximum stress obtained was compared to the ultimate stress of the used PLA to find out if the cylinder would resist to the connection.

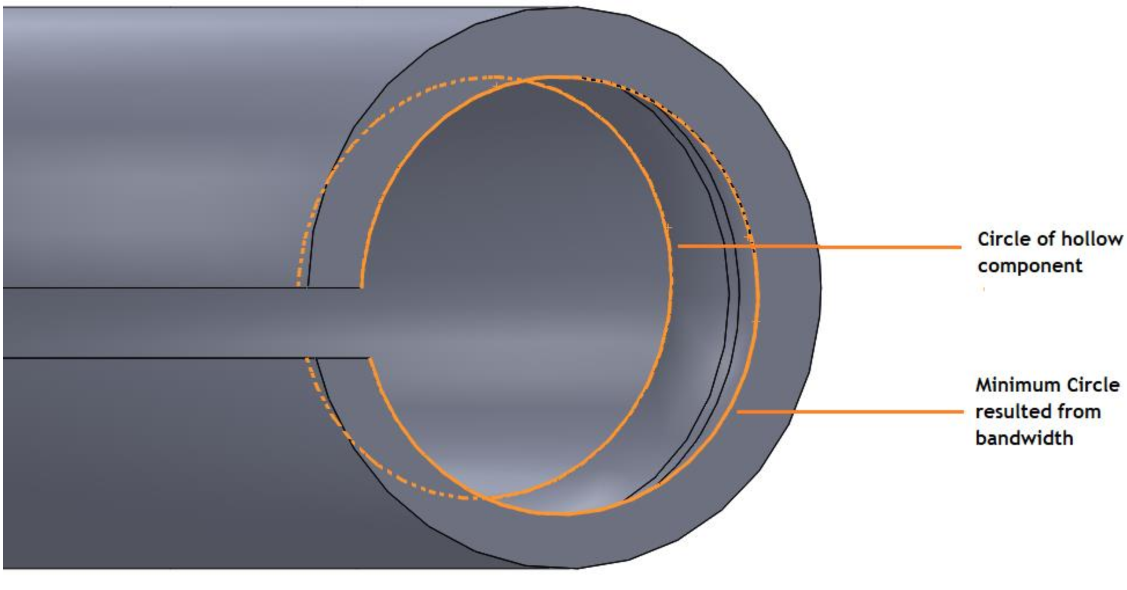

Figure 55. Representation of the minimum circle resulted from bandwidth and circle of hollow component.

Table 5. Wire: applied bandwidth, diameter used for the hollow component inside the cylinder, the necessary force and maximum stress resulted.

Bandwidth (mm)	Diameter (mm)	Force (N)	Maximum Stress (MPa)
0,1155	9,05	1,105	0,7018
0,2059	9,03	1,250	1,118
0,3782	8,98	1,010	0,9831
0,4782	8,92	0,870	0,8211
0,6918	8,82	0,858	0,9267
0,8036	8,74	0,843	0,9951
0,9127	8,67	0,690	0,8742
1,0509	8,57	1,747	1,138
1,1455	8,49	1,738	1,080
1,3027	8,28	1,677	1,076
1,5500	8,02	2,313	1,191
1,8800	7,72	2,499	1,263

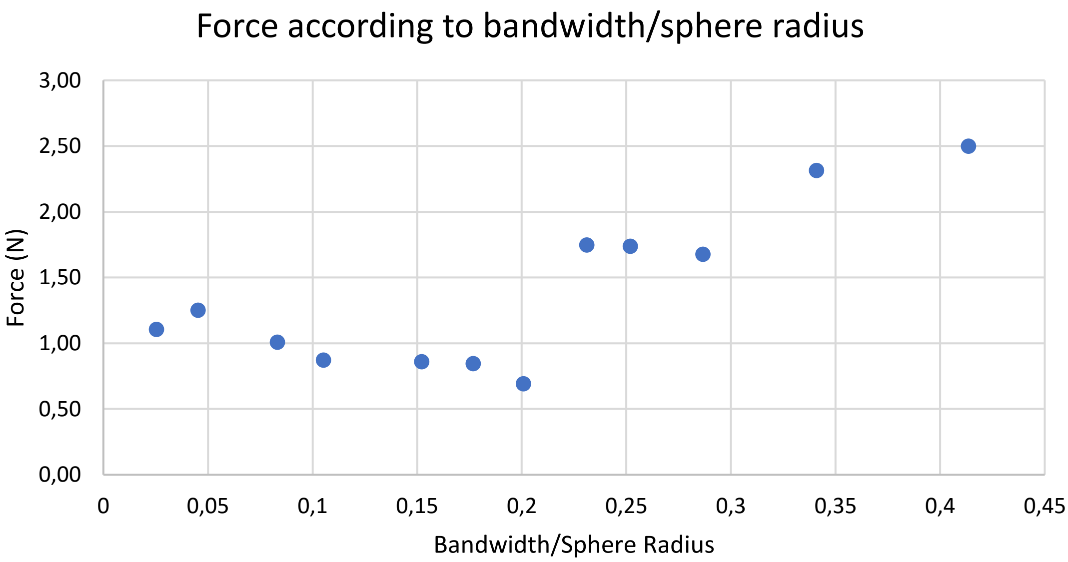

Figure 56. Force as a function of the bandwidth/sphere radius resulted from the wire simulation.

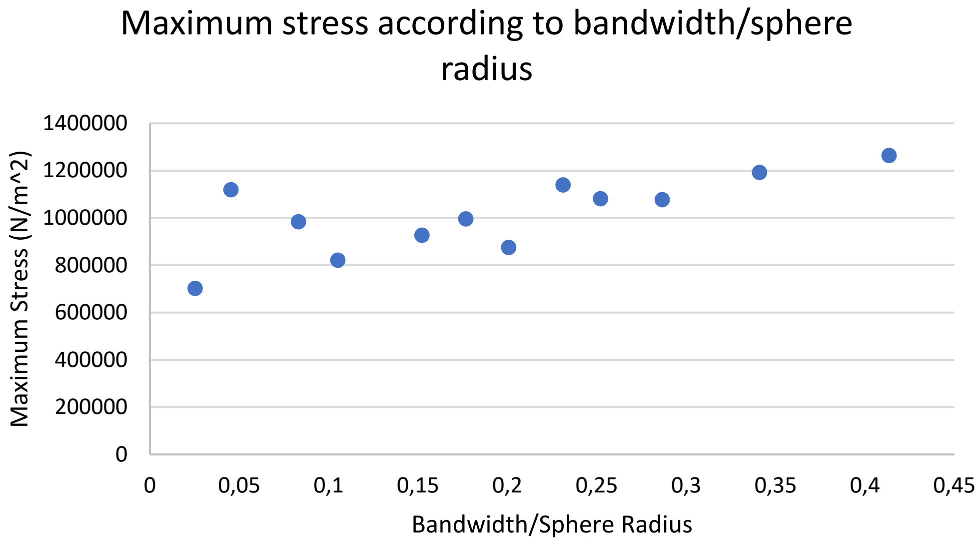

Figure 57. Maximum stress as a function of the bandwidth/sphere radius resulted from the wire simulation.

From these results, it was concluded that the minimum force necessary to connect the stent wires is applied at a bandwidth of 0,9127 mm, which was the value used in 3D printing. Therefore, the next figure presents the stress gradient resulted from the force applied, Figure 58. It is possible to visualize that the maximum stress obtained (0,8742 MPa) is lower than the tensile strength of PLA (105 MPa), which allows to conclude that the model resists the application of the necessary forces.

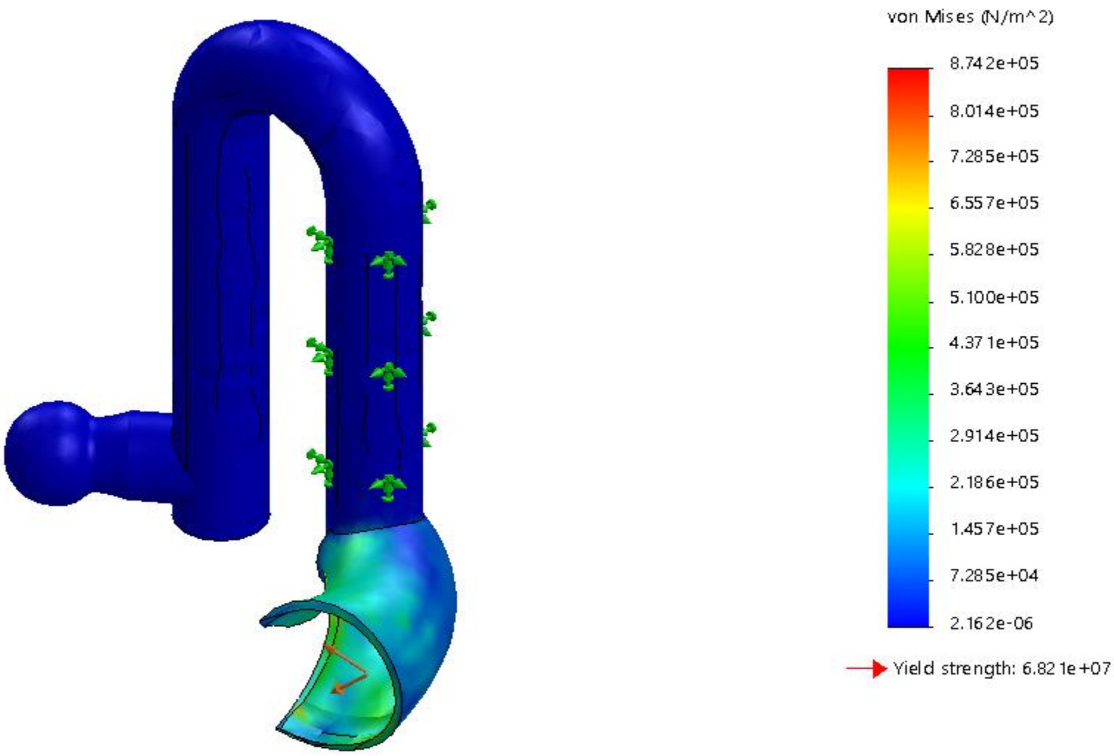

Figure 58. Stress gradient of the zigzag with the optimum bandwidth (0,9127 mm) resulted from the applied force.

3. 3D Printing

The last step consists in 3D printing of the developed models. For that, it was used an FDM 3D printer and three different types of PLA (non-biocompatible) with a diameter of 1,75mm: a Premium PLA from FormFutura, a normal PLA from BQ and a SOFT PLA-Flex from Filament2Print. The Premium PLA is a slightly harder PLA with higher thermal stability and faster crystallization process of the 3D printed layers. The SOFT PLA-Flex is a flexible filament with a strong resilience and tear resistance, high inter-layer adhesion, low friction coefficient, and high thermostability. The main physical, mechanical and thermal properties of these types of PLA are presented in Table 6. In Table 7, the 3D printing settings used for all models are also presented.

Table 6. Main characteristics of the used types of PLA.

Properties	**Premium PLA**	**BQ PLA**	**SOFT PLA-Flex**
Density	1,24 g/cm^3	1,24 g/cm^3	1,25-1,27 g/cm^3
Melt flow rate	6,0 g/10 min	-	2,7-4,9 g/10 min
Tensile strength	105 MPa	50 MPa	35-44 MPa
Tensile modulus	3145 MPa	1230 MPa	-
Elongation at break	175%	9%	560-710%
Flexural strength	±54,4 MPa	108 MPa	-
Flexural modulus	±2364,3 MPa	3600 MPa	-
Print temperature	±190-225ºC	±200-220ºC	±215-230ºC
Melting temperature	±210±10ºC	±145-160ºC	±175ºC

Table 7. Main settings of 3D printing.

Properties	Values
Layer height	0,16 mm
Perimeters	2
Solid layers	3 (Top and Bottom)
Infill density	20%
Infill angle	45º (cross type)
Infill pattern	Rectilinear
Support material	The same used for the model
Cooling	Fan ON (50%) from the 2nd layer
Bed temperature (all layers)	45ºC
Extruder temperature (all layers)	205ºC
Nozzle Diameter	0,4 mm

The Model 1 dimensions are the ones used in commercial stents. However, once the technology does not allow yet printing such small dimensions with a sufficient accuracy, this model got a scale adaption of 10/3. Then, it was vertically printed with supports using PLA from BQ and only one wire was printed, whose diameter was 2,00 cm and the height 1,80 cm. After its printing, this model, which can be visualized in Figure 59, showed poor quality and it was very fragile due to its very thin components, so it broke soon after. Therefore, it was the model with the smallest scale and the most fragile one too.

Figure 59. The printed Model 1.

The Model 2 dimensions are also the ones used in commercial stents and, for the same reason than the previous one, this model suffered a scale adaption of 25/2. The Model 2 was performed into a plane to be horizontally printed (in order to not use support) and then it was welded at the lateral ends to close the stent. Three wires were printed using a BQ PLA and its printed dimensions were a diameter of 2,50 cm and a height of 7,10 cm (Figure 60). Thus, it provided higher resistance than the first one, but it was still very fragile at the welded parts, as it can be seen in Figure 61.

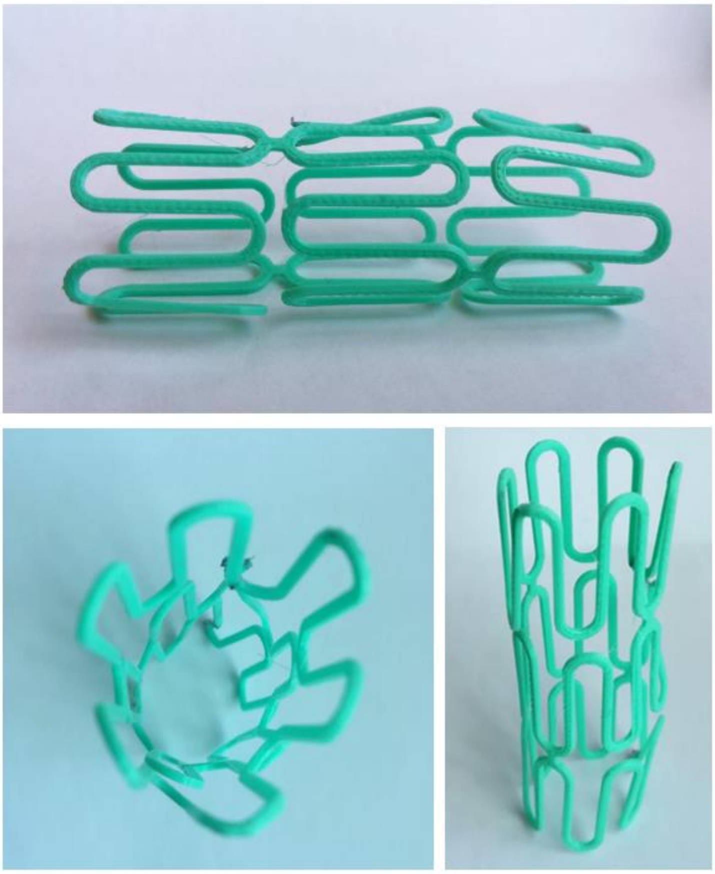

Figure 60. The printed Model 2 using BQ PLA.

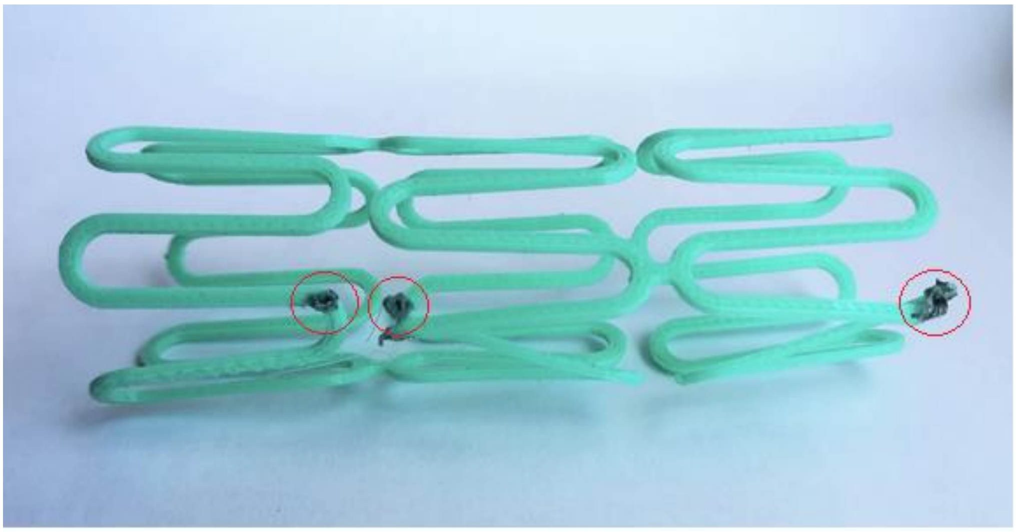

Figure 61. Welded parts surrounded.

Then, the Model 2 was printed again, but only two wires with four zigzags in each. It was used the SOFT PLA-Flex and the resulted model is presented in Figure 62. This structure was more resistant than the previous one, but it was too flexible, so if a balloon were blown inside of it, the stent would not hold the required shape.

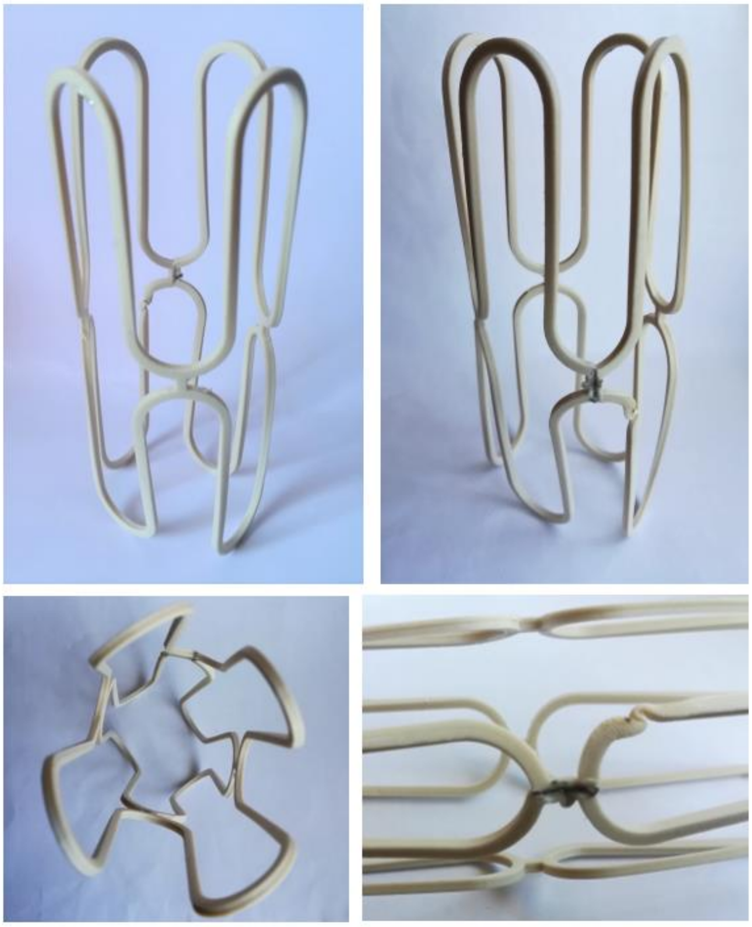

Figure 62. The printed Model 2 using SOFT PLA-Flex.

On the other hand, the Model 3 dimensions are too large when compared to the real stents' ones. Thus, for a diameter of 10 cm and a height of 12 cm, this model was printed with a scale of 43/50. It was printed vertically with support using the Premium PLA (as shown in Figure 63). Although the stent was very rigid and resistant, the first trial has not succeeded due to some design and printing issues, as it is shown in Figure 64. The thickness of cylinder was very thin, so its printing had low resolution. Additionally, it was applied the use of support material bellow the arch, which increased the printing time and material waste, and also the use of supports inside of the cylinder, which were not possible to be removed due to the small scale.

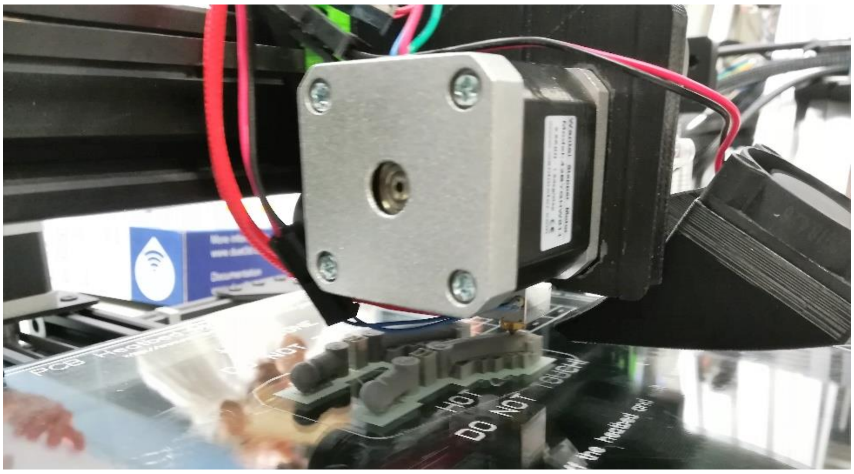

Figure 63. The 3D printing of the Model 3.

Figure 64. First printing of Model 3.

After this printing, the Model 3 was printed again vertically with support material using in all the necessary parts except inside of cylinder, using the Premium PLA. The dimensions were the same. This printing solved the majority of the previous issues, but the support material was still hardly removed in the cylinder fissure and the spherical component was not totally spherical, as can be shown in Figure 65.

Figure 65. Improved vertical printing of Model 3.

In order to improve the printed result, the Model 3, as well as the hook, were printed, but this time lying on the platform, as shown in Figure 66. This type of printing does not need the support material in the spherical component neither in the cylinder (fissure and hollow). Therefore, the previous issues were solved, as it is shown in Figure 67, and this type of printing seems to be better. Last, the hook has generally good quality, except for one of the sides that had low resolution thanks to the use of the same material to print and to support the model, and its printing can be analysed in Figure 68.

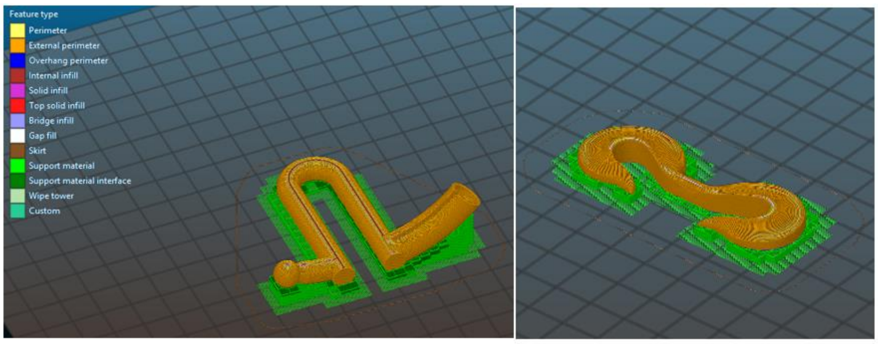

Figure 66. Preview of the Model 3 “lying on platform”-printing and the hook.

Figure 67. The printed Model 3 using the “lying on platform” printing.

Figure 68. The printed hook.

As the printing presented positive characteristics (high resistance, stability and finishing quality), the Model 3 was assembled, forming 2 wires of 6 zigzags each one. Both wires were connected by 6 hooks, as shown in Figure 69. This type of geometry had low stability in the indent connectors, so it is not possible to ensure its *in vivo* function. The zigzag wires connectors detached easily, disrupting its structural stability.

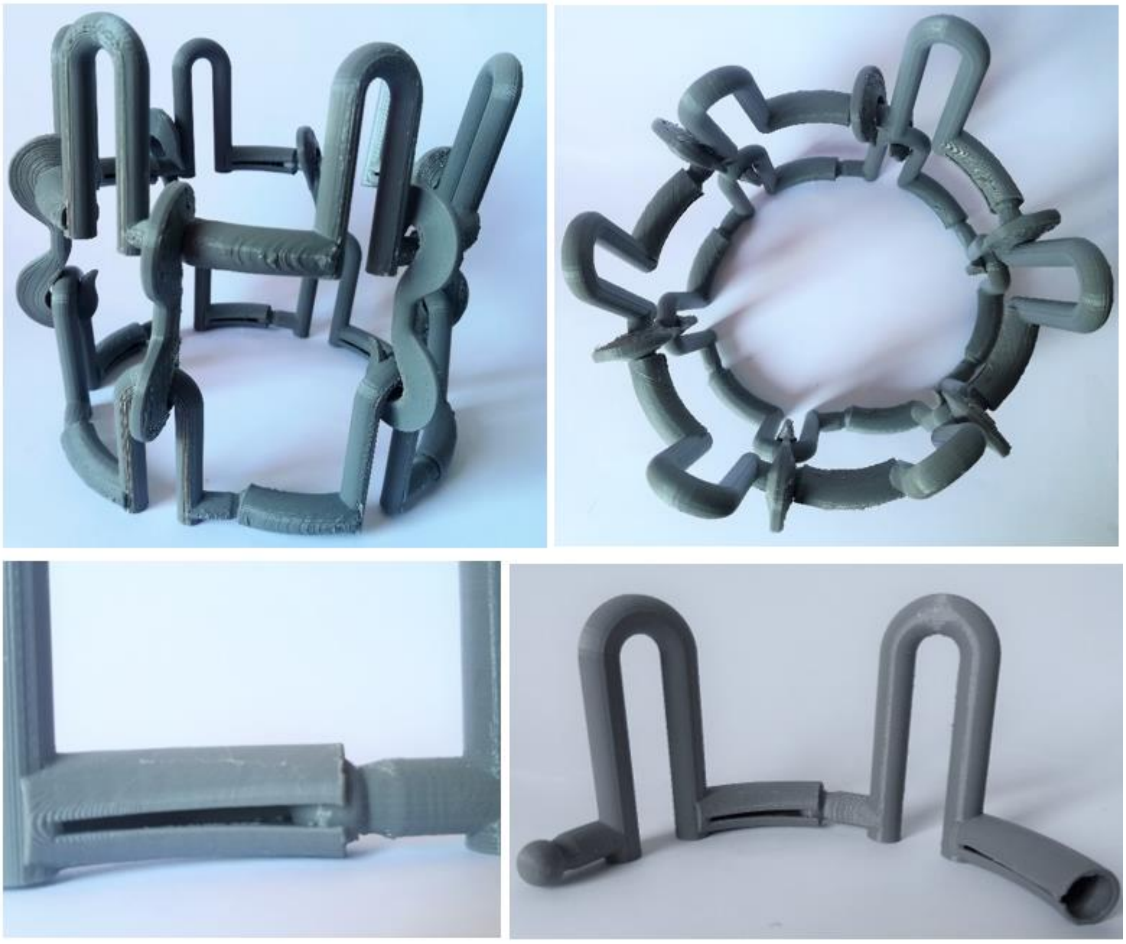

Figure 69. The Model 3 assembly.

In order to improve the assembly, Model 4 was also printed with a scale of 43/50 and it was printed “lying on the platform” using the Premium PLA and the dimensions were the same as the previous one. This model was the most successful one, because it solved all the previous issues (such as stability, resistance, finishing quality) and it is simpler than the Model 3. The printed components are shown in Figure 70. Thus, the assembly of it, forming 2 wires of 5 zigzags each one, showed higher stability at the connection components, so it is a very stable geometry, and it can be visualized in Figure 71.

Figure 70. The printed Model 4.

Figure 71. The Model 4 assembly.

However, the material used is very resistant and rigid, so it is not possible to expand to a balloon insufflation at this scale. Also, the used PLA was not biocompatible, and the printing scale was much higher than the medical stents for human purpose. Although this study was short and had these limitations, when compared to the traditional method, it consisted of a pioneering study to provide the possibility to customized biostructures (such as stents) in a low-cost perspective. In the future, with the advancement of technology, particularly 3D printers and PLA, 3D printing for the development of customized stents using the FDM technique for small scales with PLA will be possible.

Chapter 4

Conclusion

Currently, cardiovascular problems are one of the main factors of death worldwide, and these are mainly due to the formation of atherosclerotic plaques in the blood vessels. Thus, one of the most common treatments are stents, which are endovascular biodevices that enlarge the vessels so the blood can circulate. Traditional methods of manufacturing are still the only commercial techniques used to produce stents. However, these techniques are high-cost and do not enable the possibility to customize the device for each patient. Therefore, over the years, there was an increase demand for alternative techniques, such as additive manufacturing. There are currently several AM techniques, including fused deposition modeling, which is the most popular extrusion technique and it has been expanding for broad applications in the field of biomedical engineering, such as the development of personalized and functional medical devices. This technique has several advantages over traditional manufacturing techniques such as customization, almost total freedom in manufacturing and also low-cost. Moreover, during the development of a biodevice it is necessary to analyse its mechanical performance, so the perform of the finite element method presented itself as more flexible, faster, less expensive and less invasive than the traditional analysis.

Therefore, this work seeks to present the AM as the solution for stent manufacturing, proposing the production of stents by fused deposition modeling using polylactic acid, a biocompatible and low-cost material. Thus, in this work, it was presented the state of art of the additive manufacturing, as well as their techniques, obstacles and innovations. Furthermore, it was also developed, tested numerically and produced different types of stents, so all the goals proposed were achieved.

About the stents design, four different geometries were developed in order to test which one performs better. The model 1 is one of the most popular geometries, characterized by ten wires, each formed in twenty-one zigzags and the wires were connected at the crown points to complete the stent. This geometry was easy to be developed since it was based on the pre-existing stents. The model 2 is similar to the previous one, but it was composed by ten wires, each one formed in six zigzags. This model is less compacted than the previous one because it has less zigzags. This type is also frequently used for medical use, so the design was also based on pre-existing stents available in literature. After these geometries, the model 3 was developed and it is an indent connection model, which consisted of wires formed in six zigzags bonded at their indent connectors and, to connect each wire, a hook was developed. This geometry is new, so it was developed in such way to be more resistant to the 3D printing than the previous ones. Last, it was developed the model 4, which is a cylindrical grip model composed of wires formed in five zigzag that are bonded by a cylindric connectors and also, to connect each wire, it was used the hook previous developed. This model is also innovative, and it was developed in order to be more easily fixed and stable to the printing and to the assembly.

For the model 3, it was necessary to perform a biomechanical simulation to analyse the stent assembly behaviour and the best bandwidth/force correlation to print the stent. For that, it was used the finite element method. Firstly, it was measured the opening dimension required for the wire to fit into the hook, which value is 0,2864 mm. Then, it was applied different values of a distributed force on the inner surface of the hook to analyse how much the hook has opened and also the resulted stress. This procedure served to analyse what value of force was required for the zigzag component to get into the narrower component of the hook. Also, the maximum stress was compared to the ultimate stress of the used PLA to find out if the hook would resist to the connection, which was succeeded. Posteriorly, it was measured the opening required for the spherical component to fit into the cylinder of the wire, and what was the value of the necessary force to this assembly. Therefore, the minimum force necessary was obtained and the maximum stress obtained was compared to the ultimate stress of the used PLA to find out if the cylinder would resist to the connection. As a result, the component would resist to the applied forces and the minimum force was resulted from a bandwidth of 0,9127 mm, which was the value used in 3D printing.

Related to 3D printing, it was used an FDM 3D printer and three different types of PLA to test the differences. For the 3D printing of model 1, it was applied a scale of 10/3, because the technology does not allow yet printing such small dimensions with a sufficient accuracy. This model was vertically printed with supports and with normal PLA and it presented poor quality and the higher fragility due to its very thin components, so it broke soon after. The model 2 was also printed with a scale of 25/2 and with normal PLA and it was performed into a plane to be horizontally printed and then it was welded at the lateral ends to close the stent. This time of printing provided the non-use of support materials and higher resistance than the first one, but it was still very fragile at the welded parts. This model was printed again but with flexible PLA, which resulted in more resistance but very high flexibility, so if a balloon were blown inside of it, the stent would not hold the required shape. On the other hand, the model 3 was printed with a scale of 43/50 and with supports using the Premium PLA. The first trial was vertically printed, and it was very rigid and resistant. However, it had very thin walls of cylinder. Also, the use of support material bellow the arch increased the printing time and material waste, and also the use of supports inside of the cylinder precluded the supports removal. Therefore, the second printing was again vertically with support material used in all the necessary parts except inside of cylinder, which solved most of the previous issues, but the support material was still hardly removed in the cylinder fissure and the spherical component was not totally spherical. Thus, this model was printed again lying on the platform, which enables the non-use of support material in the spherical component neither in the cylinder (fissure and hollow). Nevertheless, this geometry had low stability in the indent connectors and the zigzag wires connectors detached easily, disrupting its structural stability. Last, model 4 was also printed with a scale of 86% and it was printed "lying on the platform" using the Premium PLA. This model was the one with highest stability, resistance, finishing quality and the simplest one.

The proposed methodology is a very simple and basic method, with a low-cost and customized purpose. Thus, this study was a very compact and short research, so in the future it should be performed more numerical analysis in all the models and biomechanical analysis too. It has also to be used a biocompatible PLA and to test these stents *in vivo* to analyse how they would perform in a human body. In addition, the material used is very resistant and rigid, so it is not possible to expand by inflating a balloon. Also, the PLA used is not biocompatible and the printing scale was much higher than commercial medical stents for humans.

On the other hand, in recent years, there has been an exponential development of 3D printing. Thus, this technology is expected to have a promising future and the ability to produce functional products. In the future, with the advancement of technology, particularly 3D printers and PLA, 3D printing for the development of customized stents using the FDM technique for small scales with PLA may be possible. So, this study consisted of a pioneering study to provide the possibility of customized biostructures (such as stents) from a low-cost perspective using such an innovative technology that is 3D printing. During the development of this work, the author was capable to publish 1 paper in indexed international journal IEEE-Xplore [94] and 4 works in international and national conferences.

References

1. Bonsignore, C., *Open stent design*. ed: Fermont, CA: Nitinol Devices and Components, Inc, 2011.
2. Gibson, I., D. Rosen, and B. Stucker, *Development of additive manufacturing technology*, in *Additive manufacturing technologies*. 2015, Springer. p. 19-42.
3. Relvas, C., *O Mundo da Impressão 3D e o Fabrico Digital*, ed. Engebook. 2018.
4. Mahamood, R.M., et al., *Revolutionary additive manufacturing: an overview*. 2014.
5. Mello, C.H.P., C.d. Silva, and S.d. COSTA, *Comparação de três diferentes tecnologias de prototipagem rápida em relação a critérios de custo e tempo*. XXVI ENEGEP, 2006.
6. Berman, B., *3-D printing: The new industrial revolution*. Business horizons, 2012. **55**(2): p. 155-162.
7. BeeVeryCreative. *3D Printers*. 2018 20/01/2018]; Available from: https://beeverycreative.com/3d-printers/.
8. Gkartzou, E., E.P. Koumoulos, and C.A. Charitidis, *Production and 3D printing processing of bio-based thermoplastic filament*. Manufacturing Review, 2017. **4**: p. 1.
9. Regadas, J.J.L.M., *Otimização de uma impressora 3D Delta e desenvolvimento da impressão simultânea de 3 cores*. 2017.
10. Beginners, D.P.f. *Learn How to 3D Print*. 2016 18/01/2018]; Available from: http://3dprintingforbeginners.com/.
11. Araújo, R.d., *Desenvolvimento e avaliação de geometrias de stents cardiovasculares considerando parâmetros mecânicos e de implantação*. 2016.
12. ManufacturingGuide. *Fused Deposition Modeling, FDM*. 2016 21/01/2018]; Available from: https://www.manufacturingguide.com/en/fused-deposition-modeling-fdm.
13. Abreu, S.A.C., *Impressão 3D baixo custo versus impressão em equipamentos de elevado custo*. 2015.
14. Stratasys. *Objet1000 Plus*. 2019 20/01/2019]; Available from: https://www.stratasys.com/3d-printers/objet1000-plus
15. Makerbot. *The MakerBot Replicator MINI+* 2019 20/01/2019]; Available from: https://www.makerbot.com/3d-printers/replicator-mini/.
16. Pandilov, Z. and V. Dukovski, *COMPARISON OF THE CHARACTERISTICS BETWEEN SERIAL AND PARALLEL ROBOTS*. Acta Technica Corvininesis-Bulletin of Engineering, 2014. **7**(1).
17. Bell, C., *3D Printing with Delta Printers*. 2015: Apress.
18. Dumas, J., J. Hergel, and S. Lefebvre, *Bridging the gap: automated steady scaffoldings for 3D printing*. ACM Transactions on Graphics (TOG), 2014. **33**(4): p. 98.
19. Ferreira, I.A., *Impressão tridimensional de baixo custo aplicada à pasta de açúcar*. 2015.
20. Abreu, J.T.F., *Desenvolvimento de uma Impressora FDM tipo Delta*. 2017.

21. RepRap. *Fab@Home*. 2014 17/01/2019]; Available from: https://reprap.org/wiki/Fab@Home.
22. Ligon, S.C., et al., *Polymers for 3D printing and customized additive manufacturing*. Chemical reviews, 2017. **117**(15): p. 10212-10290.
23. Xiao, K., et al., *Developing a 3D colour image reproduction system for additive manufacturing of facial prostheses*. The International Journal of Advanced Manufacturing Technology, 2014. **70**(9-12): p. 2043-2049.
24. RepRap. *Darwin/AssemblingDarwinElectronics*. 2013 12/01/2019]; Available from: https://reprap.org/wiki/Darwin/AssemblingDarwinElectronics.
25. Go, J. and A.J. Hart, *A framework for teaching the fundamentals of additive manufacturing and enabling rapid innovation*. Additive Manufacturing, 2016. **10**: p. 76-87.
26. Al-Ahmari, A., et al. *Patient specific mandibular implant for maxillofacial surgery using additive manufacturing*. in *Industrial Engineering and Operations Management (IEOM), 2015 International Conference on*. 2015. IEEE.
27. Wohlers, T., *Wohlers report 2016*. 2016: Wohlers Associates, Inc.
28. Pinkerton, A.J., *Lasers in additive manufacturing*. Optics & Laser Technology, 2016. **78**: p. 25-32.
29. Ferreira, J., et al. *Desenvolvimento integrado de produtos e ferramentas por metodologias de engenharia inversa e prototipagem rápida*. in *3º Congresso Brasileiro de Gestão de Desenvolvimento de Produto, Florianópolis*. 2001.
30. Steenhuis, H.-J. and L. Pretorius, *The additive manufacturing innovation: a range of implications*. Journal of Manufacturing Technology Management, 2017. **28**(1): p. 122-143.
31. Brajlih, T., et al., *Speed and accuracy evaluation of additive manufacturing machines*. Rapid prototyping journal, 2011. **17**(1): p. 64-75.
32. Petrovic, V., et al., *Additive manufacturing solutions for improved medical implants*, in *Biomedicine*. 2012, InTech.
33. Standard, A., *F2792-12a*. Standard terminology for additive manufacturing technologies ASTM International, West Conshohocken, 2012.
34. Jesus Faria, A.S.T., *Additive manufacturing of custom-fit orthoses for the upper limb*. 2017.
35. Silva, A.F.B.M., *Impressora FDM tipo Delta: estudo de impressão de cor e comparação de propriedades*. 2018.
36. Chua, C.K. and K.F. Leong, *3D Printing and Additive Manufacturing: Principles and ApplicationsFifth Edition of Rapid Prototyping Fivth Edition*. 2016: World Scientific Publishing Company.
37. Morgan, A.J., et al., *Simple and versatile 3D printed microfluidics using fused filament fabrication*. PloS one, 2016. **11**(4): p. e0152023.
38. Goyanes, A., et al., *Fused-filament 3D printing (3DP) for fabrication of tablets*. International journal of pharmaceutics, 2014. **476**(1-2): p. 88-92.
39. Kotlinski, J., *Mechanical properties of commercial rapid prototyping materials*. Rapid Prototyping Journal, 2014. **20**(6): p. 499-510.
40. Drummer, D., S. Cifuentes-Cuéllar, and D. Rietzel, *Suitability of PLA/TCP for fused deposition modeling*. Rapid Prototyping Journal, 2012. **18**(6): p. 500-507.

41. Zhang, B., et al., *3D printing of high-resolution PLA-based structures by hybrid electrohydrodynamic and fused deposition modeling techniques*. Journal of Micromechanics and Microengineering, 2016. **26**(2): p. 025015.
42. Chacón, J., et al., *Additive manufacturing of PLA structures using fused deposition modelling: Effect of process parameters on mechanical properties and their optimal selection*. Materials & Design, 2017. **124**: p. 143-157.
43. Salmi, M., et al., *Patient-specific reconstruction with 3D modeling and DMLS additive manufacturing*. Rapid Prototyping Journal, 2012. **18**(3): p. 209-214.
44. Ciurana, J., L. Serenóa, and È. Vallès, *Selecting process parameters in RepRap additive manufacturing system for PLA scaffolds manufacture*. Procedia Cirp, 2013. **5**: p. 152-157.
45. Bellini, A., *Fused deposition of ceramics: a comprehensive experimental, analytical and computational study of material behavior, fabrication process and equipment design*. 2002.
46. Sun, Q., et al., *Effect of processing conditions on the bonding quality of FDM polymer filaments*. Rapid Prototyping Journal, 2008. **14**(2): p. 72-80.
47. Sood, A.K., R.K. Ohdar, and S.S. Mahapatra, *Parametric appraisal of mechanical property of fused deposition modelling processed parts*. Materials & Design, 2010. **31**(1): p. 287-295.
48. Bellini, A. and S. Güçeri, *Mechanical characterization of parts fabricated using fused deposition modeling*. Rapid Prototyping Journal, 2003. **9**(4): p. 252-264.
49. Allen, S. and D. Dutta, *Determination and evaluation of support structures in layered manufacturing*. Journal of Design and Manufacturing, 1995. **5**: p. 153-162.
50. Chalsani, K., L. Jones, and L. Roscoe. *Support generation for fused deposition modeling*. in *1995 International Solid Freeform Fabrication Symposium*. 1995.
51. Alexander, P., S. Allen, and D. Dutta, *Part orientation and build cost determination in layered manufacturing*. Computer-Aided Design, 1998. **30**(5): p. 343-356.
52. Frank, D. and G. Fadel, *Expert system-based selection of the preferred direction of build for rapid prototyping processes*. Journal of Intelligent Manufacturing, 1995. **6**(5): p. 339-345.
53. Cheng, W., et al., *Multi-objective optimization of part-building orientation in stereolithography*. Rapid Prototyping Journal, 1995. **1**(4): p. 12-23.
54. Majhi, J., et al., *On some geometric optimization problems in layered manufacturing*. Computational Geometry, 1999. **12**(3-4): p. 219-239.
55. Wang, W., et al., *Cost-effective printing of 3D objects with skin-frame structures*. ACM Transactions on Graphics (TOG), 2013. **32**(6): p. 177.
56. Takagishi, K. and S. Umezu, *Development of the improving process for the 3D printed structure*. Scientific reports, 2017. **7**: p. 39852.
57. Koff, W. and P. Gustafson. *3D Printing and the Future of Manufacturing*. in *CSC Leading Edge Forum*. 2012.
58. González, S.G., *Impresión 3D*. 2016: Marcombo.
59. Canessa, E., et al., *Low-cost 3D printing*. ICTP—The Abdus Salam International Centre for Theoretical Physics, 2013.
60. Farah, S., D.G. Anderson, and R. Langer, *Physical and mechanical properties of PLA, and their functions in widespread applications—A comprehensive review*. Advanced drug delivery reviews, 2016. **107**: p. 367-392.

61. Pan, A., et al., *Effect of FDM Process on Adhesive Strength of Polylactic Acid (PLA) Filament*. Key Engineering Materials, 2016. **667**.
62. Ning, F., et al. *Additive manufacturing of CFRP composites using fused deposition modeling: effects of process parameters*. in *ASME 2016 11th International Manufacturing Science and Engineering Conference*. 2016. American Society of Mechanical Engineers.
63. Filament2print. *Filamentos*. 2016 25/01/2019]; Available from: https://filament2print.com/pt/179-filamentos.
64. Formfutura. *Products*. 2018 20/01/2019]; Available from: https://www.formfutura.com/page/products.
65. Jardini, A.L., et al., *Cranial reconstruction: 3D biomodel and custom-built implant created using additive manufacturing*. Journal of Cranio-Maxillofacial Surgery, 2014. **42**(8): p. 1877-1884.
66. Unwin, P. *Fabricating specialised orthopaedic implants using additive manufacturing*. in *Laser 3D Manufacturing*. 2014. International Society for Optics and Photonics.
67. Beer, N. and A. van der Merwe, *Patient-specific intervertebral disc implants using rapid manufacturing technology*. Rapid Prototyping Journal, 2013. **19**(2): p. 126-139.
68. Sutradhar, A., et al., *Experimental validation of 3D printed patient-specific implants using digital image correlation and finite element analysis*. Computers in biology and medicine, 2014. **52**: p. 8-17.
69. Lathers, S. and J. La Belle, *Advanced Manufactured Fused Filament Fabrication 3D Printed Osseointegrated Prosthesis for a Transhumeral Amputation Using Taulman 680 FDA*. 3D Printing and Additive Manufacturing, 2016. **3**(3): p. 166-174.
70. Belter, J.T. and A.M. Dollar, *Strengthening of 3D printed fused deposition manufactured parts using the fill compositing technique*. PloS one, 2015. **10**(4): p. e0122915.
71. Singamneni, S., et al., *Modeling and evaluation of curved layer fused deposition*. Journal of Materials Processing Technology, 2012. **212**(1): p. 27-35.
72. Muthu, S.S. and S.M. Mahesh, *Carbon Footprint Assessment of Additive Manufacturing: Flat and Curved Layer-by-Layer Approaches*, in *Handbook of Sustainability in Additive Manufacturing*. 2016, Springer. p. 101-114.
73. Matsuzaki, R., et al., *Three-dimensional printing of continuous-fiber composites by in-nozzle impregnation*. Scientific reports, 2016. **6**: p. 23058.
74. Kim, H., et al., *Experimental study on mechanical properties of single-and dual-material 3D printed products*. Procedia Manufacturing, 2017. **10**: p. 887-897.
75. Klabunde, R., *Cardiovascular physiology concepts*. 2011: Lippincott Williams & Wilkins.
76. Willerson, J.T., et al., *Cardiovascular medicine*. 2007: Springer Science & Business Media.
77. KC, D.R., *A comprehensive iterative design, simulation and finite element analysis of bare metal stent and diseased artery*. 2015, Wichita State University.
78. Raymond Llorens, S., *2D functionalized films and 3D direct printed patterned PLLA stents for cardiovascular applications*. 2016, Universitat Politècnica de Catalunya.
79. Gomes, I.V., et al. *Finite element analysis of stent expansion: Influence of stent geometry on performance parameters*. in *Bioengineering (ENBENG), 2017 IEEE 5th Portuguese Meeting on*. 2017. IEEE.

80. Eshghi, N., et al., *Finite element analysis of mechanical behaviors of coronary stent.* Procedia Engineering, 2011. **10**: p. 3056-3061.
81. Spranger, K., et al., *Comparison and calibration of a real-time virtual stenting algorithm using finite element analysis and genetic algorithms.* Computer methods in applied mechanics and engineering, 2015. **293**: p. 462-480.
82. Neves, J., et al., *Uso de stents no tratamento da coarctação da aorta.* Rev Bras Cardiol Invas, 2005. **13**(3): p. 153-66.
83. Perry, M., S. Oktay, and J. Muskivitch, *Finite element analysis and fatigue of stents.* Minimally Invasive Therapy & Allied Technologies, 2002. **11**(4): p. 165-171.
84. Colombo, A., G. Stankovic, and J.W. Moses, *Selection of coronary stents.* Journal of the American College of Cardiology, 2002. **40**(6): p. 1021-1033.
85. Salmon, S., et al., *Stent with self-expanding end sections*. 2006, Google Patents.
86. Stinson, J.S., *Cobalt-chromium-molybdenum alloy stent and stent-graft*. 1999, Google Patents.
87. Schievano, S., et al., *Finite element analysis of stent deployment: understanding stent fracture in percutaneous pulmonary valve implantation.* Journal of interventional cardiology, 2007. **20**(6): p. 546-554.
88. Kang, Y., *A Review of Self-Expanding Esophageal Stents for the Palliation Therapy of Inoperable Esophageal Malignancies.* BioMed research international, 2019. **2019**.
89. Araújo, R., et al., *SIMULAÇÃO DO PROCESSO DE EXPANSÃO DO STENT PARA ANGIOPLASTIA POR HIDROCONFORMAÇÃO.*
90. Wiebe, J., H.M. Nef, and C.W. Hamm, *Current status of bioresorbable scaffolds in the treatment of coronary artery disease.* Journal of the American College of Cardiology, 2014. **64**(23): p. 2541-2551.
91. Tamai, H., et al., *Initial and 6-month results of biodegradable poly-l-lactic acid coronary stents in humans.* Circulation, 2000. **102**(4): p. 399-404.
92. Soares, J.S., J.E. Moore Jr, and K.R. Rajagopal, *Constitutive framework for biodegradable polymers with applications to biodegradable stents.* Asaio Journal, 2008. **54**(3): p. 295-301.
93. Zhao, D., et al., *Experimental Study of Polymeric Stent Fabrication Using Homemade 3D Printing System*. Polymer Engineering & Science, 2019.
94. Malafaya, B.A., et al. *Additive Manufacturing from a Biomedical Perspective*. in *2019 IEEE 6th Portuguese Meeting on Bioengineering (ENBENG)*. 2019. IEEE.