POLITECNICO DI TORINO

Master Degree in Engineering and Management

Master's Degree Thesis

The adoption of Additive Manufacturing in the orthopaedic prostheses industry and its impact on firm performance

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Abstract

3D printing, belonging to the field of Additive Manufacturing (AM), has been defined by Financial Times and other important newspapers as being more powerful and more influential than the Internet. We do not know if this is true. What we are sure about, instead, is that it represents the next industrial revolution, whose focus is personal fabrication. 3D printing allows people to vent their potential to create and bring to reality what at first was impossible. In other words, this technology will change the world.

This thesis intends to give a complete picture about 3D printing and its economic implications.

In the first chapter, we deal with the history of 3D printing: we start from its invention, defining which are all the key aspects of the process. Then, attention will be moved to the technologies that have been developed during the years and which materials are involved in.

The second chapter is instead concerned about the economic aspect of 3D printing, understanding which are the costs related to the materials used, the economic models applied to the various technologies. More precisely, we try to figure out whether 3D printing has particular consequences on the existing manufacturing models. Lastly, the impact of 3D printing on the market will be studied, with respect to different sectors encompassing the 3D printing.

In the third chapter we set out to widen the horizon of Additive Manufacturing, trying to focus on the aspect of Intellectual Property and business ethics; more precisely, we will be analysing which are the main consequences of an open-source technology and the risks related to the fact of giving anybody the possibility of printing whatever they want to by using their own printer at their own home.

Finally, in the last chapter we examine in depth the 3D printing related to the medical industry, trying to analyze the most innovative breakthroughs made in these last years. We find how the limits of the traditional surgery are overcome by this technology which prints a unique piece, fully customized and at an affordable cost, entering de facto on the rise of this industry. Our research sets out to understand how the impact of 3D printing on the Healthcare sector.

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Nomenclature

3MF	3D Manufacturing Format
AM	Additive Manufacturing
AMF	Additive Manufacturing File
CAD	Computer Aided Design
CFL	Cubital Facet List
CLIP	Continuous Liquid Interface Production
CMM	Coordinate Measuring Machine
CNC	Computer Numerical Control
CT	Computer Tomography
CT	Nuclear Magnetic Resonance
DED	Direct Energy Deposition
DLP	Direct Light Processing
DMD	Direct Metal Deposition
DMLS	Direct Metal Laser Sintering
EBAM	Electron Beam Additive Manufacturing
EBM	Electron Beam Melting
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
JT	Jupiter Tessellation
LBL	Layer By Layer

LENS	Laser Engineered Net Shaping
LOM	Laminated Object Manufacturing
PBF	Powder Bed Fusion
RP	Rapid Prototyping
SHS	Selective Heat Sintering
SL	Sheet Lamination
SLA	Stereolithographic Apparatus
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
STEP	Standard for the Exchange of Product
STH	Surface Triangles Hinted
STL	Standard Triangulation Language
UAM	Ultrasonic Additive Manufacturing
XML	eXtensible Markup Language

Chapter 1

The technological scenario

1.1 Introduction

3D printing is the fabrication of objects through the deposition of a material by using a print head, nozzle, or another printer technology. The term is often used synonymously with Additive Manufacturing (AM), even if it is just one of the several processes belonging to the field of AM, defined as a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Other synonyms are “Additive Fabrication”, “Additive Processes”, “Additive Techniques”, “Additive Layer Manufacturing” and “Freeform Fabrication”.

Anyway, despite all these definitions, 3D printing is the one to get the "gold medal", as a figure of speech, becoming the de facto standard term. As a proof, we could mention a Google search dating back to March 30th, 2015, which produced 4.6 million results after entering the term *Additive Manufacturing* and 89.1 million results by entering *3D printing*.

Nowadays we distinguish among seven main processes in the field of Additive Manufacturing, used to build physical models, prototypes, patterns tooling components and production parts: Power Bed Fusion, Vat Photopolymerization, Binder Jetting, Material Extrusion, Directed Energy Deposition, Material Jetting and Sheet Lamination. The materials employed include plastics, metal, ceramics and composites. Moreover, those seven processes deal with variations on the layered 3D printing concept; in fact, all the characteristics concerning the material state (powder, liquid, filament), heat, light sources (thermal, electron beam, laser, plasma arc), number of print axes, feed systems and the build chamber are all different among the processes.

Needless to say, Additive Manufacturing is definitively changing the way companies work, relying on it as a tool for rapid product development. After more than twenty years of research, development, testing and use, more and more industries are embracing AM technologies, and we expect they will keep growing in the future.

1.2 The invention of 3D printing

Although it could be hard to believe, 3D printing technology has its origins in the early 1980s. It all began with the rapid prototyping (RP), whose first attempts are attributed to Hideo Kodama of Nagoya Municipal Industrial Research Institute, who published the first report of a working photo-polymer rapid prototyping system, in 1981. The account described a manufacturing with a layer by layer approach: a photosensitive resin polymerized by an UV light; this anticipated what at a later time would have been classified as *Stereolithography* (SLA).

With the passing of the time, another important name became part of this history: Charles "Chuck" Hull. In the 80s he had been working as employee for a company that used UV light to put thin layers of plastic veneers on tabletops and furniture. It was a good job, even if he was upset about the fact that the production of small plastic parts could take up to two months, and it is a huge amount of time. Anyway, his dissatisfaction has been the starting point of an illumination: he thought that overlapping thousands of thin layers of plastic on top of each other and then engraving the shape by using light, there would have been the possibility to form 3D objects. And so he did, developing a system in which the light was shone into a vat of photopolymer (a material that turns from liquid into plastic-solid after being hit by light) and etched the shape of one level of the object, keeping it up this way until all the layers are printed.This technology was then patented with the name of "Apparatus for Production of Three-dimensional Objects by Stereolithography" in 1986. Later on, he founded the company 3D SYSTEMS with the aim of commercializing his invention. In fact, in 1988, he came up with his first machine, the SLA-1, which gave an important shock among automotive, aerospace and medical companies. Nevertheless, it was the SLA-250 the first model to be sold to the public.

In the same year, Scott Crump invented the *Fused Deposition Modeling* (FDM) technique, patenting it, and the year later (1989) he founded one of the most important existing AM companies, Stratasys. The first model based on this technique was the **3D Modeler**.

The 1988 saw the light of another important technology: *Selective Laser Sintering* (SLS), patented by Carl Deckard at the University of Texas. Its main feature consists of powder grains fused together locally by a laser. However, four years must pass before the startup DTM (today merged with 3D Systems), in 1992, produced the world's first SLS machine.

Time goes by, and another year worth mentioning is 1990, in which Electro Optical Systems (EOS) of Krailling, Germany, sold its first Stereos stereolithography system and Quadrax introduced the Mark 1000 SL System, featuring a visible light resin.

Two years later, in 1992, 3D Systems created the world's first Stereolithographic Apparatus (SLA) machine, which made it possible to produce complex parts, layer by layer, in a fraction of time it would normally take.

In 1997 EOS sold its business of stereolitography to 3D Systems, although it preserved the fame of being the greatest AM company in Europe.

In March of the same year, the World Technology Division (WTEC), which was formerly known as Japanese Technology Evaluation Center (JTEC), published a report titled *"Rapid Prototyping in Europe and Japan"*, reviewing the status of the capabilities of selected European countries and Japan in developing and implementing layered manufacturing technologies.

Almost ten years later, in 2005, Adrian Bowyer, a senior lecturer in Mechanical Engineering at Bath University (United Kingdom) gave life to the *RepRap Project*, which stands for *Replicating Rapid Prototyper.* It is worth mentioning because it is the first open-source project, oriented to the development of cheap and Do-It-Yourself (DIY) solutions for the hobby and domestic 3D printing, by using a variation of FDM technique.

The idea on the basis of this project is to give the printers the possibility to print their own parts necessary to make a working clone of the original printer; this way of acting, makes potentially obsolete the economies of scale logic in the field of goods production.

Later on, in 2006, on-demand manufacturing came to light for industrial parts: this constituted a great checkpoint for the AM, since we start to see different co-creation services, bringing to the birth of the easily accessible 3D marketplace. Finally, people could freely express their own creations, ideas, designs and share information with the others.

Another important character of this period was MakerBot, founded in 2009 by Bre Pettis, Adam Mayer and Zach Smith. The company was the first to provide the service of open-source DIY 3D printer kits, allowing people to learn all about this avant-guarde technology and build their own machines, at an affordable cost. This was the exact moment in which 3D printers became accessible to the general public.

Another company worth mentioning it Formlabs, founded in September 2011 by Maxim Lobovsky, Natan Linder and David Cranor. Their wish was to project and develop a 3D printer easy to use and at an affordable cost. And so they did. In fact, Formlabs has gone down in history for raising almost 3 million dollars in Kickstarter campaign, money then used to produce its first machine, the FORM 1 3D Printer; this was the first of a series of photopolymer-based desktop printers after the expiration of stereolithogaphy patents. Nevertheless, in November 2012 Formlabs was sued by 3D Systems for the use of that technology and then it settled patent litigation in exchange for 8% of net sales.

In conclusion, in order to have the whole picture, we may think that Charles Hull could not imagine how big it would get. Nowadays, people can print with other materials apart from plastics: metals, glass, paper, wood. The key, furthermore, is in being able to print anything you want to, or almost; musical instruments, jewels, clothes, homes, drones and even human body parts and food are today printed. In other words, it seems that limitations are none.

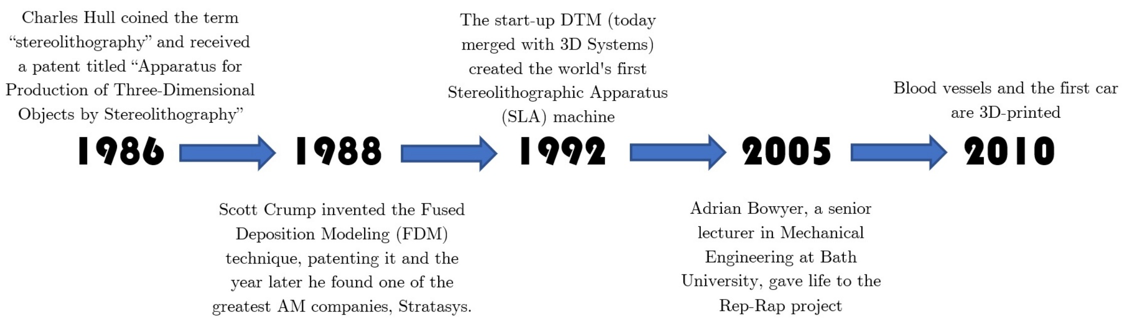

Figure 1.1: Timeline of the most important years in 3D printing history [66]

1.3 The process

Although there are many technologies regarding AM that we will be discussing onward, now we focus merely on the general process, from the design to the final part, which includes five many core steps: modelling of a 3D file, STL creation and file manipulation, printing, removal of prints and post processing.

1.3.1 Modeling of a 3D file

The first step in 3D printing process is producing a digital model. The most common method for doing this is *Computer Aided Design* (CAD), even if *Reverse Engineering* can be also used to generate a digital model via 3D scanning.

CAD software can be used to produce realistic models of parts and assemblies, which can then be used to test functions or to run simulations before any physical model is created, thus letting a faster and cheaper workflow. There are three main methods of CAD modeling: solid modeling, surface modeling and sculpting.

1.3.1.1 Solid Modeling

Solid modeling is the method that more gets closed to the traditional manufacturing, creating 3D models as if they are actual parts. We start with a solid block of material and then we get to the final shape by adding or removing sections and taking the advantage of operations like extrusion, cutting, sweeping and revolving.

This method presents itself also as a customized one: in fact, every change or parameters entered are saved at any stage of production, meaning that editing is allowable at any time during the design phase.

An important part of this method is the *assembly modeling*, using to handle multiple files that represent components within a product, that can be therefore be assembled together.

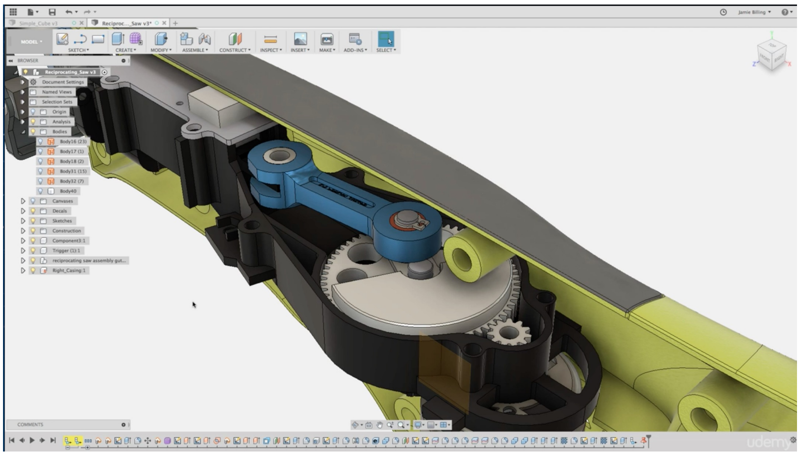

Figure 1.2: Solid Modeling [13]

1.3.1.2 Surface Modeling

When it comes to organic shapes, surface modeling turns to be the best approach to use. In fact, differently from solid modeling, whose procedure is baed on moves in three dimensions, the creation of organic curves is much easier with surface modeling. The method consists in placing a number of poles over a surface and then manipulate them in order to get the desired shape.

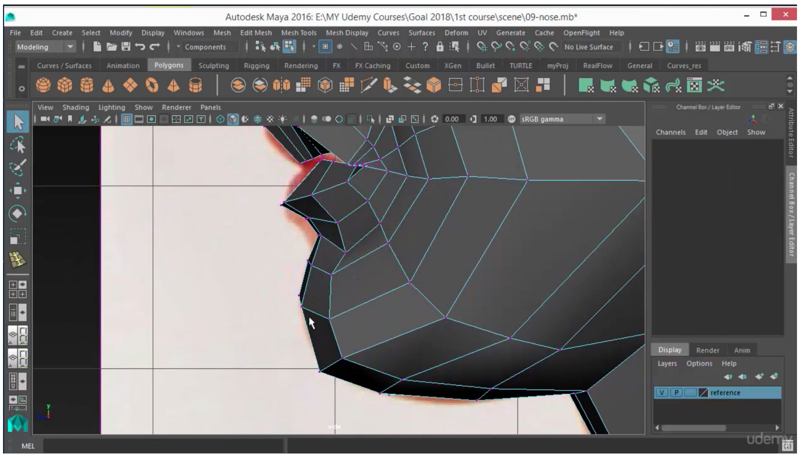

Figure 1.3: Surface Modeling [13]

However, the other side of the coin consists in lack of constraints, which can bring to problems related to accuracy. In fact, this method is not parametric as the solid modeling, and this can lead to difficulties if there is the willing to make changes.

1.3.1.3 Sculpting

Forms with a lot of details like jewels, trees, rocks or any other kind of organic shapes require the method of sculpting, also known as *organic modeling*.

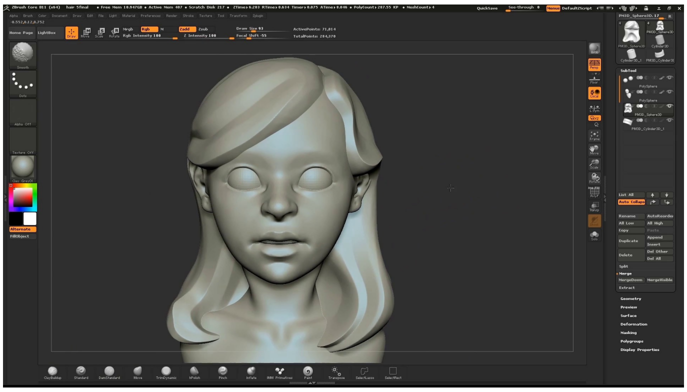

Figure 1.4: Sculpting [70]

Software used in this method allow users to start from the traditional ball of clay and then use a drawing tablet to realize the object desired. At the end, the process is completed with digital brushes that simulate classic tools as a scraper or thumbs in order to add or remove material.

Nowadays there are different CAD software programs available. They all are able to output OBJ and STL files, which approximate the shape of a part or assembles it using triangular facets that allow to have a higher surface quality, for 3D printing, or STEP and IGES files for CNC (Computer Numerical Control) manufacturing. Here are the most diffused software:

- Autodesk 3DS MAX: professional 3D computer graphics program for making 3D animations, models, games and images
- Autodesk AUTOCAD: used since 1982, AUTOCAD is used across a wide range of industries by architects, engineers, project managers and many other professionals
- Autodesk FUSION 360: it is similar to Solidworks, with the addition of integrated manufacturing sculpting tools. It is also available for free for students, hobbyists and startups
- Autodesk INVENTOR: one of the most popular programs available, offering professional 3D mechanical design, drawing and product simulation tools.
- Onshape: it is a full internet based CAD software package, making extensive use of cloud computing, processing and rendering with cloud-based servers
- PTC Creo: it is a suite of design software with a focus on product design for discrete manufacturers

- Rhinoceros: it is a multi-use program, useful for modelling free-form surfaces. Similar to Autodesk 3DS MAX but less powerful.
- Google SketchUp: very easy to use and entry-level software, it is employed for applications as architectural models and interior design.
- Solidworks: standard engineering software use for part and assembly modeling. It mainly includes simulation features, drawing and assembly tools.
- Solid Edge: it is used for solid and assembly modeling and 2D ortographic view functionality for mechanical designers.
- ZBrush: it is a digital sculpting tool that combines 3D/2.5D modeling, texturing and painting.

The potential of those modeling software lays in a wide range of applications: architects may use them to design buildings and landscapes, engineers to make sketchs or design cars, scientists to make detailed models of chemical compounds. Furthermore, 3D modelling it is even used for videogames and special effects in movies.

As mentioned above, reverse engineering is another way to generate 3D models. It concerns with the process of analysing existing parts or products in order to see how they are manufactured, usually by disassembling all the parts and then make use of computer digitalization to recreate all the parts as 3D files. There are two main categories that mark out reverse engineering:

- 3D Scanning: it is the process of studying the surface of a part to make a 3D model of its appearance with no having contact with it. After million of measurements, that is point by point, digital files are obtained. This approach, in turn, is divided into *Laser Scanning* and *CT Scanning*. The first consists in capturing data of an object in the form of points which then generate a 3D surface. Since there is no contact between the laser scanner and the surface of the object, this method best fits free-form surfaces of medium details. Furthermore, laser scanners can be handheld, fixed or mounted on robotic arms for a more accurate tracking.

  CT Scanning, instead, where CT stands for Computed Tomography, deals with X rays. The approach is simple: the object is placed on a turntable between an x-ray tube and a detector; as the object rotates 360 degrees, the detector captures x-ray images of it, acquiring the surface, dimensions and internal geometry. In the end, all those 2D images are subjected to an algorithm which creates a 3D volumetric model.

- Physical Measuring: it consists of measuring specific points on a component relative to a datum point in order to produce 3D model similar to the original object.

  This method distances itself from 3D scanning methods from the moment that it requires direct contact with the object and even because it presents itself to be a more accurate technique.

Figure 1.5: 3D laser scanning the geometry of a bridge [11]

Figure 1.6: A CT scan used as medical equipment [37]

As the 3D scanning, even Physical Measurement is separated into two other approaches: *Coordinate Measuring Machine (CMM)* and Manual Measurement. The first method deals with the use of a sensor to literally touch parts of an object in order to understand its characteristics, then registering digitally each touch point and then compare them against a 3D model, as shown in Figure 1.7.

In its most uses, CMM is used to verify the dimensions of parts rather than obtaining 3D files, but it potentially could. This is definitively the best approach to use if we are looking for accuracy.

Figure 1.7: An employer analysing the dimensions of an object by using CMM [9]

Manual Measuring, instead, as the name itself can let someone intend, consists in manually measuring features of parts of an object, recording each verification and then make the 3D file in CAD, as shown in Figure 1.8. Of course, the time needed is much more than the one requested in other methods, but the cost is pretty low.

1.3.2 File conversion and manipulation

Once the 3D file is completed, we have to give the printer the possibility to read that file, so the CAD model has to be converted in a format the printer is able to read; the format depends on the process technology taken into consideration. Here are the most important ones:

- STL Format: standing for Stereo Lithography Language, this format is the most used one. It consists on slicing the part in consideration and then stretching out horizontally the triangular facets, whose size indicates the layer thickness and the resolution; in fact, the more are the number facets (thus smaller their size), the greater is the resolution and the dimension of the file. During the years, alternatives

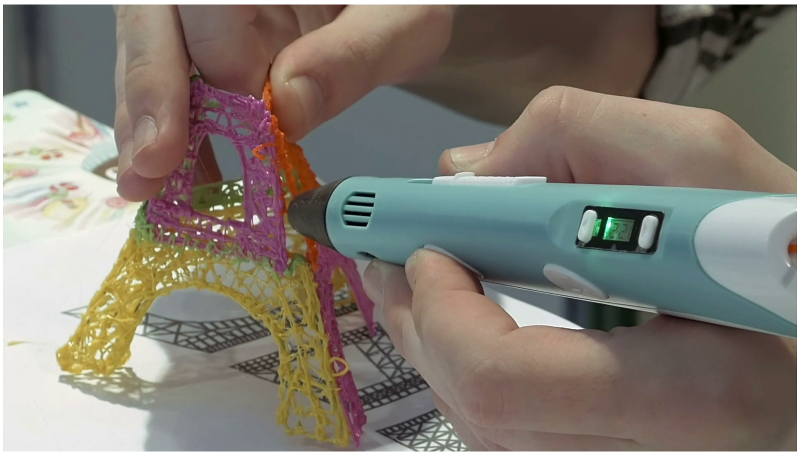

Figure 1.8: How Manual Measurement works [62]

to STL have been developed, as STH (Surface Triangles Hinted), CFL (Cubital Facet List) and RPI.

Once the conversion is done, the next step concerns in some final adjustments, made by specific algorithms.

- AMF Format: it stands for Additive Manufacturing File and it is a format specified in ISO/ASTM and it is a XML (eXtensible Markup Language). An important advantage of AMF over STL is that the triangles are curved and not planar and that there are embedded features, as colours and materials.

- STEP Format: Standard for the Exchange of Product model data. It is an exchange protocol embracing all the functionalities in manufacturing. For example, it can be used to slice an object using polyline or exact geometry.

- STEP NC Format: it is a machine tool language, considered as an extension of the previous STEP format, adding geometric dimension and tolerance data for inspection. Moreover, it also allows to use multiple materials.

- VOXEL BASED Format: it basically consists in discretizating (*"The process of transferring continuous functions, models, variables, and equations into discrete counterparts.", Wikipedia*)the volume. A voxel in a 3D space can be compared to a small unit cube centered in a point. In this format, features (colour, material) are represented through a scalar value associated to the voxel. Generally, the process of converting the CAD into a voxel model is called *voxelization*, even if it can also be obtainted by means of scanning a human body through Computerized Tomography (CT) or Nuclear Magnetic Resonance (NMR).

- 3MF Format: developed by the Consortium for AM application, the 3D Manufacturing Format is a file XML which embraces all the information regarding colours, materials and so on.

- JT Format: standing for Jupiter Tessellation, this is a standardized format employed for the product visualization and data exchange, this last thanks to its reduces size. The main advantage is that this format supports most of the commercial CAD 3D formats. Furthermore, this format embraces an high level of detail and exact geometry description.

As the STL file is generated, this is then imported in a program whose aim is to slice the design into layers than in second moment will be used to build the part. To do this, the program converts the STL file into G-code, which is a numerical control programming language used to control automated machines tools, as indeed a 3D printer.

Another important feature of this program is to provide the 3D printer operator all the parameters for the building, as support location, layer height and part orientation. Usually, AM companies create their own program, even if there are universal provider as Netfabb, Simplify3D and Slic3r, or add-ons for CAD software like Slicer for Autodesk Fusion 360 (see Figure 1.9).

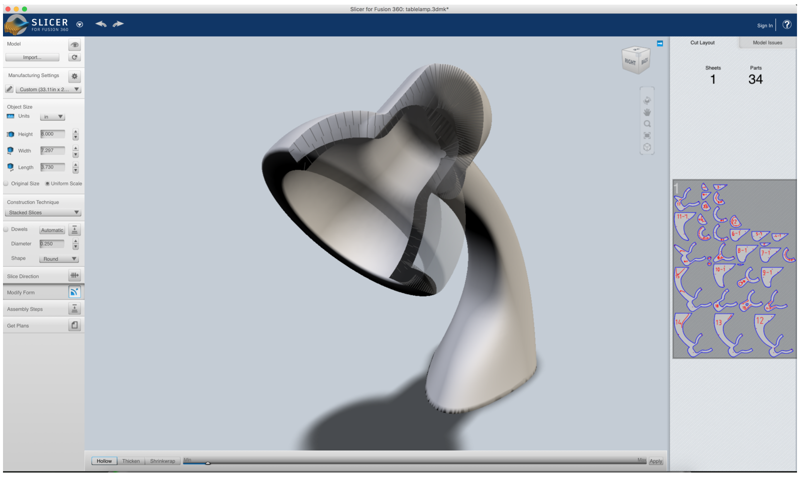

Figure 1.9: Slicer, a tool for Autodesk Fusion 360 [7]

1.3.3 Printing

In the actual phase of creation of the object, we should first set up the device. Each device, in fact, has its own prerequisites for how to use it for each new print, for example adding or refilling all the materials that the printer will use or adding a tray as a basis.

Later on, the process is mainly automatic: the printer will first read the .STL file and then will start to stretch out the layers of the selected material (liquid, powder or other materials we will be discussing about later) in order to realize the model through a series of horizontal sections. These ones, will be then merged or melted in order to obtain the object desired.

From a geometrical point of view, the thickness of layers is about 0,11 mm each, even if it can be thicker or thinner. Hanging on the size of the object, the machine and materials employed, the whole procedure might take hours or even days, thus, it is always recommended to check occasionally that there are no errors.

1.3.4 Removal of prints

This phase is different depending on the AM technology we are dealing with: for some, it simply consists in separating the printed part from the platform, as shown in Figure 1.10; for other technologies, it concerns a highly technical and accurate approach involving the extraction of the printed part while it is still mounted on the build material. Naturally, this operation can be executed only by highly skilled operators.

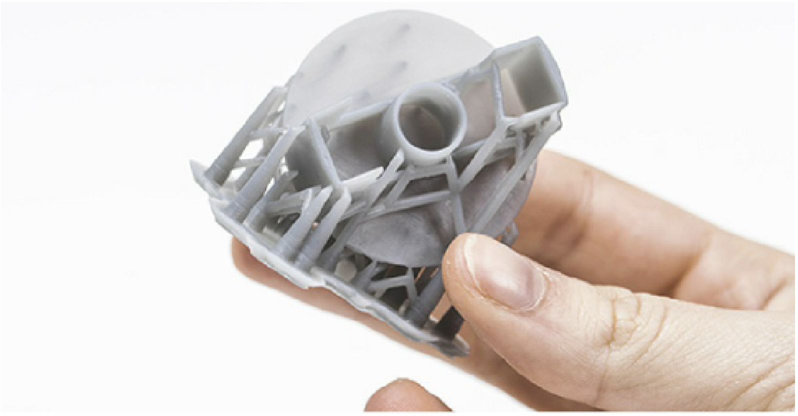

Figure 1.10: The shaft end cap after being removed from the build platform with support structures still attached [48]

1.3.5 Post processing

As the previous phase, also post processing procedures vary with the underlying AM technology: some of them require that a component has to be cured under UV before handling it while others do not; for technologies utilizing support, for example the water-soluble ones, this is removed during this phase.

The most common post processing approaches (i.e. Sanding, see Figure 1.11 below) will be analysed more accurately later, together with the discussion of the technologies of 3D printing.

Figure 1.11: Sanding, and example of Post Processing technique [33]

1.4 AM process types and related technologies

Considering the general process described in the previous section, we will now move our focus to the printing phase, in particular on the different technologies available nowadays on the market. As shown in the Figure 1.12 below, it is possible to choose among many kind of printing processes types that involve different materials and even sundry technologies. The selection of one of these technologies depends on which properties are needed, such as dimensional accuracy, surface finish and post processing requirements. However, until few years ago there was a lot of confusion about process names and material designations because in many cases these names where created by AM system manufacturers. For this reason, in 2015 was created the ISO/ASTM 52900 Standard in order to have a common terminology and a clear classification of the processes. A total of seven process categories were established, instead Inkjet-bioprinting has been developed successively and for this reason has not been categorized yet.

In the next section a detailed description about all the processes and technologies that goes under the AM umbrella will be provided.

1.4.1 Powder bed fusion

Powder bed fusion is an AM process type that involves the utilization of a thermal energy source to fuse selective regions of a powder bed. The thermal source hit a precise location inducing a fusion between the particles of the selected material, which then become solid as it cools. The principal producers of printer with powder bed fusion system are 3D Systems, EOS, SLM Solutions and ReaLizer for Selective Laser Melting, Arcam AB for Electron Beam Melting.

However, there are a lot of other companies that sell this technology such as Aspect (Japan), Beijing Long Yuan (China), Hunan Farsoon (China), Blueprinter (Denmark) that produce SHS printers and many others.

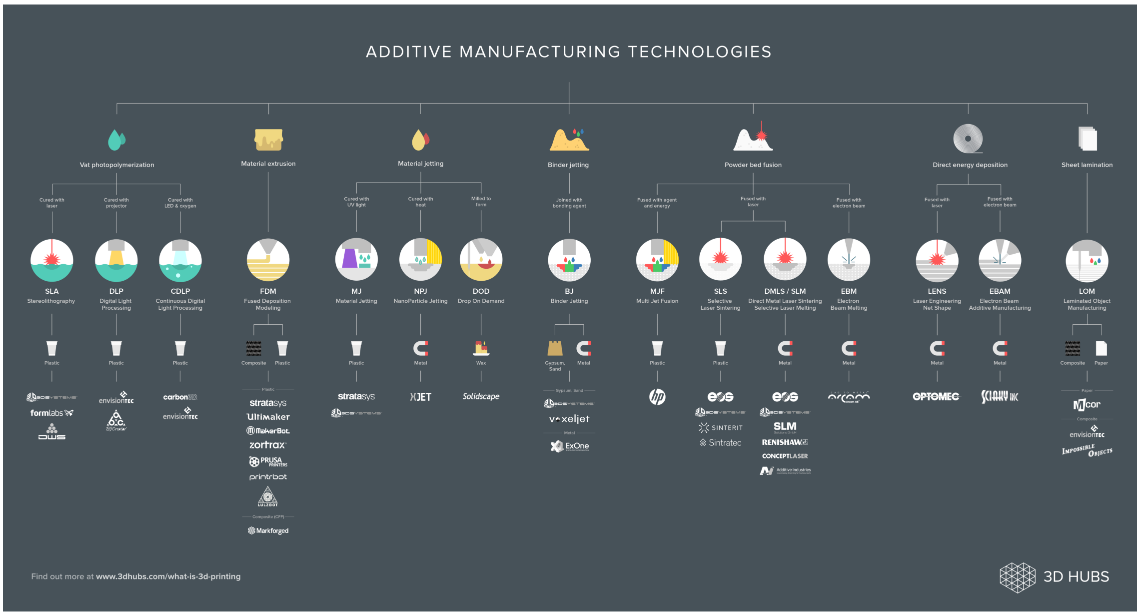

Figure 1.12: Map of all the existing AM processes and related technologies [1]

As reported in the Figure 1.12 above, for this kind of process are available both polymer and metal materials. For polymers it is possible to choose among two technologies : **Selective Laser Sintering** (SLS) and **Selective Heat Sintering** (SHS). For metals, instead, the available technologies are: **Direct Metal Laser Sintering** (DMLS) and **Electron Beam Melting** (EBM).

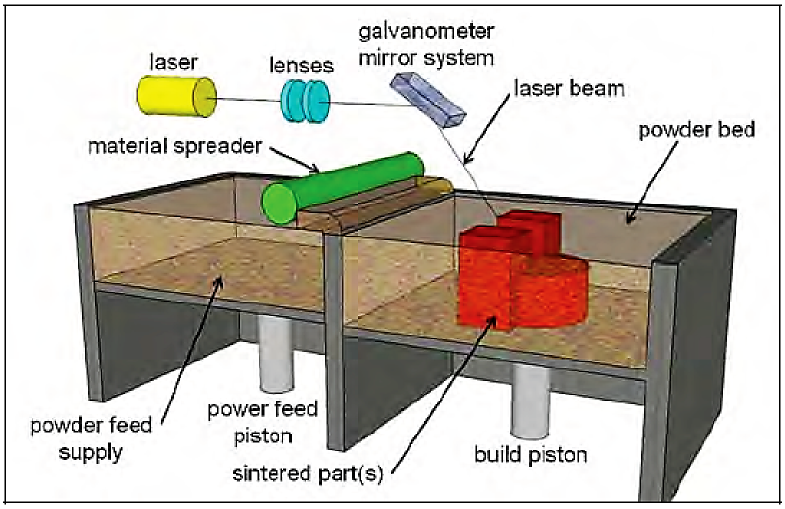

Figure 1.13: Powder bed fusion process [66]

1.4.1.1 Selective Laser Sintering

The Selective Laser Sintering technology was invented in the mid-1980s by the undergraduate student Carl R. Deckard and his professor Joe Beaman at the University of Texas at Austin. The SLS process starts heating the polymer powder in a bin until the temperature reached is a little bit less than the polymer melting point, in this way will be reduced the likelihood of parts warping and shrinking. The warm powder is then deposited layer-by-layer (generally 100 microns) using a roller in an iterative way after each cross-section has been selectively sintered and solidified from the powder bed layer. At the end of the printing process, once the parts in the building chamber have cooled down, the solid products is detached from the powder by means of air compressed or a blasting medium.

One of the greatest advantages in using this technology is that no additional support structures are needed thanks to the unsintered powder that remains in the building chamber. At the same time, this represent a disadvantage because it creates waste, since only the 50% of the unfused polymer powder is recyclable, even though it can be recycled a finite number of time. Thus because the powder in the building chamber degrades each time is exposed to high temperature.

The most important parameters to take in consideration on this kind of printer are surely the accuracy and the surface finish of the final part and these depend on the layer height and laser spot size. Another aspect to take into account in order to have a smoother part surface is the powder particle geometry and size: in fact, the smaller the particles are, the smoother the final part will be and the harder will be for the roller to handle and spread the powder. Here are the main advantages of this technology:

- Good for strong functional parts with complex geometry
- High level of accuracy (but lower than Vat Polymerization or Material Jetting)
- No structural supports needed (no negative effect on surface like FDM or SLA), so it is possible to create hollow section
- Tolerance similar to SLA technique

Conversely, the drawbacks are:

- Printer cost
- Skilled operator required
- The energy cost to manufacture can reverse the saving in materials

1.4.1.2 Selective Heat Sintering

The Selective Heat Sintering technology is really similar to the SLS one, in fact the only difference is due to the source of thermal energy where the laser is replaced by a less intense thermal printhead. For this reason, the selective heat sintering represent a cheaper solution that finds its best application in the production of inexpensive prototype for concept evaluation.

1.4.1.3 Direct Metal Laser Sintering and Selective Laser Melting

The DMLS (Direct Metal Laser Sintering) and SLM (Selective Laser Melting) techniques work similarly to SLS; in fact, the real difference is given by the material used, that is metal powder and not polymeric. Moreover, differently from SLS, these two techniques require an additional structural support to avoid possible distortions during the printing phase, even if, like in SLS, the problem of warping is still present. The most important parameters to take into account for both DMLS and SLM printers are similar to the once of SLS, thus layer height, the geometry and size of the powder and the spot size.

Considering the differences between DMLS and SLM we can state that in the former the thermal energy source just heats the powder, without melting it , so the last layer can fuse with the previous one on a molecular level. In the SLM technique, instead, a laser is used to completely melt the metal powder in order to have a homogeneous part. For this reason, the part has a single melting temperature, not possible with a metal alloy; in fact, SLM is used to manufacture products from a single metal element, differently from DMLS that is used for alloys.

Here are the main advantages for DMLS ans SLM:

- High dimensional accuracy
- No geometry limitations
- High level of customization

Drawbacks, instead, are:

- Require additional support during printing phase differently from SLS
- Require skilled operators
- Printer cost
- Small build size

Direct Metal Laser Sintering and Selective Laser Melting find their application mostly in fields where it is not possible to use traditional manufacturing techniques. For example, they have reduced the lead time and increased the geometry freedom in dental and medical applications. Furthermore, DMLS and SLM allow cost reduction and design constraints removal even in the aerospace and automotive industries.

1.4.1.4 Electron Beam Melting

The Electron Beam Melting (EBM) technique was patented in May 2003 as “Electric Beam Melting method for metallic material” and operates like the other technologies described till now in this section dedicated to the Powder Bed Fusion. The main feature of

EBM is the higher energy beam consisting of electrons, differently from laser that uses photons to heat or fuse the particles. In this way, it is possible to reach higher temperatures that allow to work a larger number of materials with respect to the traditional melting. Another important characteristic is that EBM parts are produced in a vacuum to avoid the possible oxidation of metal powder.

For this technique, the main advantages are:

- Faster than SLM and DMLS thanks to higher energy
- Larger number of material can be used
- No geometry constraints
- In many cases, no additional work required for the finish

The drawbacks, instead, are:

- Larger minimum feature size than SLM and DMLS
- Larger layer thickness than SLM and DMLS
- Larger surface finish than SLM and DMLS
- Most expensive technology under AM umbrella;
- Lower tolerance than SLS;
- Requires additional support during printing phase differently from SLS;

This technology finds application in the same fields of DMSL and SML, thus when it is necessary to work at higher temperatures.

1.4.2 Direct Energy Deposition

A printer that embodies the Direct Energy Deposition technology consists of a 4- or 5- axis arm that, starting from the build platform, moves around the printed object. This moving arm is provided with a nozzle that deposit a metal material in powder or wire form. The focused thermal energy source of the printer is a gun that shoot a laser, electron beam or plasma arc (electric arc formed between an electrode) to melt and fuse the material deposited onto existing surfaces.

Among the advantages of this technology, these are the ones worth mentioning:

- Concurrently deposition of several material
- Multi-axis moving arm allows to build not only horizontal layers on parallel planes
- Multi-axis movement allows to repair a damaged part adding material

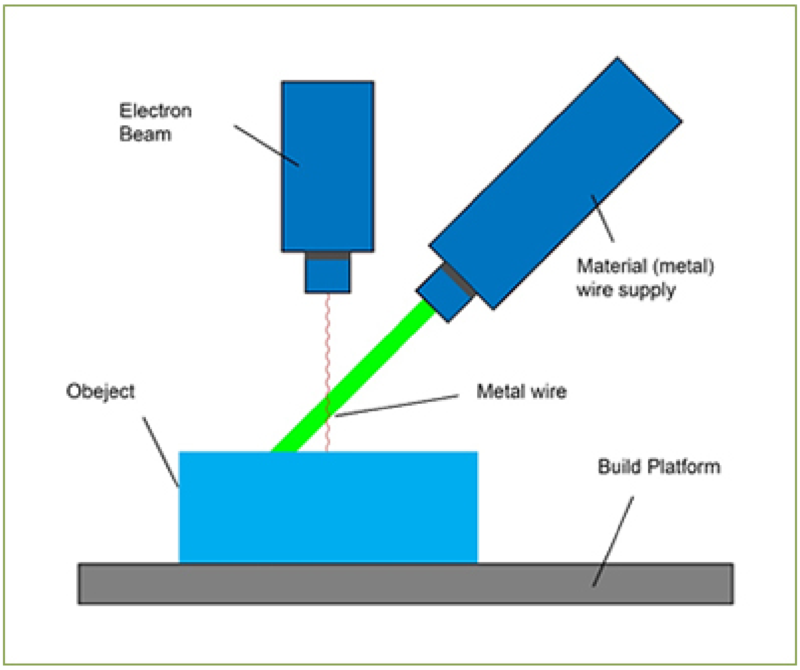

Figure 1.14: Direct Energy Deposition process [24]

- Larger size object than those obtained by SLM

The only drawback of this technology appears to be the cost, which is pretty high, even because of metal material processing, the possibility to choose multiple materials, the multi-axis motion and the process control.

Despite all the advantages mentioned above, this technology has had a limited success. The producers around the world gave different name to express their DED system , even though the most known is Laser Engineered Net Shaping (LENS) from Optomec, which is a directed energy deposition process that injects metal powder into a pool of molten metal created by a focused laser beam, as shown in Figure 1.15.

Another term used is Direct Metal Deposition (DMD) introduced by the producer POM Group that in 2012 was purchased by DM3D. An interesting product available on the market is provided by Trumpf that sells an upgrade package to turn laser systems into metal AM machines. Other DED systems were developed by the National Research Council of Canada, Honeywell Aerospace and Sciaky. The latter uses an electron beam as thermal energy and metallic material in wire form, this system is called Electron Beam Additive Manufacturing (EBAM) and it is faster than the others but is more likely a part distortion (see Figure 1.16 below).

1.4.3 Material Extrusion

The Material Extrusion process was invented and patented as “Apparatus and methods for creating three-dimensional objects” in 1992 by spouses Scott and Lisa Crump whom

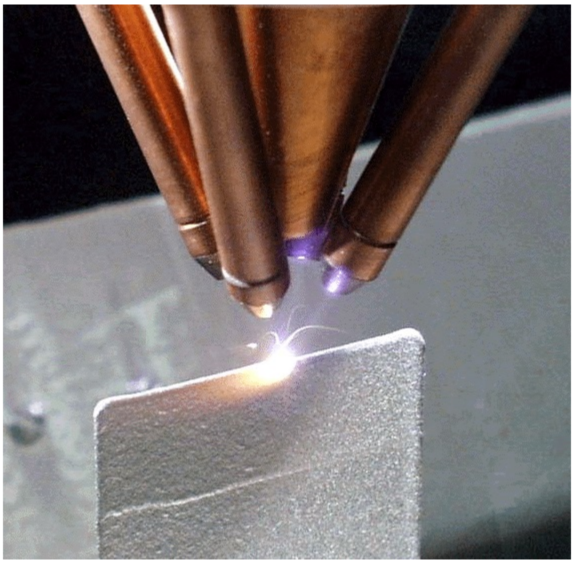

Figure 1.15: Laser Engineered Net Shaping [58]

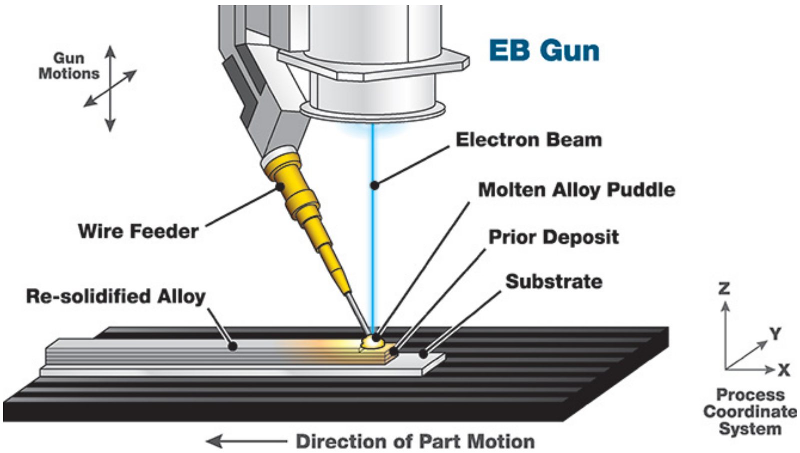

Figure 1.16: Electron Beam Direct Manufacturing[52]

were also the founders of Stratasys, that by the time has become one of the most important printer manufacturer in the world.

In the material extrusion, AM process material is selectively dispensed through a nozzle or orifice. Indeed, as depicted in Figure 1.17, the printer is composed by an extrusion head where one or more materials in spool form are forced by respective nozzles (many material extrusion printers have just one nozzle for the build material, many other models have 2 or 3 nozzles). In the extrusion head the nozzles are embodied with an heating system to melt the material. When the desired temperature is reached, the material is dispensed to create the layer starting from the foam base. On the market two kinds of printers are available, one in which the build platform moves in the x-y plane after a layer is printed, and a second

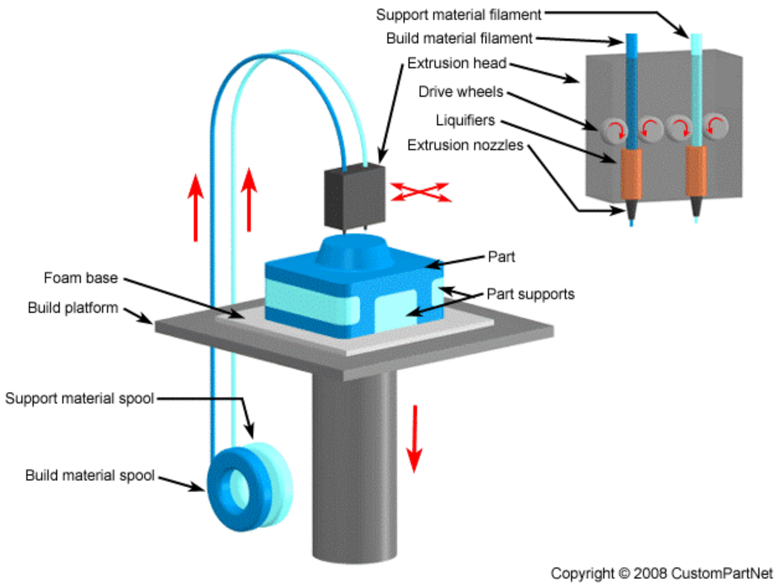

Figure 1.17: Fused Deposition Modeling or Material Extrusion process [15]

model that instead moves the extrusion head, but in the end the process is pretty much the same. The most common technology derived from the material extrusion process is Fused Deposition Modeling (FDM), a name trademarked by Stratasys. Nevertheless, such as for the other processes, even for FDM there are multiple names; in fact, another way to call it is, for example, Fused Filament Fabrication (FFF). The material mostly used for the material extrusion process is polymeric one like thermoplastic, even if this technique allows the use of many other materials in liquid form, such as ceramics, metal-filled clays, concrete, food, etc.

The main pros compared to the other techniques available under the AM umbrella are:

- Ease of use, no skilled operator needed
- Cheaper than other AM technologies
- Low cost materials
- It is the AM technology with the largest diffusion worldwide, so a large amount of materials and features are available

The drawbacks, instead, are:

- Risk of warping and shrinking due cooling, for this reason used a heated build plates
- Usually visible layer lines then post processing needed to obtain smooth surfaces
- Anisotropic parts (having a physical property that has a different value when measured in other directions)

- Supports needed for product features that overhangs less than 45° degrees, even if angled surfaces loose quality

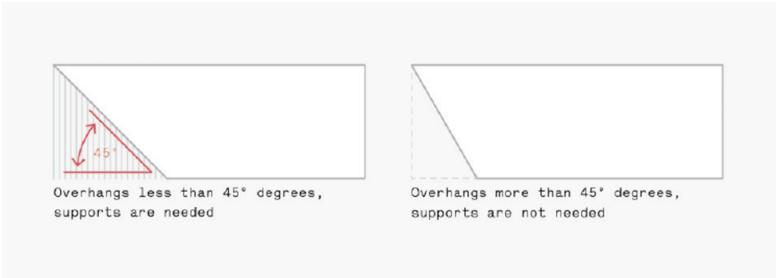

Figure 1.18: FFF support requirements [48]

The main parameters to consider for the assessment of a printer are for sure how fast is to print, extrusion speed and the nozzle temperature control, even if what is fundamental for accuracy is the nozzle diameter and layer height. Considering instead the build chamber for industrial machine, it is around 1000 mm^3 while for desktop printer is 200 mm^3. Another important parameter to take into account in finished parts for this technology is the infill percentage (see Figure 1.19 below), that define the internal density percentage of a structure; in this way, it is possible to save time and material, since if a model is used just for testing, it could be printed at a low infill percentage (e.g. 10%), instead for high strength parts could be used an 80% infill percentage. Finally, the geometry of the infill impacts too and generally are used triangular, rectangular or honeycomb structures.

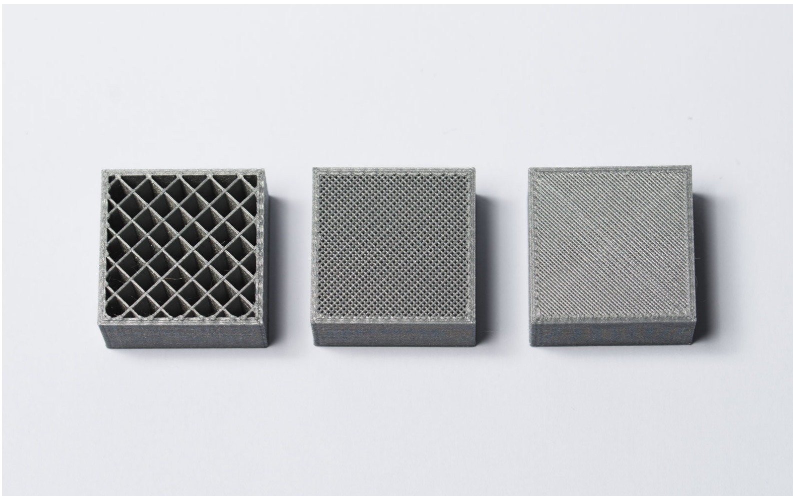

Figure 1.19: Infill percentage ranging from 10% (left), 50% (center) and 80% (right) [48]

As already mentioned earlier, one of the biggest producer of printer with this technology for industrial application is Stratasys, instead for desktop 3D printers the open-source project RepRap and their derivative give a lot of opportunities. Other companies are

MakerBot Industries, Beijing Tiertime, Aleph Object, Ultimaker and many others. There are a lot of applications for the products of these technology, for example investment casting patterns, electronic housing, form and fit testing and in general for rapid prototyping.

1.4.4 Vat Photo Polymerization

Vat photo polymerization is an additive manufacturing process in which a liquid photopolymer resin in a vat is selectively cured by light-activated polymerization. As already mentioned earlier, this process could be considered the first AM technique invented and patented in 1986 by Charles W. Hull with the name "Apparatus for production of three-dimensional object by Stereolithografy". This process finds application in many fields as prototyping, jewellery, dental application and hearing aids.

Concerning the advantages of this technique, we have:

- Smooth surface finish
- Dimensional accuracy also for high detailed parts

The only drawback, instead, is that this technology is not suitable for functional part given low mechanical strength or durability of photopolymers.

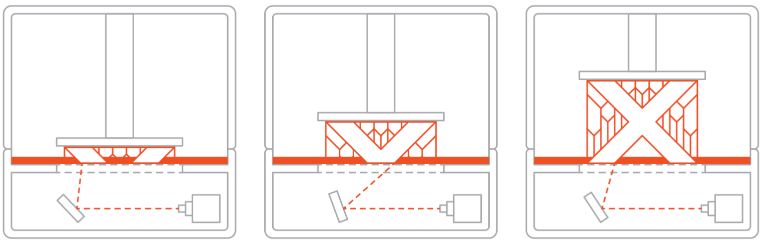

Figure 1.20: The Vat photo polymerization priting process [48]

Focusing on part orientation, it is necessary to say that Vat Photo Polymerization printers, independently from the technology adopted that we are going to deal with later on (SLA, DLP, CLIP), they are able to work in two configuration : Bottom-up and Top-down.

1.4.4.1 Bottom-up configuration

As shown in the Figure 1.21 below, in the bottom up approach the build platform starts its run near the transparent base of the vat, and between these two there is a little layer of uncured resin. Then the light source, positioned below the vat, cures the resin layer and solidifies it. Once this operation is complete, the build platform moves up creating another gap of uncured resin, thus the process goes on until the part is finished. The biggest drawback in this operation is that sometimes the part remain stick to the vat rather than the build platform creating stress in the part. For this reason, it is preferable to apply a special coating to the base of the vat that avoids the adhesion. As for many other AM technologies, this kind of printers (see Figure 1.22) requires support structures to accurately print a part.

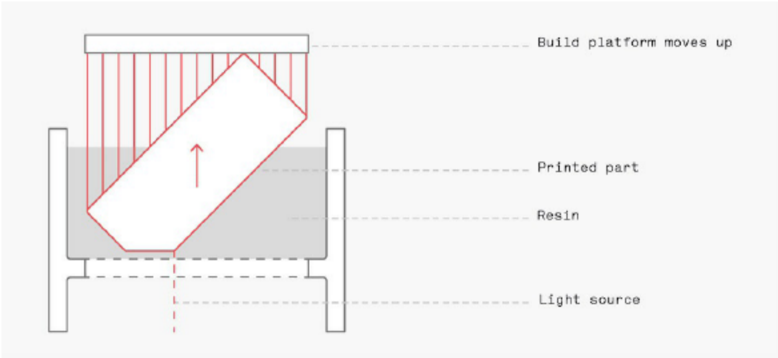

Figure 1.21: The Bottom-up approach [48]

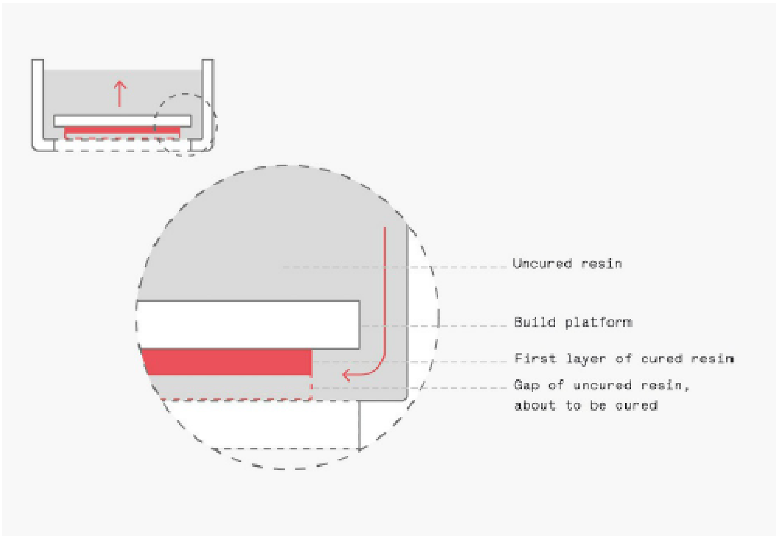

Figure 1.22: Bottom-up printer configuration [48]

The advantages of this approach are:

- Little resin needed, because the part is pulled out of the vat
- Better control of layer thickness

The disadvantages, instead, are:

- Need to periodically change the coating on the vat

- Stress for the part in the peeling stage

1.4.4.2 Top-down approach

In the top-down approach, at the beginning of the process, the build platform is close to the surface of the liquid in order to leave a thin layer of uncured resin. As depicted in the Figure 1.23 below, the light source is positioned above the vat and once a layer is cured the build platform starts to move down until the part is completely printed. Same as in the bottom-up approach, it is critical to fix the first layer, but the most important operation during printing is that every time the build platform goes down the part is uniformly covered by a liquid layer. To fulfil this requirements it is necessary to have an adequate resin viscosity. For these kind of printers support structures are needed for product features that overhangs less than 45° degrees similarly to FDM, and the only difference is that the structures are printed with the same build material and then removed manually, this because there is only one vat.

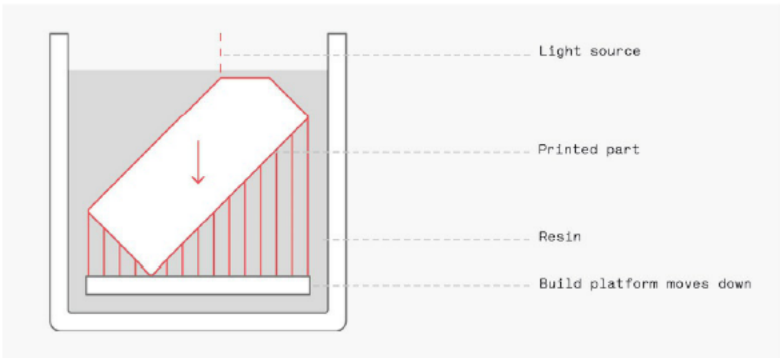

Figure 1.23: The Top-down approach [48]

The advantages of this approach are:

- Faster process, (you don't need to separate the part from the vat)
- Lower stress on part
- Easier to create support structures

The disadvantages, instead:

- More resin needed, so printers are bigger in dimensions
- Constantly control resin viscosity, to have uniform layer
- Resin substitution difficult and expensive
- Likelihood of curling

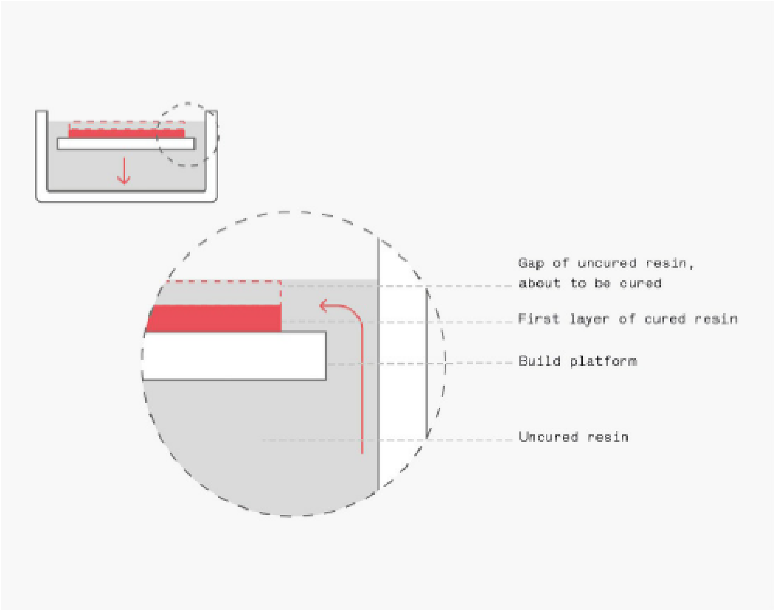

Figure 1.24: Top-down printer configuration [48]

1.4.4.3 Technologies

Nowadays there are three technologies used in the Vat Photo Polymerization process, although all of these use similar mechanism to produce parts.

The most famous technology is for sure **Stereolithography (SLA)** where mirrors, called galvanometers, are used to direct a laser beam across the transparent vat for bottom-up devices (as depicted in the Figure 1.25 below) or directly on the first layer for top-down printers in order to cure and solidify the liquid resin. The most known companies the manufacture printers for industrial use are 3D Systems and many other Japanese firm, instead considering the low-cost sector a good quality product is offered by Formalbs.

The second technology is called **Direct Light Processing (DLP)** and the only difference with SLA is given by the light source, since DLP printers use a digital light projector screen to directly flash with diodes (LEDs) an entire layer at once, not just a spot, for this reason DLP is faster to print a part. There are many companies around the world that provide these kind of printers such as Envisiontec, DWS, Asiga, Rapid Shape and many others.

The last technology appeared on the market in 2014 is **Continuous Liquid Interface Production (CLIP)** that works similarly to a DLP printer with bottom-up approach, but the only difference is that the build plate has a continuous upward motion. Moreover, as shown in Figure 1.27, the printer creates a "dead zone" of uncured resin by the means of an oxygen-permeable window in order to avoid that the part remains stick to the vat and the result is a faster build time.

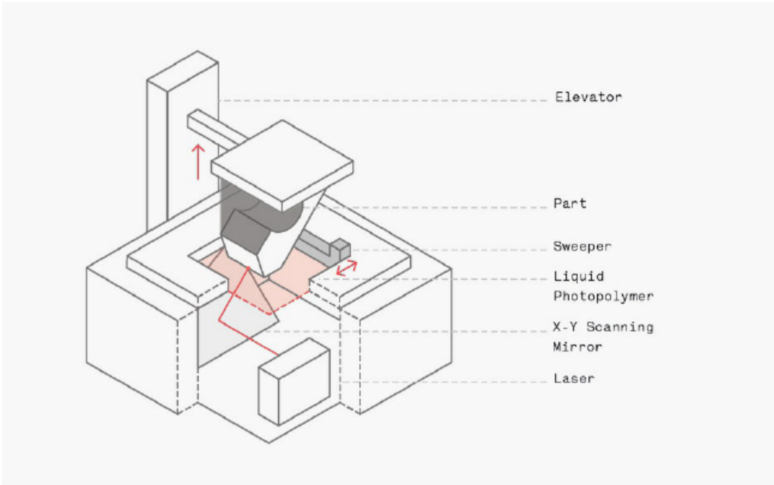

Figure 1.25: Schematic of a SLA printer [48]

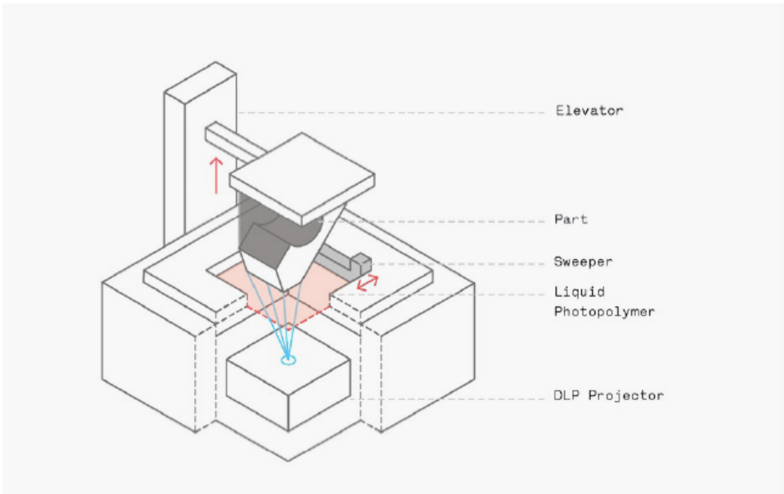

Figure 1.26: Schematic of a DLP printer [48]

1.4.5 Binder Jetting

Binder jetting is an additive manufacturing process, developed in 1993 at the Massachusetts Institute of Technology, by which a liquid bonding agent is selectively deposited through inkjet printhead nozzles on to a powder bed to form a part layer-by- layer.

The printers that embody this technique work in a similar manner to Powder Bed Fusion (PBF) because at the beginning of the process a layer of powder is dispensed on the build platform thanks to a level roller. Nevertheless, here it is not used a laser to sinter the powder but a printhead that deposit binder droplets; this, in fact, makes the process similar to material jetting too with the only difference that the material dispensed

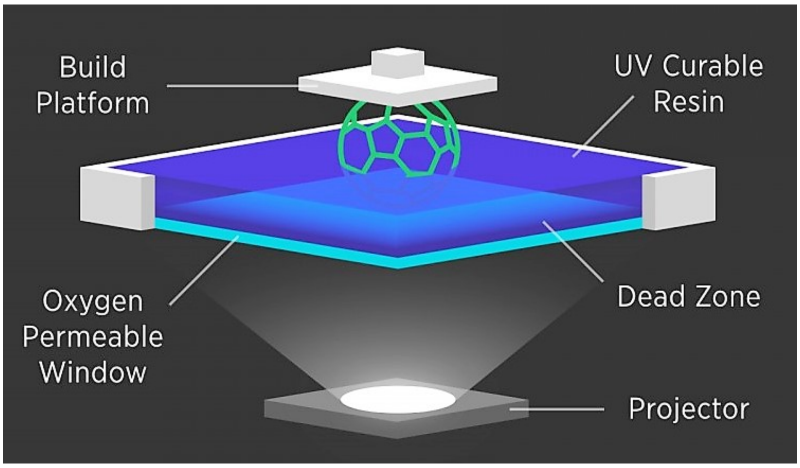

Figure 1.27: The CLIP technology [48]

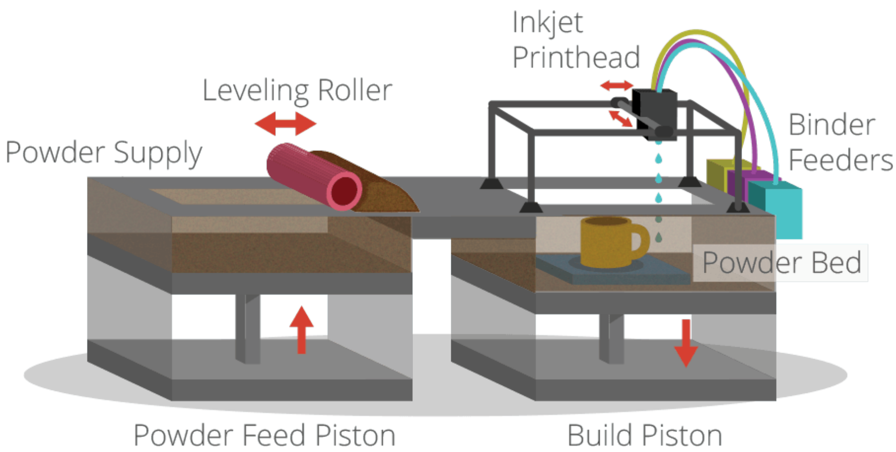

Figure 1.28: The Binder Jetting process [57]

is a bonding agent rather than a building material. Once a layer is completed, the build platform moves downward. Later on, as in the Powder Bed Fusion, no support structures are required because the printed part remains sunk in the sand to gain strength, but differently from the other, in Binder Jetting the powder is 100% recyclable. The printer parameters to take into account in order to have a discrete accuracy and surface finish are the specified layer height, the size and geometry of either the powder and the droplets. This process can be used to produce part in polymers, foundry sand and metals, but according to the powder selected different processes are needed. In fact, we can distinguish two categories: **Sand Bitter Jetting** and **Metal Binder Jetting**.

Sand Binder Jetting is used mainly to print presentation models and sand casting cores or molds, it is perfect for these applications because it allows to print even complex geometries at low cost, without any additional process needed.

In Metal Binder Jetting the printing process is almost the same, even if the production of functional metal parts requires a secondary process to enhance the mechanical properties, which usually is infiltration or sintering. Infiltration process starts once the part is completely cured and consists in placing the printed part in a furnace where the binder is burnt and then this creates voids in the part that are filled via capillary action with bronze. Notwithstanding the infiltration process, binder jetting metal parts have lower mechanical properties compared to parts produced with a powder bed fusion process. In the sintering process instead, after the printed part is complete, it is cured in a oven and sintered in a furnace to a high density, but sometimes this operation creates a non-uniform shrinkage.

Here are the main advantages of this AM process:

- Low cost process than powder bed fusion
- Complex geometry allowed
- No support structures needed, because printed parts are surrounded by powder
- Better then Powder Bed Fusion because parts are printed without heat, so no risk of distortions

The only drawback, instead, is that it presents lower mechanical properties (strength in particular) compared to Powder Bed Fusion, even if a secondary strengthening process is carried.

Among the producers of printers that use this technology, it is necessary to mention Z Corporation, the first company to obtain an exclusive license in 1995 that brought to the production of ZPrinter, which used plaster-based powders and a water-based binder. In 2012, 3D Systems acquired Z Corporation and its license that by the time has become not exclusive; in fact, ExOne Company, Voxeljet and Digital Metal are some other companies in possession of this license.

1.4.6 Material Jetting

Material jetting is an additive manufacturing process by which droplets of build material, polymers or wax-like, are selectively deposited using an inkjet printing head. The printhead is usually provided with multiple nozzles that jet the build material, but also a binder (as depicted in Figure 1.29 below) or support material or even another build material to manufacture multi-material parts. Once the material is deposited, the photopolymers or wax droplets are exposed to ultraviolet rays. Drop On Demand (DOD) printers have two nozzles, one to deposit the build material (i.e. wax) and the other for support material.

The producers of this kind of printers include Stratasys with its Connex and Connex3 technology which allow to print respectively digital materials (photopolymers) and

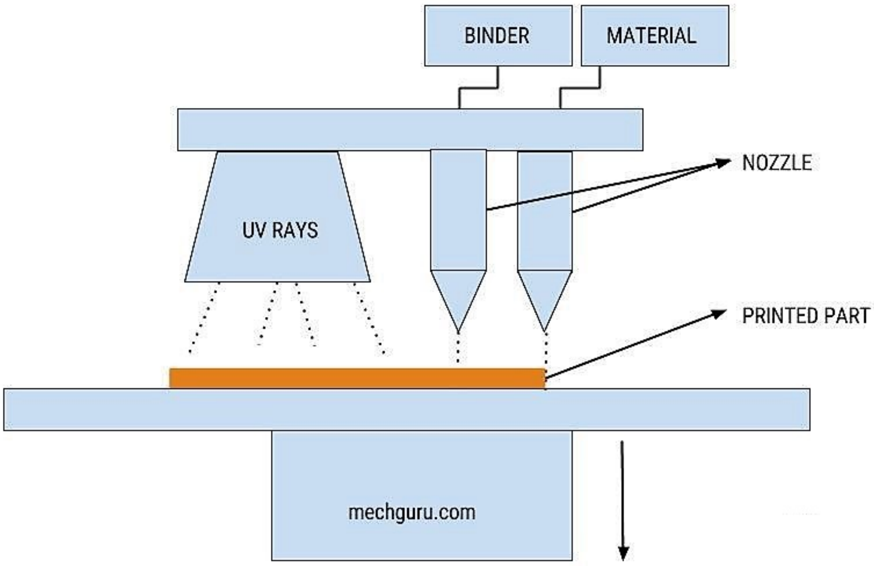

Figure 1.29: The Material Jetting process [36]

multi-material simultaneously. Even in this AM sector we find 3D Systems that sells a technology called Multi-jet Modeling (MJM). Then there is Solidscape which sells a printer without UV lights, in fact the latter is not required because the build material is not a photopolymer but instead wax used to manufacture patterns for casting small metal parts. Other producers are Keyence, Optomec, nScrypt and Voxel8. These last three sell a technology called "Direct-Write" that employs functional inks, enabling the printing of electronic circuits.

Here are the advantages of this technology:

- Linewise material deposition, faster than the other 3D technologies with point-wise deposition
- Accurate finished parts (16 micron layers) and smoother surfaces compared to the other 3d processes with heat involved
- Support structures dissolvable with light agitation
- Support structures printed simultaneously allow more flexible part orientation

The disadvantages, instead, are:

- Support structures generally printed solid, thus a lot of material is wasted
- Parts produced have low mechanical properties like SLA, so parts produced generally used for prototypes, medical models on patient anatomy and injection molds

- One of the most expensive 3d method

The parameters that influence the surface finish and the minimum feature size of a part are the layer height and the jet diameter, that is influenced by the droplet size. Another important aspect is that the build material must remain in liquid form and for this reason MJ printers heat up the build material to get it at an optimal temperature and consequently also at an optimal viscosity.

1.4.7 Sheet Lamination

Another important AM process is Sheet Lamination (SL), in which sheets of building material are cut by using a laser or knife and that are joined one after the other either by using and adhesive or by letting the laser cut sheets together to form the 3D object.

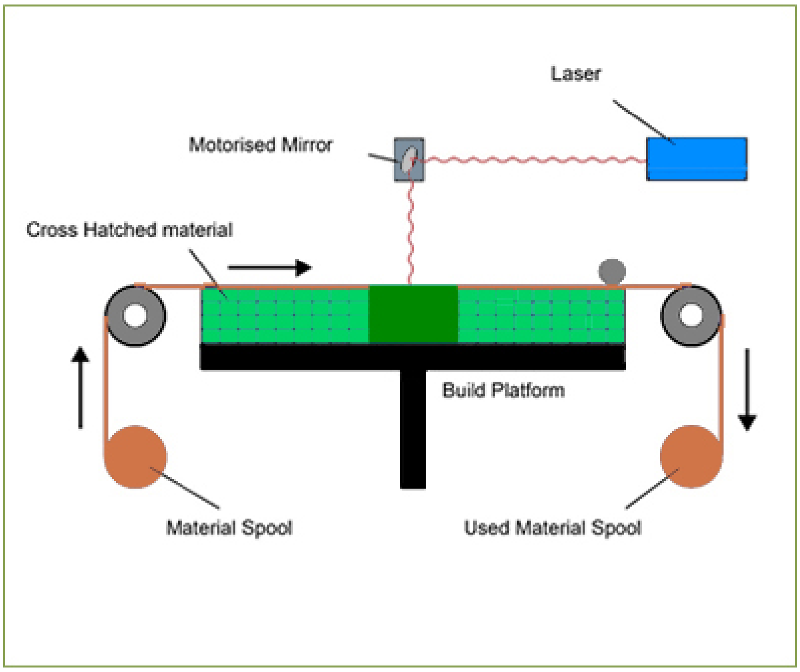

Figure 1.30: The Sheet Lamination process [19]

The advantages are:

- Benefits include speed, low cost, ease of material handling, but the strength and integrity of models is reliant on the adhesive used
- Cutting can be very fast due to the cutting route only being that of the shape outline, not the entire cross sectional area

The drawbacks, instead, are:

- Finishes can vary depending on paper or plastic material but may require post processing to achieve desired effect
- Limited material use
- Fusion processes require more research to further advance the process into a more mainstream positioning

The two main technologies of this process we are going to deal with are **Laminated Object Manufacturing (LOM)** and **Ultrasonic Additive Manufacturing (UAM)**.

1.4.7.1 Laminated Object Manufacturing

Developed and commercialized in 1991 by Helisys, Inc. (now Cubic Technologies), the LOM technique was one of the first to appear on the market. It consists of a layer-by-layer lamination by using paper material sheets that are cut using a CO_2 laser and every sheet concerns one cross-sectional layer of the CAD model of the part. Furthermore, all the paper sheet portions not included in the final part are sliced into cubes using a crosshatch cutting operation. Objects that are characterised by this kind of process may then be modified by machining or drilling after printing.

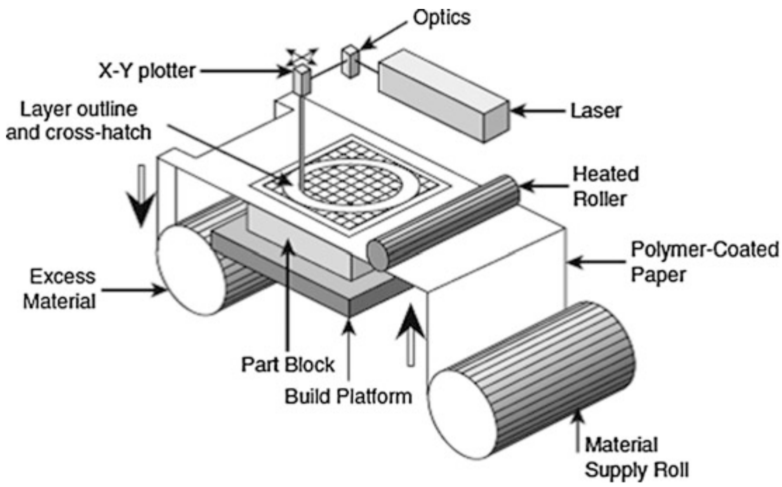

Figure 1.31: Schematic of the LOM process [6]

Worth mentioning is the fact that most SL techniques are featured with a paper build material bonded using a polymer-based adhesive. In fact, at the beginning, LOM was developed using adhesive paper similar to the paper used by the butcher to wrap the meat, whose thickness goes from 0.07 mm to 0.2 mm.

The main features of this technique are:

- Low cost due to readily available raw material

- Paper models have wood like characteristics, and may be worked and finished accordingly
- Dimensional accuracy is slightly less than that of stereolithography and selective laser sintering but no milling step is necessary
- Relatively large parts may be made, because no chemical reaction is necessary.

1.4.7.2 Ultrasonic Additive Manufacturing

Originally commercialized by Solidica, Inc. in 2000 and then licensed to Fabrisonics, UAM is the other imporant SL technology. It consists in combining ultrasonic metal seam welding and Computer Numerical Control (CNC) milling.

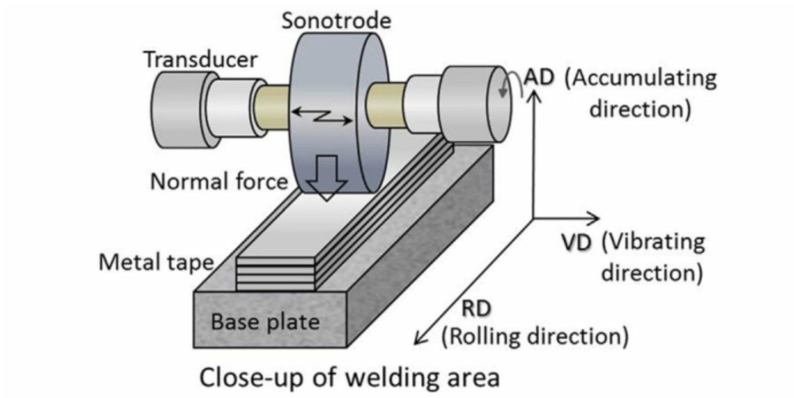

Figure 1.32: Ultrasonic Additive Manufacturing technique [27]

In this technique, the object is located on a held base plate bolted in a heated platen, and temperatures goes from the ambient ones to about 200°C. Subsequently, parts are build bottom-up and each layer (made by metal foils) is laid side by side and then trimmed by using CNC milling.

In using UAM technique, we see a rotating sonotrode moving along a thin metal foil (typically 100–150 µm thick). The foil is held in contact with the base plate by applying a normal force via the rotating sonotrode. Later on, the sonotrode oscillates transversely to the direction of motion, at a constant 20 kHz frequency and user-set oscillation amplitude. After depositing a foil, another one is placed close to it and this procedure is repeated until the formation of a complete layer. The next layer is bonded to the previous one using exactly the same procedure. Typically, one level in UAM is characterised by four layers. After deposition of one level, the CNC milling head shapes the deposited foils/layers to their slice contour. and the process continues until the final geometry of the part is achieved.

In using the SL process, the biggest producer for the low cost printers is Mcor Technologies Ltd., whose machine is able to hold several reams of A4 or letter-sized paper and to dispense a water-soluble adhesive that bonds the layers. The company makes three models: Mcor Arke, Mcor Iris HD (which integrates a color printer) and Matrix 300+.

1.4.8 Inkjet Bioprinting

An important breakthrough in 3D printing has been the recent application in the medical sector. This, in fact, has allowed to print complex, delicate e precise sections of living tissues, organs or cells substrates thanks to the development of bioinks and biopapers suitable for this technology.

The discovery of 3D inkjet printing is recent; it is done by laminating printed layers where the shaping liquid is ejected to the stereostopic shaping powder or where the ink is cured by heat or UV rays. The way in which this technique operates, moreover, perfectly commits to the intent of printing living tissues using biomaterials and cells as bioinks. In fact, the on-demand property of inkjet printing is perfect for the medical sector even thanks to the contactless printing, which let the nozzle tips to be not contaminated by getting in contact with the printing object; and this is a great advantage, if one thinks about the troubles that contamination brings.

Nevertheless, other issues came to life. At the beginning, printing bioinks including cells was a process of trial and error; the difficulty, in fact, is that inks are too fast to dry and paper is hygroscopic, so printing cells is not that easy, from the moment that dryness causes cells death. The challenge was to overcome these properties, trying to maintain wet conditions and prevent dryness.

In the years, researchers have been developing bioinks to fix these problems, bringing this innovative technology to its consolidation.

Biofabrication has the purpose of producing biological products. This all started as a necessity, since when dealing with the organ transplantation, which however has constituted a great progress to treat diseases and ill organs, it has become hard to find available organs and donors.

Despite all the efforts that researchers have made during the last years, problems have not missed. In fact, the range of tissues that can be printed is very limited, including cartilages, skin and cornea. Other tissues regarding heart, kidney and liver, instead, have got histological issues that today have not been overcome yet: extreme thickness, characteristic microstructures for respective organs, heterogeneous structures composed of multiple types of cells and extra-cellular matrices, tissues with a lot of capillaries and composed of large amount of cells.

Given these histological troubles, there have been considered necessary some technologies as 3D fabrication and deposition, microscaled cell manipulation, fabrication of heterogeneous structures, construction of perfusion structures and the ones for the manipulation of large amount of cells. In addition, it has been considered that cells have never been employed as materials for manufacturing, given some technical difficulties as the size (10-30 µm in diameter), the enormous number of cells that researches has to do with (we talk about 100 million cells, thus humanly impossible) and the physiological environment in which they have to be treated, supposed to be wet as them. Hence, little by little, researchers have started developing a Computer Aided Machine together with CAD in order to overcome these issues and, to achieve this, inkjet bioprinting has to be applied to biofabrication.

There are two types of bioinks: a solution suspended with cells and a solution that contains proteins or deoxyribonucleic acid (DNAs). Since there are several materials used for bioinks, we can classify them in two categories: indirect printing, concerning materials whose cells are seeded and cultured after the ejection of materials and direct printing instead materials printed together with the cells.

1.4.8.1 Indirect Printing

In this technique the quick-drying inks, as the ones we use for our domestic inkjet printer, can be used as bioinks from the moment that cells would be seeded after printing and drying the bioinks. Kim et al. printed various patterns of (polylactic-co-glycolic acid) (PLGA) on a polystyrene (PS) substrate for stem cell patterning, as shown in Figure 1.33. They used a mixture of PLGA and N,N-dimethylformamide as bioinks, and then evaluated the relationship between the concentration of polymer solutions and the viscosity. For the design of patterned surfaces they used Adobe Photoshop CS. However, although cells were not perfectly patterned onto the PLGA printed surfaces, they managed to print the synthetic polymer onto the plastic substrates and prepared the cell patterning surfaces utilizing the inkjet printing system.

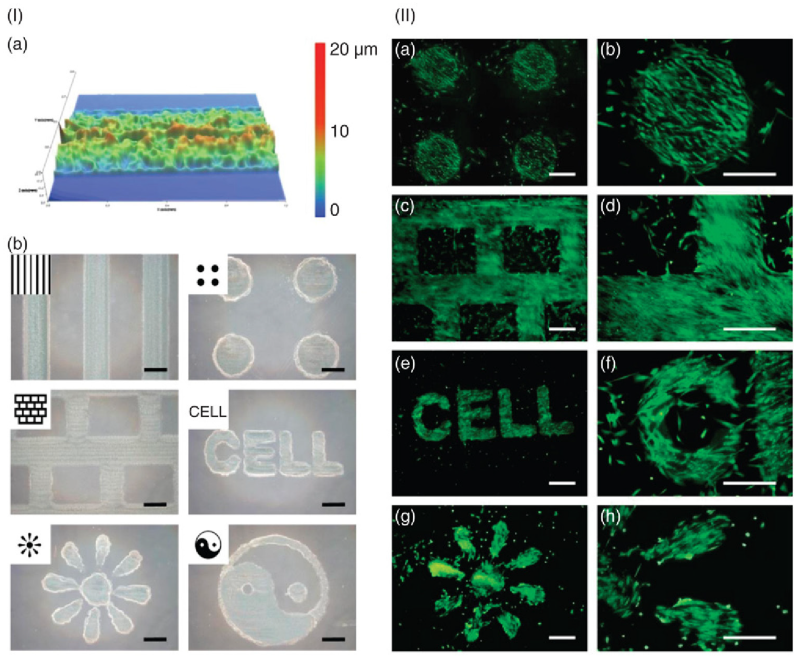

Figure 1.33: The two-dimensional patterning of PLGA onto the culture substrates [28]

The great feature of inkjet bioprinting is that we can design te patterns of the surfaces on the computer and then print them, simply by changing the combination of inks and culture substrate. Later on, the printed surfaces (proteins or plasmids) can be used for drug or gene delivery to the cultured cells, operation usually run by virus vectors or cesium phosphate particles.

In addition, bioinks can be ejected onto the cultured cell layers as printed substrates by using the layer-by-layer (LBL) technique. This is very important since the lamination of the layers in 2D enables the inkjet printing technology to turn into 3D bioprinting, allowing to produce the scaffolds of the cells in the shape we wish.

1.4.8.2 Direct Printing

As mentioned earlier, physical and chemical properties of bioinks are limited; in fact, the solvent has to be water while pH, osmolality, and ion intensity of the solution must be the same as the physiological environment. Furthermore, these limitations are all linked to the problems of cells dryness and physical stress when ejecting toward the cells. However, dealing with this last issue in particular, researchers have found that the stress from the nozzle did not affect the cell viability, letting them start studying direct printing. In this case, the main drawback consisted in the rapid drying of cells because of the volume of the ejected droplets, which is ultramicro. Reason why, researchers managed to find a solution by making tissue structures with hydrogel materials.

The most used one is alginate hydrogel: it contains a lot of water and it is characterised by a very short gelling time, thus preventing cells from drying and bleeding. Furthermore, since this material forms gels into the printed surfaces, it also behaves like a biopaper, constructing the 3D structures by laminating the alginate biosheets. Last but not least, it has high biocompatibility hence cells do not suffer any damage and it is able to solve the problem of cellular cytotoxicity.

However, on the other side of the coin, the alginate hydrogel presents the problem of poor cell adhesiveness: in fact, it is known that cells need to attach to scaffolds or substrates to grow and if they do not, they die. Some researchers got to the bottom of it: they fabricated structures of cells by printing a calcium chloride solution suspended with cells as bioink into a mixture of alginate and collagen solution. Unfortunately, this was not sufficient since collagen takes a lot of time to form a gel and so they worked it out again by creating 3D structures where cells could adhere and proliferate inside by mixing the two materials.

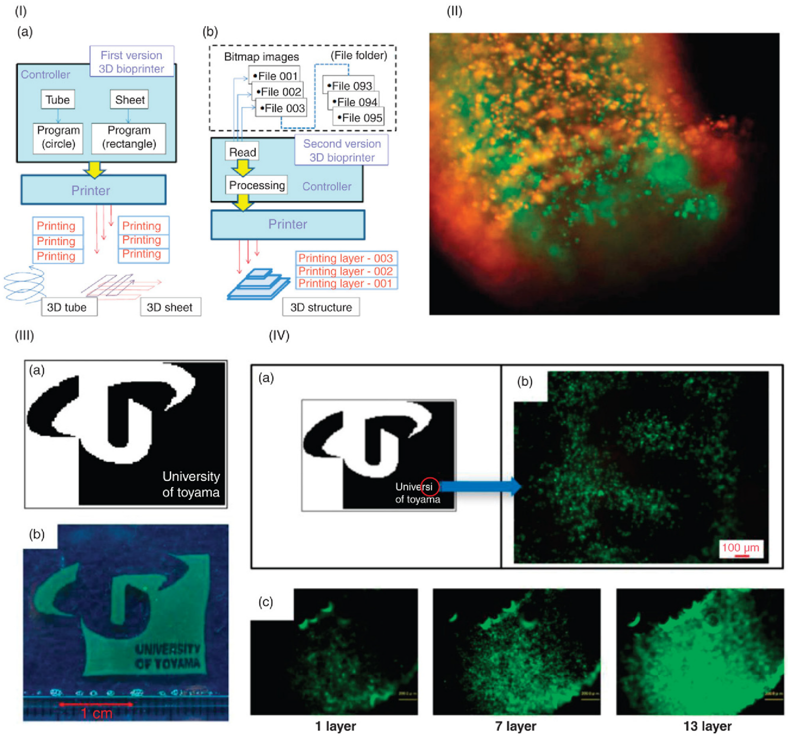

Figure 1.34: The tissue-like structures consisting of alginate hydrogel and cells. [28]

1.5 Conclusion

The picture presented earlier has had the aim of showing the world of 3D printing from the technical side, even if it has not been explored all yet. Researchers, scientists, developers and all the others involved are working very hard both to refine the existing techniques and processes and also to discover new ones (just consider that Inkjet Bioprinting, for instance, has not been categorized yet, being a very new process), in order to make them more and more competitive and to allow them come up beside other manufacturing techniques.

After having dug deep into the origins, the process phases and the techniques of 3D printing, we will now move our attention to the economic impact that this sector is entailing on the society.

Chapter 2

AM impact on the production system

2.1 Introduction

After having shown the 3D printing from a merely technical point of view, it is time to move our focus on the impact that this technology has been having from a broad point of view on a firm.

In order to do this, the first part of the chapter analyses the impact of Additive Manufacturing on all the life cycle phases of the product, that goes from product and process design, to material input, manufacturing and closing the loop that consists in fixing and support after sales but also recycling.

Subsequently are going to be analysed the phases of new product development putting more emphasis on testing prototyping phase as well as on the production systems available, so from economies of scale to economies of one, short-run and customized production.

Last but not least, we will study the economic impact of Additive Manufacturing on the current economic models (Open-source, maker spaces, marketplaces, communities), highlighting its main economic features, both advantages and limitations.

2.2 AM impact on product life cycle

The manufacturing landscape lives a constant evolution thanks to the continuous invention of advanced manufacturing technologies. Among these one of the most revolutionary nowadays is surely 3D printing, for this reason a lot of companies are being forced to rethink how and where they conduct their manufacturing activities. Obviously one of the most important parameter to take in consideration for the upgrade of the current manufacturing systems is how much sustainable AM it is, in fact from one point of view 3D printing could lead to shorter and smaller value chains, more localised with a considerable reduction in waste and time. On the other hand the worst scenario is a localised production less eco-sustainable with an higher rate of product obsolescence that could bring to increasing the consumption of resources.

The aim of this section is to highlight the consequences on sustainability of AM identifying the types of benefits rather than quantify them. The analysis has been conducted using a product life cycle prospective (figure 2.1) that take into account four main stages: design; material input; product manufacturing; closing the loop. Subsequently is reported a tool called Sustainable Value Roadmapping Tool (SVRT), from the paper "Sustainable Value Roadmapping Framework for Additive Manufacturing" by Mélanie Despiesse.

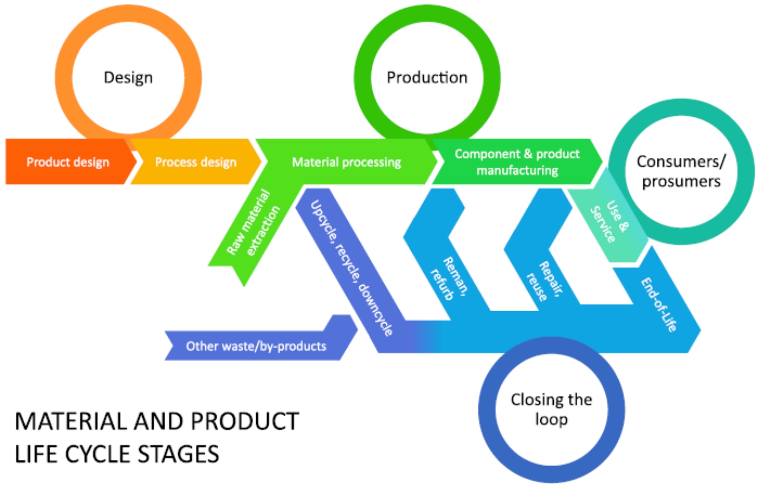

Figure 2.1: Product life cycle stages [21]

2.2.1 Design

One of the most important feature of additive manufacturing is the product design flexibility given by the freedom in shape and geometry, that enables the production of complex and optimised goods with structures often inspired by nature, the possibility to merge all the components in one single object and the reduction of weight. The benefit realised propagates over the whole life cycle thanks to greater functionality and the easier manufacturing (requires fewer parts and materials) and maintenance Worth mentioning is that the right term to use in this case is redesign rather than just design, this because even the already existing product should be redesigned taking into account the increased freedom. Indeed AM machines allows the creation of mesh arrays and cellular foam, that used to produce the core of any product could enhance attributes such as strenght, stiffness, energy savings and corrosion resistance. An example of successful product redesign is given by the LEAP engine, launched by GE in 2016, in which have been included 19 nozzles manufactured using 3D printers. This engine redesign result in remarkable advantages as nozzles five time stronger, a geometry refined to improve the combustion efficiency and a weight reduction of 25%. The latter mostly given by design simplification, from 20 separate components of the existing design, to a single one.

The product redesign has as its direct consequence a process redesign that involves less energy and resources consumption. An example is given by Salcomp, a Finnish company that produces electrical plugs and power supplies for mobile phones, which resigned moulds' structure to reduce the cooling time enabling an increment of 56000 units/month produced. One of the biggest drawback related to process is that AM systems are far from being automatised, both during the printing process, that in many cases requires skilled operators, and in the post-processing to eliminate the aesthetic discrepancies. A solution to these latter problems could be the adoption of hybrid manufacturing techniques that consists in the combination of different processes in additive, subtractive, joining and transformative technologies. Apart from the manufacturing sector, a process redesign could be brought in other sectors such as the construction one to enhance material and energy savings as well as logistic efficiency given by fewer material needed on the site and lees waste to dispose of. Nevertheless there are a lot of doubts about the durability and the safety of structures raised with these techniques.

Finally, the main benefits derived from the integration of AM techniques at the design are:

- material and energy savings;
- greater product functionality and efficiency;
- value chain reconfiguration with less materials, stages and actors;
- reduced time between design and manufacturing;
- lower environmental impact of transportation shifting to a decentralised manufacturing system;

while the limitations, instead, are:

- designers bias that AM misfits for product manufacturing, but just for prototyping;
- difficult integration of microelectronic components into AM final products;

The last advantage exposed could create new business opportunities for Services Providers, for example the providers of postal services could be interested in partnership with 3D machines manufacturers in order to move the production closer to the end-users. A real world example is given by the lately announced partnership between UPS and Stratasys, where the latter provides 3D printers to install in UPS's stores.

2.2.2 Material input

As already mentioned in the first chapter's section related to the description of AM process types, the building material employed changes with respect to the technology

selected. It is possible to identify four main groups of material composition: powder, filament or paste, liquid and solid sheet.
Talking in terms of sustainability, the big challenge to overcome is the energy consumption due to the refining process to transform metal ores in feed material ready for production. Another threat linked to raw materials is that many 3D printers' manufacturers have developed and already commercialised their own kind of raw material with specific chemical characteristics in order to ensure the best accuracy, in other words nowadays 3D machines and specific AM technologies are liked to precise types, forms and states of materials. A possible solution to these problems could be the standardisation of both processing techniques from ores, to save energy, and chemical structure. A good point in favour of many of additive manufacturing processes is that wastes and unused material could be recycled, even if this may result in the reduction of material properties. A way to solve this problem is to mix the virgin raw material with a little percentage of recycled one, mostly for polymers. Finally additive manufacturing could also enable the so called Upcycling, that consist in create value from by-product (a secondary product derived from a manufacturing process) and from what is considered waste. An example is Bewell Watches that uses wood dust from timber processing as refiller to thermosetting resins to create a wood filament for AM, then this filament is used to produce the watches' framework.

2.2.3 Product manufacturing

In this subsection is provided a general analysis about the sustainability of AM on the manufacturing stage, moreover later in this chapter will be discussed in a more extensive form how AM fits with the different scales of productions. It comes from it self, and could be considered quite obvious that nowadays 3D printers are ideal to produce highly customised goods, notwithstanding AM could direct the whole manufacturing landscape toward a make-to-order approach thanks to the savings in time. This will result into an adaptation of the Print-On-Demand technology currently used in the publishing sector, where a company starts to print the book copy in the same moment the order is placed.

A framework to integrate additive manufacturing technologies in production is proposed in a paper by Patrik Spalt and Thomas Bauernhansl. In the first part of the paper they analyse the most important factors that influence the decision whether or not to use AM. Among these factors they consider as the most important to take into account the increased flexibility in product mix, volume and new product introduction. The framework proposed is depicted in figure 2.2 and consists of four integrated modules: the module A shows the current structure of the network and helps to define the scope of the optimization problem by means of nodes (representing the actors of the market such as factories and AM machines) and edges (which length correspond with the degree of relation). An example of a network structure is shown in figure 2.3. The risk module instead describes the demand uncertainty generating all the possible scenarios the production network has to react to. Then the demand is described as a stochastic process that is solved by a Monte Carlo simulation. The module C consists in the resolution of a linear mixed integer optimization problem based on a target function (e.g the maximization of the net present value), a boundary condition (input and capacity constraints) and an algorithm to solve the problem. The module D is the analytic one, which visualize the solution of the optimization problem as in figure 2.4. Here is defined an optimal design strategy which says where to locate the 3D printers considering the different scenarios and possible costs.

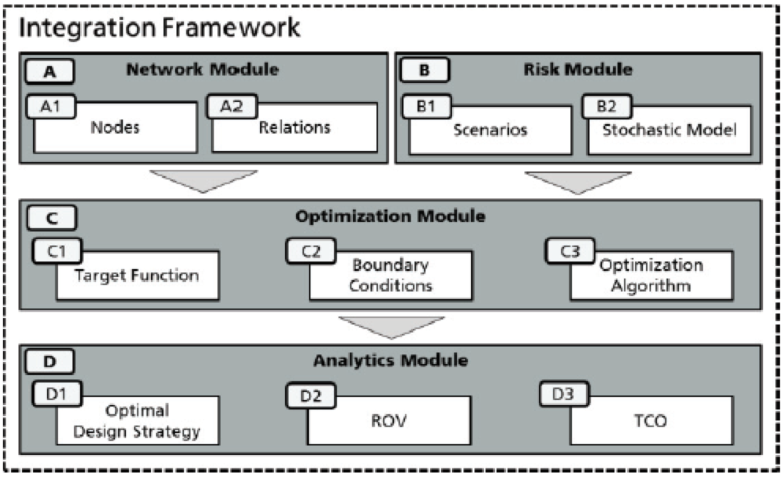

Figure 2.2: AM integration framework [53]

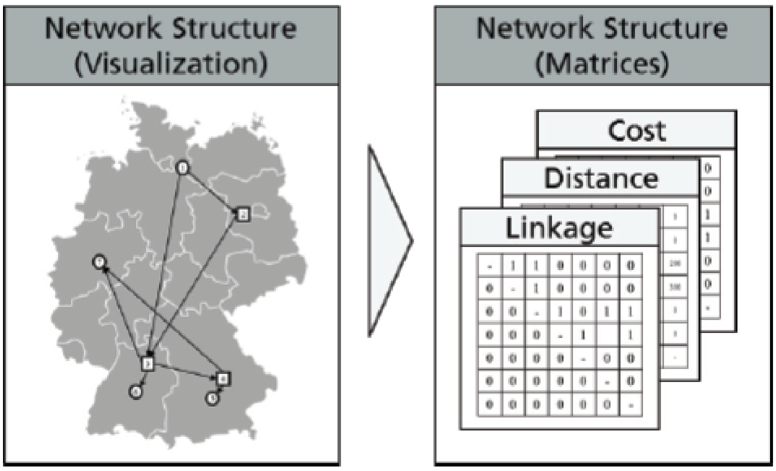

Figure 2.3: Network structure example [53]

So proportionally with the diffusion of 3D printers further reconfiguration are needed in the production, logistic and distribution processes. At first or at least for really complicated end product the manufacturers will just need to hold a database of digital designs and printers ready to be used. By the time, with the cost reduction of 3D printers, the

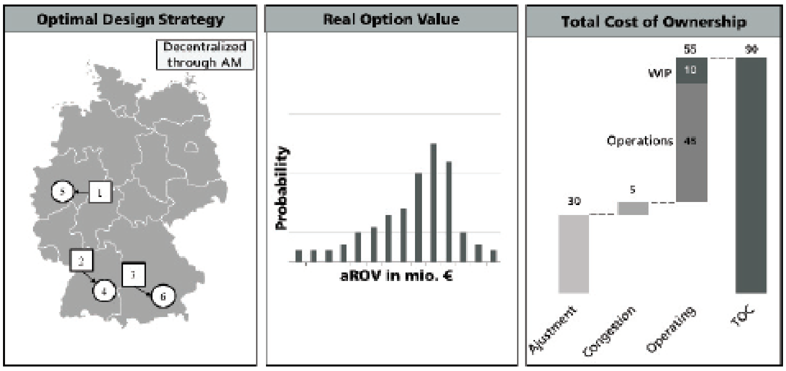

Figure 2.4: Module D output visualization [53]

technology users will play the role of both producers and consumers, at that point the only task for the firm will be to sell the designs. Taking into account the the first scenario described, from a sustainability prospective the biggest drawbacks are that AM is more energy intensive per unit produced with limited speed and quality, however the advantages would be obvious, in fact there will be:

- warehouses size reduction;
- inventory waste minimization, with practically zero chance to have unsold finished goods;
- flatter cash flow structure cause goods will be paid prior to being produced;
- simplified logistics;

2.2.4 Closing the loop

As depicted in figure 2.1 it is possible to close the loop at different stages of the product life cycle. Recalling what said in the subsection related to material input, AM machines allow to reclaim unused material during the printing process, and this represent the highest value recovery possible even if for polymers the material property loss is high, it has been estimated that 95-98% of metal powders can be recycled. Moreover the recycling could happen at the end-of-life stage, by using particular recycling system that transforms obsolete goods in new feed material, the only drawback is given by the standardization of material employed to manufacture the products, indeed the complexity of the recycling process is proportional to the diversity in materials. One innovative material regarding this problem is bio-polymer PLA that can be recycled without quality loss and provide a wide range of material properties.

Another advantage from the sustainability point of view is constituted by the recovery of value embedded in waste, moreover talking about the repair and maintenance process nowadays the one-off spare parts production is too expensive, for this reason firms are forced to have an inventory for replacement parts incurring in uncertainty about future demand of these parts. From the user prospective, when a good breaks down the consumer faces a choice, repair or discard it, taking into account the value of the product and the cost and time needed to repair it, consequently the choice with AM would falls on the second alternative. A confirmation of the latter statement is given by GE that has started to use a new technology (http://additivemanufacturing.com/2015/08/26/ge-atomic-bonding-from-a-bottle-these-scientists-use-supersonic-spray-to-repair-turbines/) called Cold Spray. The technique consists in blowing material powder four time faster than the speed of sound into good (engine) scratches, here the high speed allows to fuse the particles together when they hit the target. Another example is given by Siemens Power Generation Services (PGS) that has already made the shift and started to produce AM spare parts for wind turbines, generators and compressors. In particular they are able to repair the burner tips of the combustion systems ten times quicker with less waste generated.

In figure 2.5 is depicted the concept of circular economy that connects with a flow of resources production, consumption and use phases. In particular the maintenance and repair circular flows are shown in the right-side of the figure and involves the user, a service provider, a product manufacturer and a part and materials manufacturer. All these stakeholders are connected to the end-user on circular activities basis, indeed the easiest activity with lower environmental impact is maintenance, where just the end user is involved, then there is the reuse/redistribution which determine an interaction of the end-user with a service provider that results in a bigger environmental impact. Subsequently there is the product manufacturer whom is able to refurbish or re-manufacture the product and finally, when no further actions are possible, there is the recycling activity that involves parts and materials manufacturers. If all of these activities are economically infeasible there is an energy recovery phase or the landfills. So the diffusion of AM technologies and 3D CAD files, on internet communities, will enhance the strength of the end-user position. Indeed by the time buyers will become more independent from service providers and product manufacturers, enabling the repair and maintenance stage all at the first loop. Thus will result in considerable saving of materials, costs and energy. In the paper "How additive manufacturing enables more sustainable end-user maintenance, repair and overhaul (MRO) strategies" by Wessel W. Wits, Roberto Reyes García and Juan M. Jauregui Becker are exposed two process flows, a standard one and an optimized one, which entail the usage of AM techniques in order to carry out the end-user maintenance and repair phase and so to shorten the circular economy loop. The Standard MRO process flow using AM is depicted in the figure 2.6 and consists of three steps:

1. **Get the CAD file:** this could be obtained from the Original Equipment Manufacturer. If instead the file needed is for a standardized part, it could be downloaded from a digital repository. Finally a third way is given by the generation of the file by the end-user starting from a scan or a drawing;

2. **3D print the part;**

3. **Replace the part;**

The optimized MRO process flow is possible thanks to the increased design freedom given by AM, which enables end-users to modify the CAD file, and so even the printed part, in the best way possible according to their needs. As is shown in figure 2.7 this process has one more step with respect to the standard one, the optimized design. This consists in the choice of one over four possible strategies:

1. **Part's adaptation to user needs:** consists in modify the size or the shape of the part;

2. **Merging of parts:** from 3D models in order to avoid useless assemblies and to save manufacturing time and materials;

3. **Update parts:** starting from the original part is possible to create a new part exploitable for different applications of the same main component. This will result in the advantage for the end-user to deploy new applications without further investments in machines or tools;

4. **Mix of the above strategies:** for example, this can be done modifying the shape of two or more parts and then merge them together;

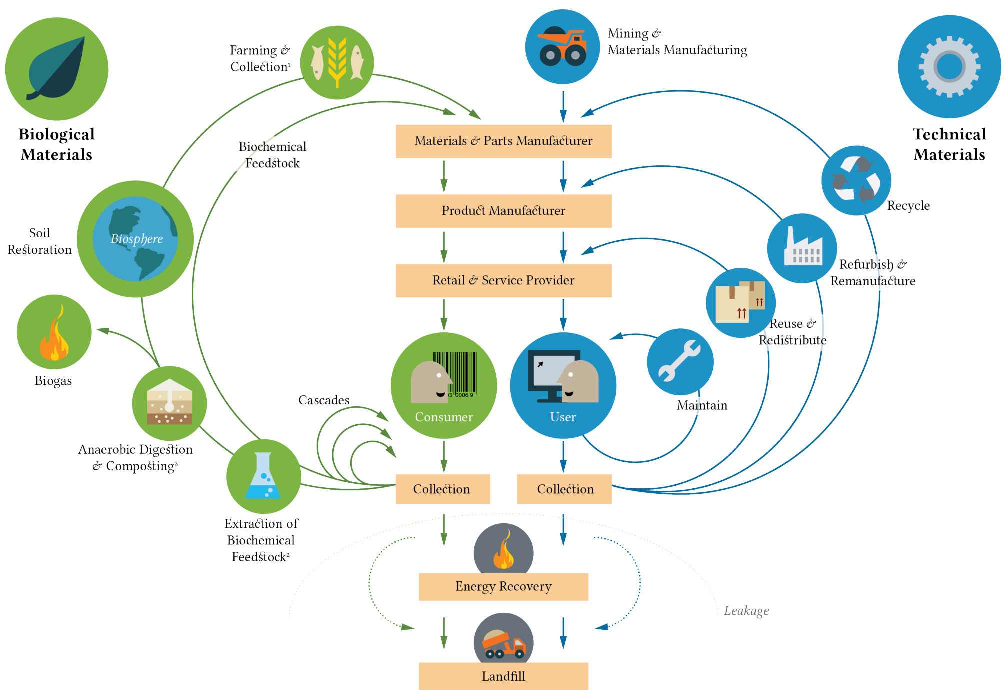

Figure 2.5: Concept of circular economy by Ellen Macarthur Foundation [16]

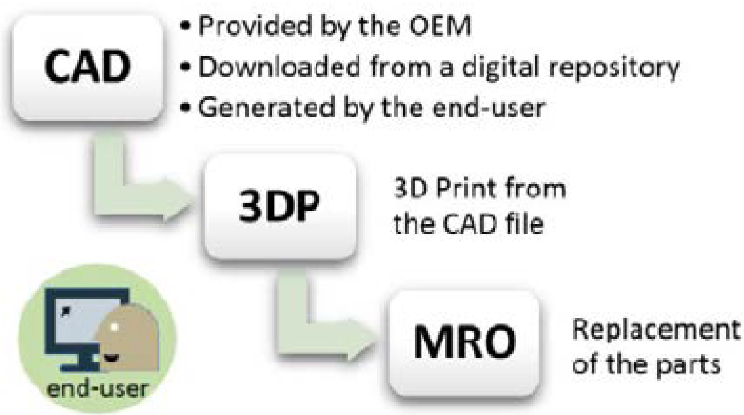

Figure 2.6: Standard MRO process flow for additive manufacturing Foundation [16]

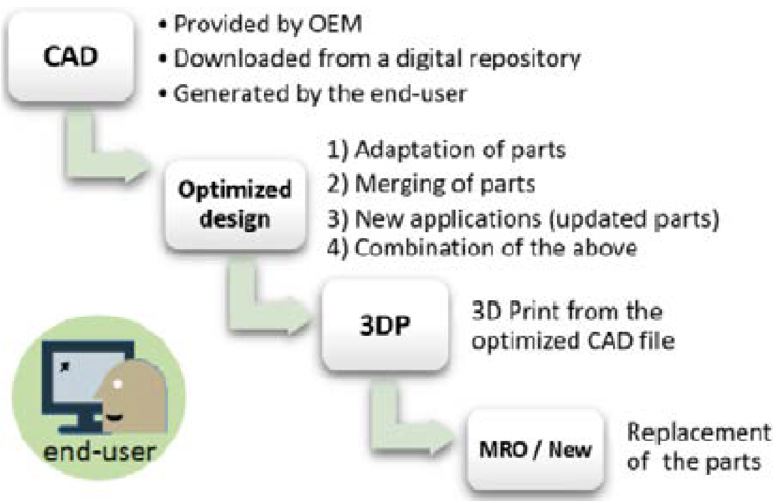

Figure 2.7: Optimized MRO process flow for additive manufacturing Foundation [16]

2.2.5 Sustainable Value Roadmapping Tool

The SVRT is a framework that mixes the sustainable value analysis tool, whom consider the sustainability implications of AM on the different phases of the product life cycle, with the strategic roadmapping approach, which is used to link the commercial (push) an technological (push) prospectives and to identify strategically when and which resources are needed to develop products and services. The objective then, is to detect the opportunities of value creation in a sustainable manner for all the stakeholders involved during the product life cycle, that here (figure 2.8) has been divided in three main parts: BoL (beginning of life), MoL (middle of life), EoL (end of life) .

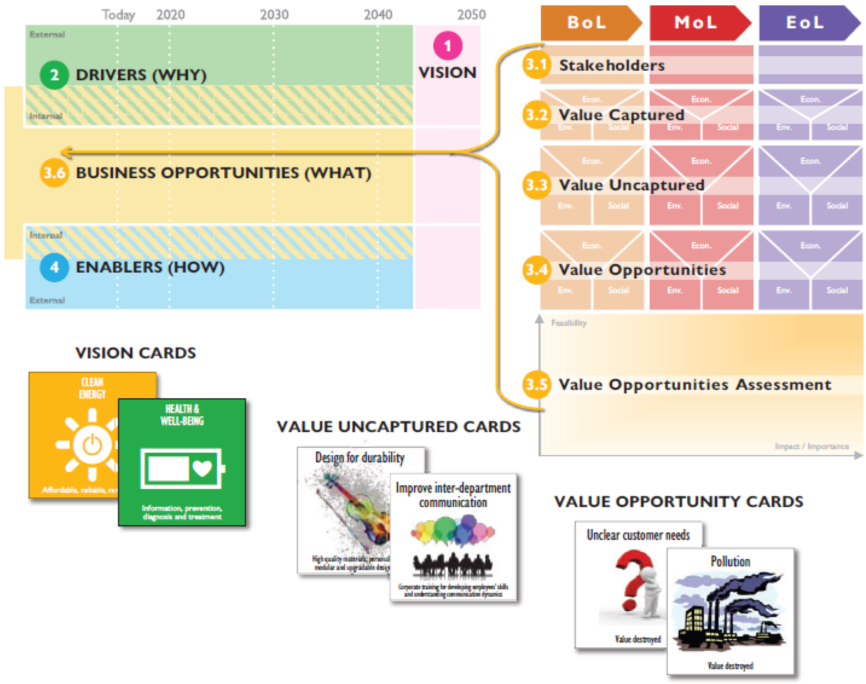

Figure 2.8: Sustainable Value Roadmapping Tool [16]

As illustrated in figure 2.8 the Sustainable Value Roadmapping Tool its a framework that includes two templates and three different kinds of cards: vision cards, value uncaptured cards and value opportunity cards. The SVTR process then consists of four main steps:

1. **Vision Identification:** set a sustainable vision in order to align the stakeholders goals;

2. **Drivers Identification:** this involves the definition of the internal and external factors that could enhance the AM adoption. Examples of external drivers are represented by political and legal implications related to intellectual property or even social and industry aspects. Instead the internal factors regard the long-term plans and the constrains faced by firms in terms of cost, time and resources;

3. **Business opportunities identification:** it helps to understand where the value is created from a sustainable point of view. This step brakes-down (figure 2.8) to the three life cycle's stages mentioned before. In particular the "beginning of life" stage includes manufacturing system configuration (push or pull, centralised or not, etc.), business model selection, product and process design. The "middle of life" stage instead, starts when the customer purchase the product and is related to the efficiency in use (in terms of energy consumption for example) and to the product life cycle extension Finally, the last stage "end of life" refers to closing the loop;

4. **Enablers identification:** the last step of the SVTR is useful to identify the factors that will enable the realization of the opportunities selected in the previous step. This includes the invention and development of new materials and techniques, the education of producers and designers, the quality standards and many other;

The cards depicted in figure 2.8 help to complete all the steps providing examples, general threats and opportunities.

2.3 AM and new product development

After the analysis of all the possible AM implications on the product life cycle, this section moves to the new product development approach, figure 2.9. Previously have been discussed the additive manufacturing implications on the product and process design phases. The following paragraphs instead concentrate, in first analysis on the test an prototyping phase, secondly on the production systems so from economies of scale to economies of one, short-run and customized production.

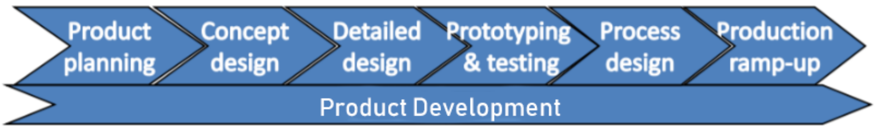

Figure 2.9: Product development process [10]

2.4 Short-run production

In the traditional and conventional processes, manufacturing parts is expensive and long-time taking. For instance, techniques like injection moulding can even take months and thousands of dollars to produce units and so they make advantage of large volume production to become cost efficient (economies of scale).

However, what if a client demands a small number of units, just for testing? Hence, in this sense, short-run manufacturing plays a crucial role, especially thanks to 3D printing, which has been making it more and more feasible. It simply consists of production of small number of units that allow higher flexibility and shorter lead time than conventional processes. There are different reasons why companies decide to implement this type of production:

- goods are made with the same materials with which they will be produced for to be sold
- to accept the *first-to-market* philosophy: company tries to introduce a limited quantity of products into the market in order to analyse the reaction of consumers and at the same time they produce a bigger quantity batch of the same product

- the product is destined to a market niche, thus it does not require high-volume production

Generally speaking, we can say that companies usually make use of short-run production for two kinds of products: prototypes, which give the start to mass production and finished goods, meaning products that are ready to be utilized by the final consumer.

2.4.1 Rapid Prototyping

Nowadays the role of prototypes has increased considerably, since it is able to support maximal reuse and innovative combinations of the existing techniques and the quick integration of new ones. However, it has not always been this way: in fact, in the previous decades prototypes were produced only at the end of the planning cycle and they were expensive, required lots of human resources and, as it was not enough, it even took long times since the tools were not always available. Today, instead, prototypes appear in a the early phase of planning and it allows developers, engineers and designers to gain more time and money and save resources.

As mentioned earlier, RP refers to a class of layer-based manufacturing technologies, as Stereolithography, Fused Deposition Modelling, Selective Laser Sintering, Sheet Lamination and 3D printing, which operate by gradually adding material layer by layer, and in a total automatic way, differently from the traditional processes.

This technology presents various advantages, among which: any shape or geometric feature can be produced, it allows reduction in time and cost (from 50% to 90%), errors and flaws can be detected at an early stage, it can be used in different industries and fields, discussions with the customer can start at an early stage, assemblies can be made directly in one go, material waste is reduced, no tooling is necessary and last but not least, the designers and the machinery can be in separate places.

However, also some drawbacks characterise RP: the price of machinery and material, the surface is usually rougher than the machined one, some materials are brittle and the strength of RP-parts are weaker in z-direction than in others.

Rapid prototyping represents today the main function of 3D printing; however, the level of technological progress does not allow mass production, even if it is possible to print items in limited quantity with perfect details and complicated forms, as we will be discussing in the next section. Nevertheless, RP is present in almost all sectors, since prototypes are much relevant when it comes to realise a product in large batches or very expensive; among them, there are: aviation, architecture, geography, art and entertainment, automotive, education, jewellery, medical, energy and consumer goods in general.

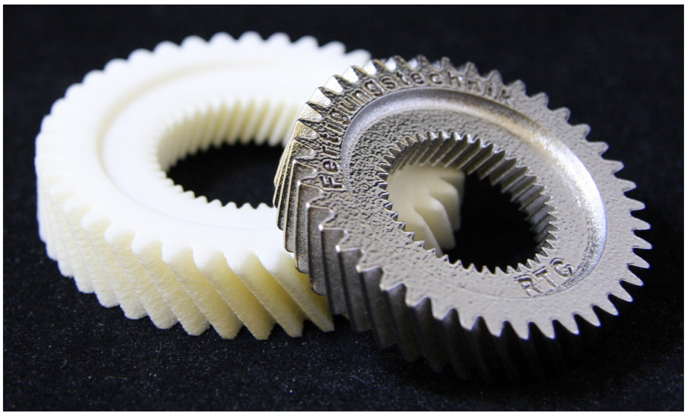

Figure 2.10: A gear made with the Rapid Prototyping technology [29]

Now we move our attention to a mere economical analysis, in order to figure out which are the main costs involved in manufacturing. Let us start from an equation:

$$COM_{i,t} = \frac{\sum_{t=t_0}^{t=t_1} \left(\sum_{i=1}^{n} \left(DMC_{t,i} + \ DLC_{t,i} \right) + \ IDMC_t \ + \ IDLC_t \right)}{n}$$

where:

- $COM_{i,t}$ represents the Cost Of Manufacturing in the t investigation time (from t_0 to t_1) at producing unit i
- $DMC_{i,t}$ represents the Direct Material Cost, so that the cost of any materials used in the final product, in the t investigation time (from t_0 to t_1) at producing unit i
- $IDMC_{i,t}$ represents the InDirect Material Cost, so that costs for activities or services that benefit more than one project, in the t investigation time (from t_0 to t_1) at producing unit i
- $DLC_{i,t}$ represents the Direct Labour Cost, so that labour costs that can be traced to individual units of products, in the t investigation time (from t_0 to t_1) at producing unit i. Sometimes this cost is called *touch labour*, because workers typically touch the product while making it. For instance, the cost of assembly line workers is a DLC
- $IDLC_{i,t}$ represents the InDirect Labour Cost, so that labour costs that cannot be physically traced to the creation of products or that can be only traced at a great cost or inconvenience, in the t investigation time (from t_0 to t_1) at producing unit i

That equation can be simplified as:

$$COM_{i,t} = \frac{\sum_{t=t_0}^{t=t_1} \left(\sum_{i=1}^{n} \left(DMC_{t,i} + \ DLC_{t,i} \right) + \ MOC_t \right)}{n}$$

where $MOC_{i,t}$ represents the Manufacturing Overhead Cost, which includes items as indirect material, indirect labour, maintenance and repairs on production equipment and heat and light, property taxes, depreciation and insurance on manufacturing facilities.

Finally, in order to obtain the Market Price (MP), we should add the Research and Development Costs (RDC), the Revenue (R), Taxes (T) and the Marketing Costs (MC):

$$MP_{i,t} = COM_{i,t} + \frac{\sum_{t=t_0}^{t=t_1} \left(\sum_{i=1}^{n} RDC_{t,i} + R_{t,i} + T_{t,i} + MC_{t,i} \right)}{n}$$

Given those variables, it has been studied that with the Rapid Prototyping, the direct and indirect costs can be importantly lowered with respect to regular linear production chain. Indeed, a recent research conducted on the production of a fork lift model has stated that its estimated cost is 2.5M USD and the production time is 52 weeks. On the other side, comparing this to the digital prototyping the cost would be around 75,000 USD and the production time would instead be 12 weeks.

2.4.2 Rapid Manufacturing

As mentioned earlier, 3D printing is not used for long-run production since it does not represent an advantage concerning time and cost. In fact, in the traditional manufacturing process the most used technology is *Injection Moulding*, in which parts are produced by injecting molten material into a mould; materials that can be used are various, ranging from metals (die-casting process), glasses, elastomers and confections to thermoplastic and thermosetting polymers. However, the main problem is that the mould is very expensive since it is made by hand or by delicate and sophisticated procedures; reason why, only an high production volume is able to amortize the costs but when it comes to few items production as Additive Manufacturing, and the mould can cost up to 8000 euros, amortization reveals to be hard.

For this reason, AM perfectly commits to Rapid Manufacturing (RM), which employs similar technologies and processes to RP, thus a tool-less manufacturing process. The Figure 3.16 below shows how AM technology for Rapid Manufacturing has been evolving during the last years, passing from 3.9% in 2003 to 42.6% of the total product and service revenues from AM; this market segment, then, grew 66.0% in 2014 to an estimated $. 1,748 billion.

This relevant growth has occurred because of the several advantages that AM has over conventional manufacturing processes; indeed, a producer would change to a new process only if this results to be cost effective, improves product functionality or increases responsiveness. Well, AM seems to meet all these requirements. Here is a list of the main advantages of AM concerning production:

- **Reduction of tooling**: differently from injection moulding or metal casting, AM reduces or totally eliminates tooling, which leads to benefits as cost and lead times decrease and improvement of product's time to market
- **Agile manufacturing operations**: reduction of tooling allows the option of changing a product mix on short notice; in fact, every build on an AM machine can be

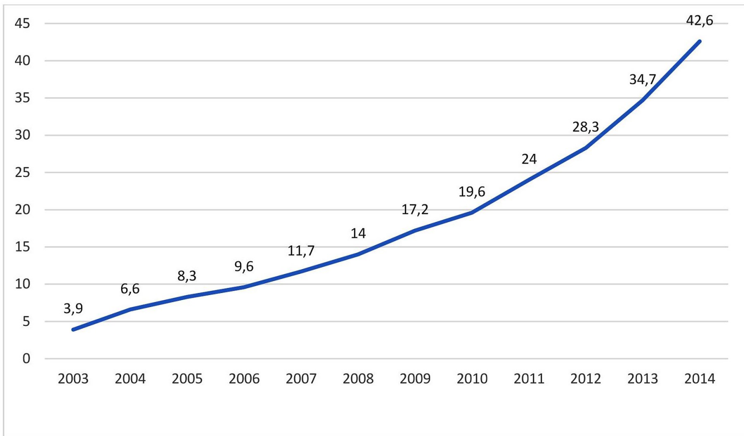

Figure 2.11: The use of AM for part production [66]

different, so they can be made on order. In this sense, producers can react more rapidly if market conditions would change and then they can modify production rates to match demand

- **Decentralized manufacturing**: if we consider a single AM machine capable to build complex part, economies of scale associated with large centralized companies with assembly lines tend to decrease. Reason why, decentralizing manufacturing in a regional or even local basis turns to be economically feasible
- **Reduction in inventory and part consolidation**: AM is able to reduce inventory by consolidating many parts into one, implying less need for bins for parts on the shop floor, on-site storage and off-site warehousing. Thanks to this, producers have more capital to invest, that can for example be used to develop new products. However, the main benefit consists in the ability to design products with fewer parts but more complex, rather than a large number of simple parts. This, in fact, cuts the overhead related to documentation and production planning and control; moreover, it takes less time and labour to assembly the product, leading to less overall manufacturing costs
- **Lightweighting**: no tooling and geometric freedom offered by AM allow parts to be to the same functional specifications as traditional parts, but using less material.
- **Improved fluid dynamics**: the flow efficiency of gases and liquids around or inside a product is strictly dependent on part geometry. Reason why, using the design freedom offered by AM, the optimum geometry can be obtained and at the same time one can get to improved fluid dynamics

However, there are some challenges that AM need to face and that can reduce its economic benefits:

- **Cost of machines and materials**: most AM machines are expensive to purchase and run, since a small number is sold and vendors need to recoup development costs. Moreover, machine depreciation lasts several years and it is divided among all the parts it builds. Material represents a direct cost included in the cost of each part and depends on the unit volume. In this sense, materials are expensive because it takes lot of money to produce them; on the other side, thermoplastic filaments used in the extrusion process are even used in the injection moulding one, with the difference that in this latter case the price is relatively low, while in the AM field they seem to be much higher, reason why the cost to the customer is artificially inflated. Only real market competitive conditions could decrease material costs

- **Speed and throughput**: Of course, a way to reduce the cost of AM parts id to increase the volume of production. How to? Faster operating speeds, larger build envelopes and easier loading and unloading of parts, like with palletized build chambers

- **Cost justification**: the fact that producing by AM costs too much with respect to the conventional processes is undeniable. However, it is shallow to just make a cost-comparison between the two ways of manufacturing, the traditional one will always have success. What it has to be done is to verify if savings can be found or if the value of a product can be increased. For instance, if a part of an airplane costs $500 dollars using AM while it costs $100 using casting, it does not seem like challenging. Nevertheless, if the weight can be decreased by 25% implying a $5,000 reduction in operating costs for the next 10 years, well, one may think about it

- **Traditional attitudes**: last but not least, the most difficult challenge to overcome in adopting AM is to convince people stuck on the traditional technology, those who do not feel like taking the risks of a new and unknown technology, and prefer to keep using the old one. Indeed, this problem can be fixed by only promoting the culture of innovation, disseminating the evidence that AM is shaping like the technology of the future. Not easy at all, since it is a challenge both for the manufacturers and for the user community

2.5 Customized Manufacturing

When thinking about the various advantages of Additive Manufacturing, one of the first that comes to mind is *customization*. What does it mean? Starting from the general definition, *Mass Customization* is the production, in series, of personalized goods or services that meet customers'needs. The main goal is to offer customized products but maintaining, at the same time, the low price, thanks to mass production. This way of producing is allowed by Computer Aided Manufacturing (CAD) or by configuring the desired product directly on-line. This all arises because customers tend to wish to have part of their personal aspect visible in a product they have spent money on, ranging from implementing their name into an existing product to changing the colour of their favourite product. However, with conventional manufacturing methods, this would be achieved by adjusting time by time the moulds or by manually adjusting the products according our requests. Needless to say, this is quite expensive and time-consuming. In fact, manually changing the product would require lot of labour, leading to so high costs that would be impossible to manage if one thinks to extend this kind of treatment to all customers. Moreover, even changing the moulds or the machineries every time seems to be a hard task. Reason why, customized production in the traditional manufacturing would embrace a little segment of the market (i.e. a well-off niche market), whose willingness to pay is as high as the price charged by the manufacturers adopting customization.

So, as to sum up, on a side we have customers wishing products in their own image, on the other side they do not want to pay an high price for this, an high price caused by additional or elaborate process steps, which make customization expensive. Is there any solution to this? Of course there is. In fact, Additive Manufacturing allows no additional costs for mass customization, since it does not require any moulds or specific tools, as we discussed about in the previous sections. Conversely, in this case, the process is very simple: the 3D file is updated by the customer herself and then the update is automatically implemented once the customer has expressed the changes she wishes for her product. Being an economy of one, the price is the same for either 1 or 10,000 objects, hence, you can customize as many products as you wish.

Apart from no affecting production costs, here are some other benefits of customization for AM:

- **A unique buyer and customer experience**: by offering your customers customized products, you will always be preferred with respect to other competitors. However, generally speaking, mass customization in AM is a new concept, which is resulting in the increase of customer satisfaction: in fact, thanks to customization, customers tend to feel more included in the production, leading to an attachment to the purchase

- **Competitive advantage**: When being able to offer customization to customers, it would be good to analyse what my competitors do. For example, companies like Nike give users the possibility to customize sneakers directly on the web site by integrating a pop-up 3D modeling windows, as shown in the Figure 2.12 below. Hence, by adding a similar customization option to your UI (User Interface), any changes made by the customer would be saved to your manufacturing system, thus creating a competitive advantage, since it allows you to know better your clients

- **Quality and speed**: with 3D printing, customers have the chance to select many different qualitative materials, from plastics to metals. Moreover, no needing additional tools, the manufacturing process results to be very fast

However, given these benefits, there are some challenges that mass customization has to face, like the cost of collecting data and including this into the design or to know when and how to integrate it. In conclusion, mass customization is surely able to disrupt a field, the challenge is to understand how and when.

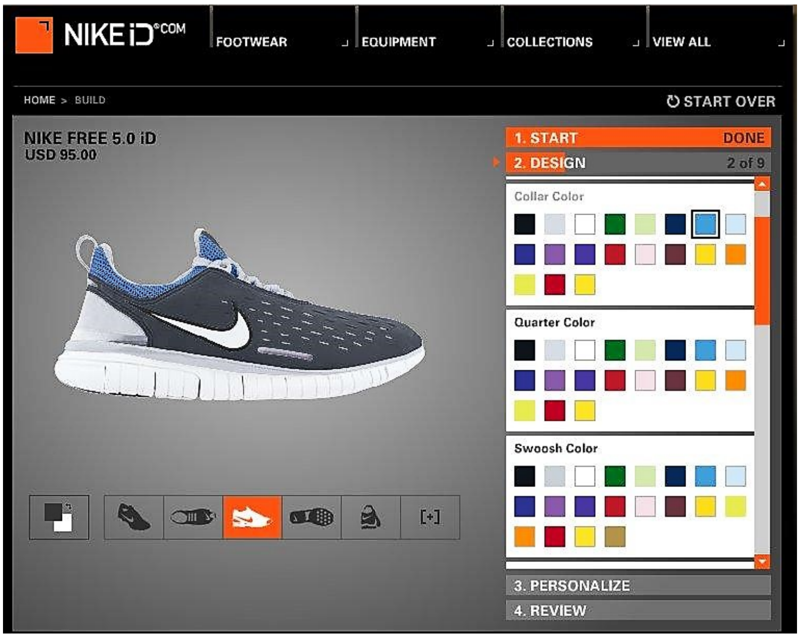

Figure 2.12: Nike ID allows customers to edit the sneakers according to their wishes [41]

2.6 Economies of scale vs Economies of one

Economies of scale happen when the average unit cost of a business decreases by increasing the total output. This phenomenon happens for several reasons:

- specialization of labour and more integrated technology increase production volumes
- bulk orders from suppliers, larger advertisements businesses and lower cost of capital can reduce the unit cost
- spread of internal functions (accounting, IT, marketing,...) costs through more units produced and sold can reduce costs

Now, differently from AM, the traditional and conventional production processes are characterised by a cost structure shaped by tooling expenses that are thought to be amortised in the long-run production; this, inevitably, leads to economies of scales deriving from indivisibilities, that is input factors that are available only in some minimum sizes (usually large) and cannot be divided into small sizes to be adapted to the small scale od production.

The interesting fact in AM is that, since it does not employ tooling, cutting, moulds, dies and so on, these economies of scale based on such features do not exist. Moreover, since the conventional processes usually belong to large and centralized manufacturing plants, some researchers stated that if AM were adopted in wide-scale, the importance of economies of scale would fall down, enabling then the decentralization to points of consumption.

Furthermore, a recent research has been conducted on two different AM systems, Electron Beam Melting (EBM) and Direct Metal Laser Sintering (DMLS), by constructing two production cost models with the aim of understanding if they could be adopted in the high volume manufacturing applications. Data showed very low deposition rates with respect to the conventional manufacturing processes (around 100 kg/h), ranging from 37.58 g/h for DMLS to 69.24 g/h for EBM. Indeed, this stated how system productivity is a main driver of manufacturing cost and thus, given the evident productivity limitations, currently it is hard to indicate AM systems to support high-volume production and so researchers should focus on reducing the various operating costs and on increasing the speed of deposition rates, instead of trying to reduce the cost of the AM machine. In addition to this technological barrier, others are:

- inability of processing large parts due to chamber size limitations
- process variability and lack of consistency among produced parts to ensure mechanical properties of the parts
- incompetency of the companies struggling with process automation and digitalization
- limited range of raw materials
- lack of international standardization

So, as to summarize, economies of scale are surely one of the most important properties of mass manufacturing. This last, which is carried out in large volumes, allows the reduction of cost per unit thanks to fixed-cost proration. However, since in AM there are no set-up costs (fixed, precisely), production in small batches is said to be economically feasible, thus AM embraces the field of the so-called "economies of one", which is more indicated for highly customizable products that can be built layer by layer; its main differences with economies of scale are shown in the Table 2.1 below.

The important fact is that both economies of scale and economies of one will continue to coexist but they will not meddle each other, meaning that factories based on economies of scale will keep supporting high-volume production, but when it comes to a very small production or, better, in single unit, or to highly demanded end-user customization, or to requests that cannot be met by conventional processes, 3D printing becomes a valid alternative.

2.7 Economic characteristics of AM

Now we move our focus on why Additive Manufacturing is advantageous even from a mere economical perspective. First of all, AM is more capable is those market segments where there is high demand for customization, flexibility, design complexity and high transportation costs for delivering final goods. Let us analyse them in detail. For what concerns design, iterations are relatively cheap and parts can be rapidly produced, as we discussed about earlier; in fact, AM is literally capable to produce any product design in

	Economies of Scale	Economies of one
Source of competitive advantage	Low cost, high volume, high variety	End-user customization
Supply chain	Sequential linear handoffs between distributed manufacturers with well-defined roles and responsibilities	Non-linear, localized collaboration with ill-defined roles and responsibilities
Distribution	High volume covers transportation costs	Direct interaction between local consumer/ client and producer
Economic model	Fixed costs + variable costs	Nearly all costs become variable
Design	Simplified designs dictated by manufacturing constraints	Complex and unique designs afford customization
Competition	Well-defined set of competitors	Continuously changing set of competitors

Table 2.1: Differences between economies of scale and economies of one

3D model, since it uses he layer-by-layer technology. In this way, the model can be modified from time to time according to the desire of a customer, rather then undergoing to the traditional production technology or supply chain constraints. This, indeed, constitutes a great advantage, since the higher is the customization, the higher is the willingness to pay of the client and the longer companies can charge a price premium. Moreover, this enables the so-called *Customer co-creation*, nowadays defined one of the best strategies to success. The interesting fact is the absence of additional costs in manufacturing as the product variety become larger, differently from conventional manufacturing where customization is gained by combining pre-assembled and modular parts, increasing both complexity and costs in the supply-chain. Hence, we can affirm that AM solves the *scale-scope dilemma*, from a cost perspective, since there are no drawbacks associated with an higher level of product variety. Another fact worth mentioning is the impact that AM can have on manufacturing locations. In fact, if one think about the relatively low fixed costs of machines and set-up, the production of small batch sizes which is economically feasible, high transportation costs for delivering final goods which are higher than transportation costs of raw materials and the penalties for late delivery, then she realizes that those factors can enable local production near the point of use. Moreover, there are new services like the start-up *TechShop* or *UPS* in U.S. and *La Poste* in France which facilitate the access to local AM manufacturing, in order to let small companies or consumers to produce 3D designs in a simple shop equipped with AM technology.

However, from the other side of the coin there are some limitations for AM. First of all, marginal production costs: in fact, since in AM there are no economies of scale but we have previously defined it as an economy of one, marginal costs tend to remain higher with respect to conventional manufacturing processes (featured by economies of scale) because of high material costs and energy intensity; despite this, these costs tend to decrease when additional suppliers enter the market. Another field in which AM could take several risks is the Intellectual Property (IP) of product designs. In fact, one can be sued for copying a physical product and then converting it into shareable 3D design data; reason why, in the era where digitalisation is the most important revolution, the issue of property rights can be one of the worst economic consequences for an AM manufacturer.

As to sum up, in the Table 2.2 below the main advantages and limitations of AM from an economical perspective are shown. Some of the limitations are inherent to the technology itself and so cannot be changed, others instead can be improved thanks to the achievements of research.

Opportunities	**Limitations**
Acceleration and simplification of product innovation: iterations are not costly and end products are rapidly available	High marginal cost of production (raw material costs and energy intensity)
Price premiums can be achieved through customization or functional improvement (e.g., lightweight) of products	No economies of scale
Customer co-design of products without incurring cost penalty in manufacturing	Missing quality standards
Resolving “scale-scope dilemma”: no cost penalties in manufacturing for higher product variety	Product offering limited to technological feasibility(solution space, reproducibility, quality, speed)
Inventories can become obsolete when supported by make-to-order processes	Intellectual property rights and warranty related limitations
Reduction of assembly work with one-step production of functional products	Training efforts required
Lowering barriers to market entry	Skilled labour and strong experience needed
Local production enabled	
Cost advantages of low-wage countries might diminish in the long run	

Table 2.2: AM technology’s opportunities and limitations from an economic perspective

2.8 Emerging business models of AM

Nowadays, Additive Manufacturing has given life to new ways of thinking and doing business, from fresh ideas to new business models. Moreover, it is leading to new educational and training programs offering experimentation, creativity, innovation and invention. In fact, educational institutions as schools as schools, universities and others are adding in their spaces 3D printing capabilities in their spaces for the public use, giving everyone the chance to immerse himself in this new and (almost) unexplored world. Many individuals and companies, furthermore, have launched new products, services and business that no one could even imagine in the previous decade. In the following subsections, we will analyse these emerging business models in detail.

2.8.1 Open-source and free resources

The RepRap (Replicating Rapid Prototyper) project, an initiative to develop low-cost 3D printer that can print most of its own components, was born in 2005 thanks to open-source licences. Magazine *MAKE:* listed 131 Maker Faires in 2014, and each of them increased the curiosity of the public through concepts of maker movement, 3D printing and creativity.

Another important fact is that Autodesk introduced *Spark* in 2014. It is an open-source platform which allows to develop applications whose aim is to improve AM software, hardware, materials and services. The company Autodesk is trying to realise how Spark can become a community of developers for the 3D printing industry ecosystem. Moreover, the platform was developed together with other relevant companies as HP, BigRep, ExOne, Shapeways, 3D Hubs, Local Motors, Ultimaker and Dremel.

A worth mentioning platform is *3D Hubs*, a network of more than 13,000 3D printers, linking resources to the buyers.

Last but not least, *Senvol* is a free database with more than 350 AM systems and more than 500 materials.

2.8.2 Maker spaces

Also known as hacker spaces and spawned in schools and educational institutes all around the world, maker spaces are locations where producers, Do-It-Yourself people, inventors and others people meet to collaborate and share their ideas, not only concerning 3D printing but also software, open hardware and traditional machine shop tools.

2.8.3 3D printing marketplaces and communities

Not only physical places, but even on-line marketplaces are growing. These include libraries of digital contents that can be purchased as data-set or as 3D-printed model. Most of the marketplaces offer Business-to-Consumer (B2C) commerce, while others, the biggest ones, offer also the Business-to-Business (B2B) one. Among the most famous of such marketplaces and communities there are Shapeways, Thingiverse, i.Materialise, Sculpteo, Threeding, Layer by Layer, Cuoyo, 3DLT, Archtype Z Studios, 3DShare and Rinkak.

2.8.4 Other AM business models

Nowadays, the AM service provider market covers many different business models. For instance, a service provider may have a low-cost 3D printer and find customers through on-line platforms as 3D Hubs; alternatively, other independent 3D print shops or large companies as UPS have local and tangible 3D printer related services, as depicted in

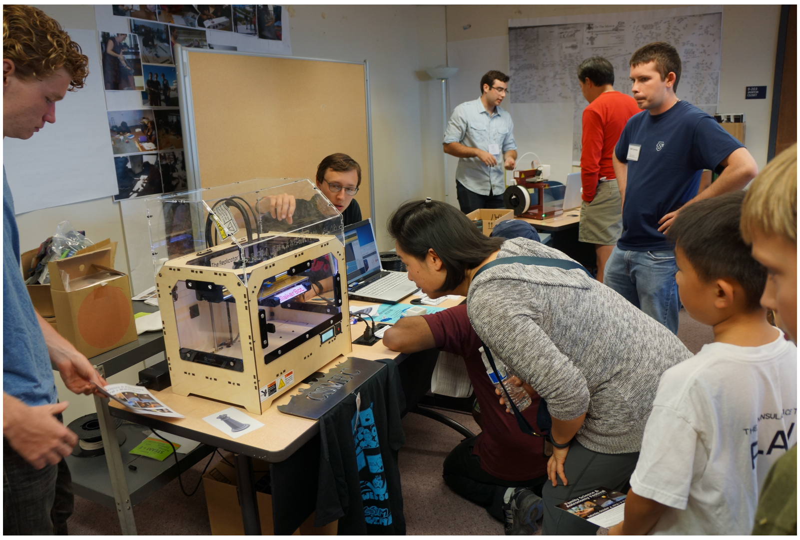

Figure 2.13: A Makerspace in the college of San Mateo, California [32]

Figure 2.14. In fact, UPS has declared the expansion of its 3D printing services to almost 100 locations in the United States.

Figure 2.14: A UPS store in U.S. with a 3D printing service [25]

On the other side, traditional service providers make use of AM equipment, combined with other engineering capabilities, reaching first the market made by industrial clients and OEMs (Original Equipment Manufacturer). Two huge corporations operating in this way are *Stratasys Direct Manufacturing* and *3D Systems' Quickparts*, which currently constitute a challenge for smaller competitors.

Another business model worth mentioning is the 3D scanning and printing in retail one. In fact, many companies have conducted their market decisions in this: Target, Hasbro, the British supermarket chain Asda, PetitMe, Clone Factory, FigurePrints and MakieLab.

All this innovation has created curiosity in many established manufacturers and important brands who have decided to enter the AM market. HP, Roland, Dremel, Ricoh and Kodak have all introduced 3D printers. Adobe, for instance, has added features in Photoshop CC for the preparation of data for 3D printing. Microsoft, too, has developed the 3D Manufacturing Format (3MF) as an alternative to STL and AMF. Ebay has launched in 2013 a new app which consents to print-on-demand products. Finally, companies such as Amazon, Dell, Home Depot, Office Depot and Staples are selling 3D printers.

Chapter 3

AM diffusion

3.1 Introduction

After having discussed about how Additive Manufacturing has impacted on the various production systems and its integration with their life-cycle phases, it is now time to move our focus on the mere diffusion of this phenomenon by analysing its S-Curve; subordinately, we will enlighten who are both the main producers and consumers of this sector, and how this has been growing thanks to them. Last but not least, our focus will move on the legal aspect, analysing which are the main issues related to the Intellectual Property of this phenomenon and to the ethics.

3.2 3D Printing innovation

First of all, this section defines the 3D printing taking into account the taxonomy and the different dimensions used to classify a technological innovation; in fact, this classification has been done from the users point of view, who nowadays are represented mostly by producers whom have already adopted AM for the production. A common mistake is to correspond an innovation to a single category, even if it has features of other ones. Subsequently, through the s-curve and hype effect concepts, we will express and explain the AM diffusion according to 3D printers' producers.

3.2.1 The innovation type

The first dimension to consider is represented by the nature of the innovation. The 3D technology constitutes a **product innovation** because it is embodied in the machines and represent a new paradigm with respect to the classic subtractive systems as has been explained in the previous chapters. Before the 80s it was not possible to find a machine with the characteristics of a 3D printer, thus, when the latter was launched on the market, there was a great clamour.

As it often happens, the product innovations are strongly correlated to process innovations. Apart from being a new kind of product available on the market, the 3D printers have modified the production methods too. The AM machines constitute a **process innovation** because they have changed the production technique of many goods that formerly were produced with traditional methods. For example, in the past the prototype manufacturing process required handicraft or complex works in order to obtain a functional good ensuring at the same time a certain level of quality; because of this, when the prototypes were too expensive, it was possible to create just a virtual model (i.e. 3D drawings).

The 3D printing brings a lot of advantages in the rapid prototyping field, indeed it allows to manufacture a model refined as if it was hand-crafted but with a lower production time. Moreover, the production cost is lower too, even if, as explained before, it depends mostly on which raw material is selected for the manufacturing process.

The second dimension is related to the intensity and to the width of the innovation, that is how much the new technology differs from old products and techniques. All the technologies under the AM umbrella embodies new technical features, completely different from the existing production processes and systems and for this reason these machines are a **radical innovation**. Wrongly, 3D printers could be thought as an incremental innovation of 2D printers. Nevertheless AM printing techniques has a new set of performance values that greatly differ from paper sheets printing: the 3D printing manufactures and creates a brand new product, it is not just some ink on a paper sheet. This new paradigm differs from the traditional production methods because the product manufacturing does not consist of many phases and machines anymore, just one machinery that correspond to only one process.

Moreover, 3D printers should be considered as a **competence destroying innovation**, given that the existing firms which manufacture products with traditional methods must put their knowledge aside if they want to switch to AM. As mentioned in the previous chapter, AM impacts on the whole product life cycle, so new strategies will be necessary in logistics, warehouse management, distribution and many other fields. Furthermore, the blue collars will be probably replaced by 3D skilled operators whom will monitor the printing phase.

Finally AM machines represent a **disruptive innovation** inasmuch they have the potential to completely change the manufacturing industry determining a change in market shares and competitors' positions and enabling new entrants or firms with a minor role to grab the lion's share. The latter scenario could actually happen for three main reasons:

- incumbents (product manufacturers) inability to follow the paradigm change given the sunk costs and old competencies or their status quo;

- incumbents focus on their current reference market (Christensen effect, see Figure 3.1 below) and its respective customers needs rather than exploring possible other markets, with lower claims in term of performance, immediately and concretely. In fact, the incumbents usually just invest some money in Research & Development to keep an eye on the new paradigm, where the trap is that sometimes the inferior performances of the emerging technology could either increase faster than expected or satisfy a new market even bigger than the old one. This behaviour is due to the perception of new markets as cannibal and to the shareholders pressure on management derived by the willing to have higher profitability now rather than pursue an innovation, mostly when the latter is proposed by the middle management which generally do not have enough authority;

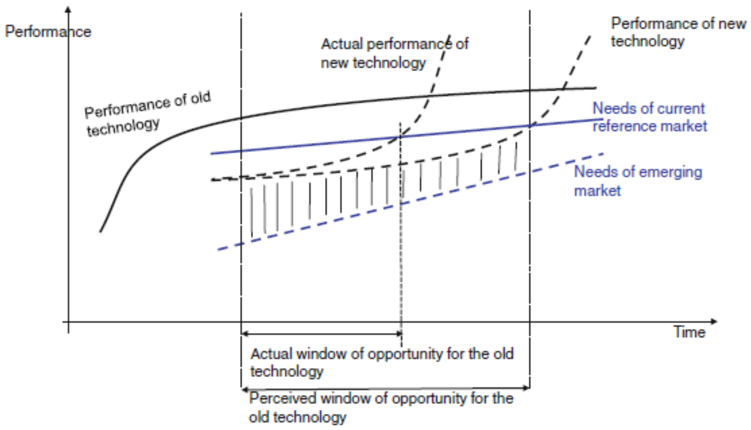

Figure 3.1: The Christensen Effect [10]

- incumbents and new entrants have different objective functions, consisting of increasing the profitability for the first and surviving for the second; this, of course, determine different timing of entry. In fact, if both believe that investment cost is going to decrease they will wait, if instead they know that costs will remain constant or increase, then they will look at the demand uncertainty, if it is low both will invest as soon as possible, otherwise the expected profitability will decrease and just the new entrants will invest early in the new paradigm hoping to destroy the old one and survive;

Notwithstanding these possible threats, the literature suggests to incumbents (manufacturing machines producers) a feasible strategy in order to delay as much as possible the new paradigm progress. In fact, incumbents could further increase the performances of the older paradigm (sailing ship effect) in such a way to create serious problems to the "new entrants" (3D printers manufacturers), because even if the latter own a better technology, the products they sell are not comparable with the incumbents ones in terms of performances.

Another possible reason for the delay of AM diffusion with respect to production could be represented by the incumbents' switching cost necessary to adapt themselves and their plants with the new technology; in fact, if substantial costs are needed the attractiveness of AM will decrease in the immediate present.

Finally, another opportunity for conventional manufacturer in order to survive could be reinvent themselves as specialists in refinements for AM printed parts, but clearly this option will be highly dependent on 3D printers performances, if the latter will give higher refined products or not.

3.2.2 The performance and diffusion S-curves of 3D printers

Taking into account a generic industry and the KPIs (Key Performance Indicators) for its products over time or investments, it is possible to draw a sequence of s-curves. The transition from one s-curve to another will represent a revolutionary innovation or a new technological paradigm, while moving along an s-curve it is possible to appreciate the evolution of a single paradigm (see Figure 3.2a): at the beginning with low performances, then always higher and growing faster proportionally with the diffusion until a technological limit is reached.

Putting instead the cumulated adoption sales on the Y axis and time on the X axis the diffusion curve is generated, which is really similar to the performance one as depicted in Figure 3.2b. The derivative of the diffusion curve is a bell-shaped curve which shows how adoptions sales change by the time (Figure 3.2c).

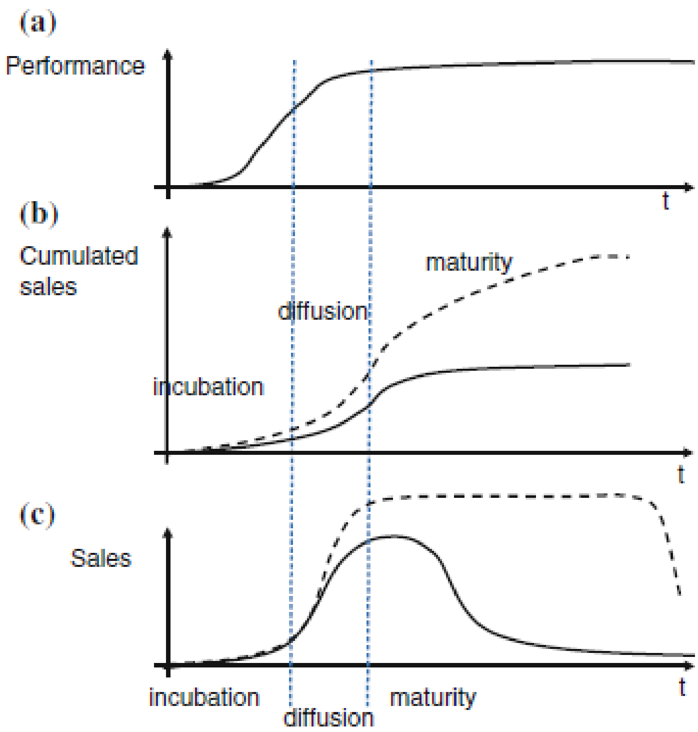

Figure 3.2: Performance and diffusion s-curves [10]

When it comes to the Additive Manufacturing paradigm and information from Wohlers Reports, we could state that from the 80's to 2000 3D printing has lived its incubation phase : little technology knowledge with small number of adopters. During this period, in fact, there were slow improvements for 3D printers, given the higher uncertainty. The experts' efforts were directed mainly towards the raw materials and to production processes.

Nowadays we are at the end of the diffusion phase, given that since 2000 so far there has been a significant growth for both performances and adopters; besides, the latter have been increasingly convinced about the utility of 3D printers.

Thanks to an increased degree of experience given by practice a more in-depth knowledge with a faster improvement rate of the technology has been reached. In this phase, in fact, the firms' focus is related to activities that help to keep constant the organizational effort, ensuring an increase in performance. An example is given by Scott Crump, who after the FDM patent filing, started to use all the possible production material that could fit with the Fusion Deposition Modeling technique. Moreover, he contributed with the development of ABS plastics.

These data are roughly confirmed in the two figures below taken from Wohlers report of 2015. The Figure 3.3 shows the number of industrial systems sold for 5000 dollars or more. Looking at the curve shape, it seems an half bell with a positive trend since 1988, characterised by a 25% average compound annual growth rate. The second one, Figure 3.4, refers instead to revenues deriving from all AM products (blue bars) and services worldwide.

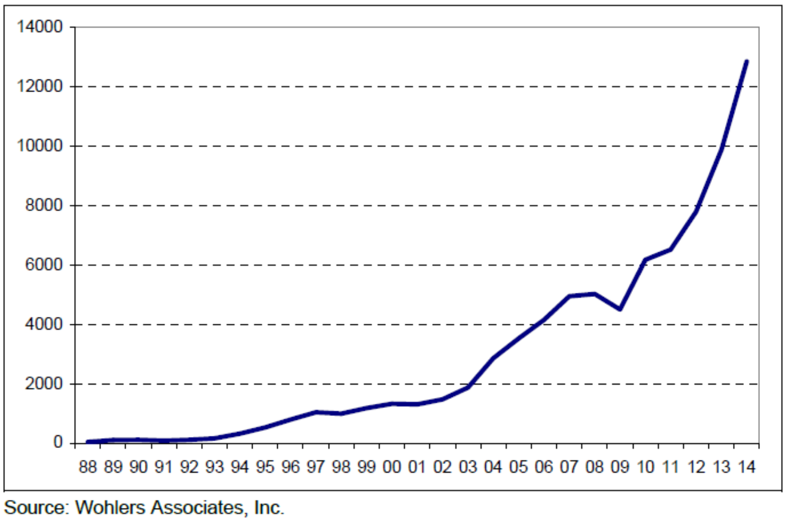

Figure 3.3: Industrial systems unit sales [66]

Finally, it starts the maturity phase where a technological limit will be reached and 3D printer's producers will rely mostly on additional and replacement sales. During this period, in fact, some standards will prevail on the others and the improvement rates will reduce. It is estimated that the future technological progress will allow to reduce the printing time of finished goods manufactured with AM machines: it is necessary at least to halve current production times.

Nevertheless, generally in the maturity phase, the course of a certain product depends

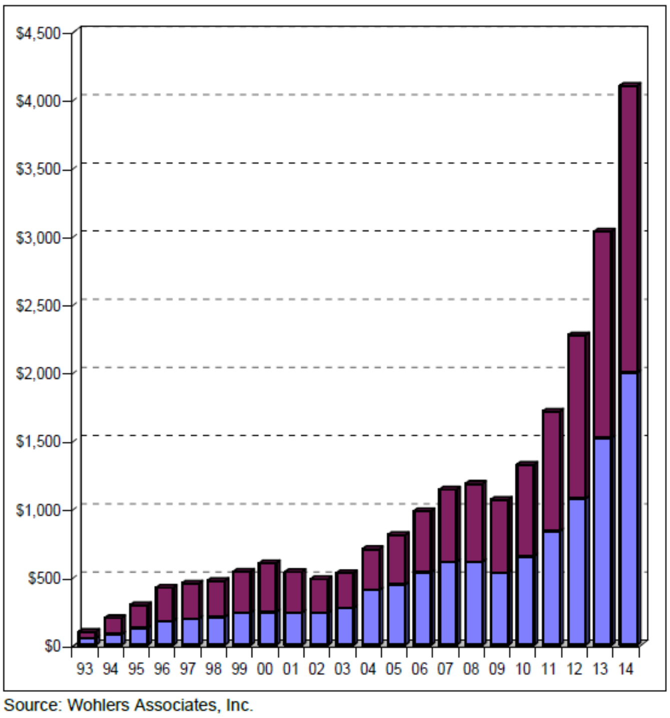

Figure 3.4: Worldwide revenues from AM products and services [66]

less on the refinement of technology and more on marketing actions. The biggest doubts are about where AM will be deployed, and many experts say that 3D printing will be successful just in rapid prototyping, but this is not a certainty.

3.2.3 The AM Hype Cycle

As suggested by Wohlers report, according to many consultants and experts, the analysis made in the previous subsection mainly regards the AM machines used for rapid prototyping rather than ones for the production of final products. In fact, the latter is still living the end of its incubation phase.

Moreover, AM has a lot of others potential applications in various industries, each of these in a different evolution phase. The latter statement is confirmed by the consultancy firm Gartner, which continuously analyses the expectations in technologies during the time through the hype cycles.

Hype cycles are used to understand the position of a given technology that is living its incubation phase. Generally, the latter is a really critical phase because there are a lot of promises and expectations that in many cases are hyperinflated, from which hype derives. During the hype cycle it is possible to distinguish five subphases (see Figure 3.5):

1. Technology Trigger : when the potential paradigm appears on the market;
2. Peak of inflated expectation: as the name suggests, here for many reasons the expectations of the market increase exaggeratedly;
3. Trough of disillusionment: the expectations do not materialise and the market loses its interest;
4. Slope of enlightenment: people start to understand better the technology and its real utility;
5. Plateau of productivity: the technology gets mature and everybody understand its value.

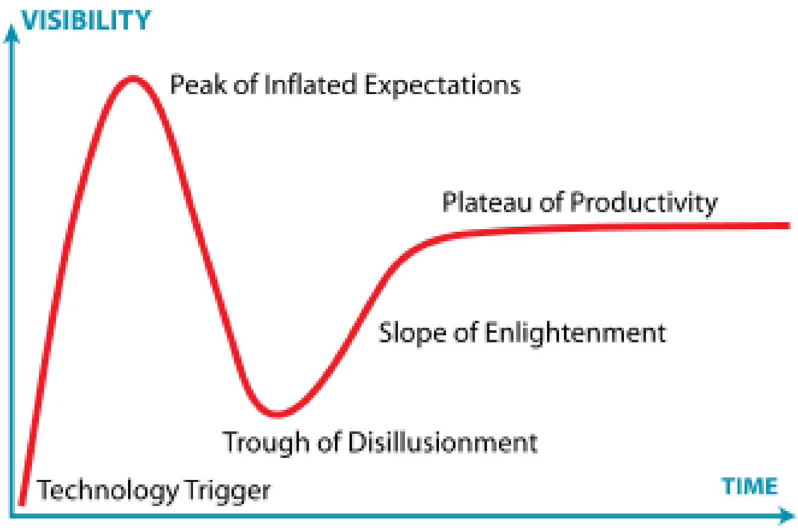

Figure 3.5: Hype cycle phases [26]

In figures 3.6 and 3.7 it is clearly observable an example of the hype effect in the stocks price's evolution of the two biggest 3D printer producers on the market, respectively 3D Systems and Stratasys. As depicted, they both have had the peak of inflated expectations between the end of 2013 and the beginning of 2014, where Stratays stock prices goes to 136,46 USD from an initial 1,83 USD at the end of 1994, instead 3D Systems ones goes to 96,42 USD. After that moment, the prices drop cogently, and now stock price of both firms is around 20-30 USD. This hypothesis is further confirmed by the hype cycle related to 3D printing (see Figure 3.8) proposed by the ICT consultancy firm Gartner. However, as explained above, the Gartner's hype cycles show many other applications of 3D printing that nowadays are in the peak of inflated expectations or just at the beginning of their hype cycle as depicted in Figure 3.9, examples are represented by: "3D Printing Workflow Software", "4D Printing", "Nanoscale 3D Printing" and many others.

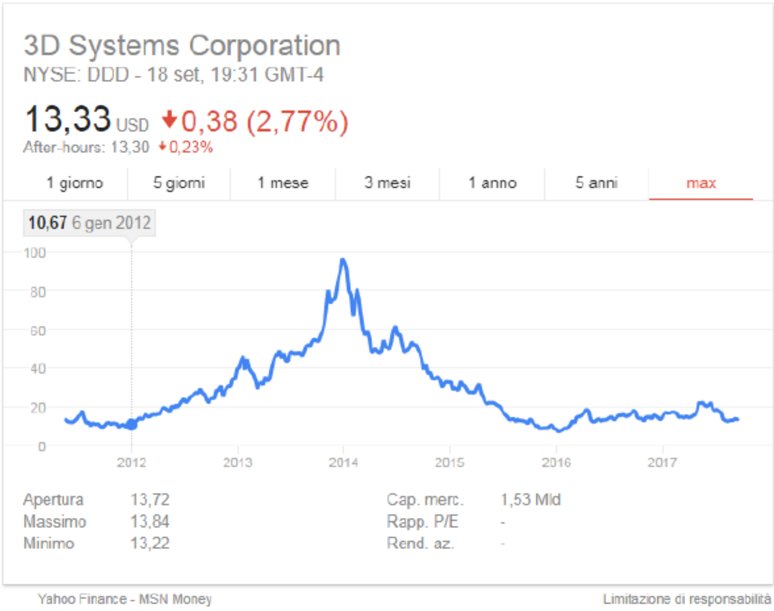

Figure 3.6: 3D Systems stock price evolution [3]

Figure 3.7: Stratasys stock price evolution [3]

3.3 AM industry growth

As it could be expected, growth in Additive Manufacturing has considerably accelerated over the last years, as more and more companies have decided to turn to this

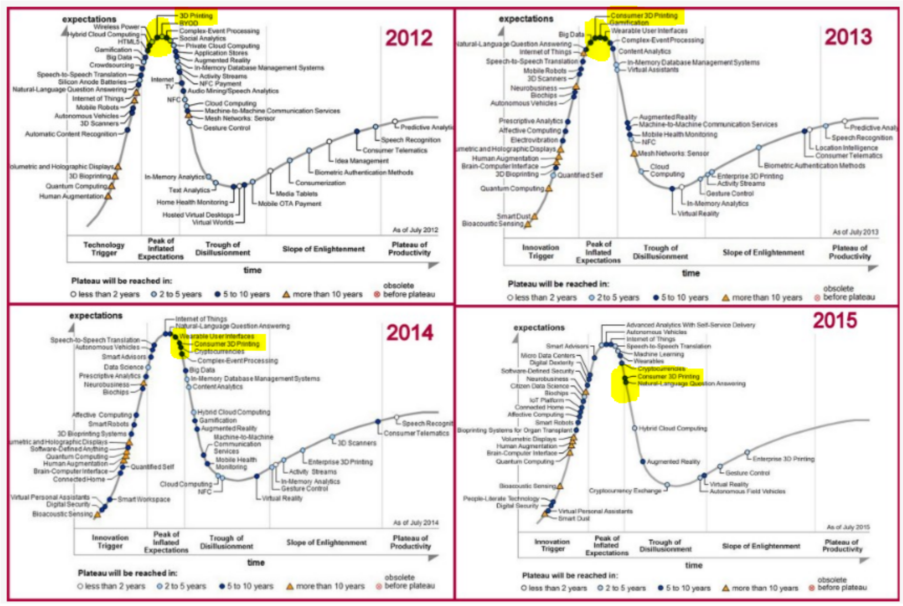

Figure 3.8: Gartner consumer 3D printing hype cycles [2]

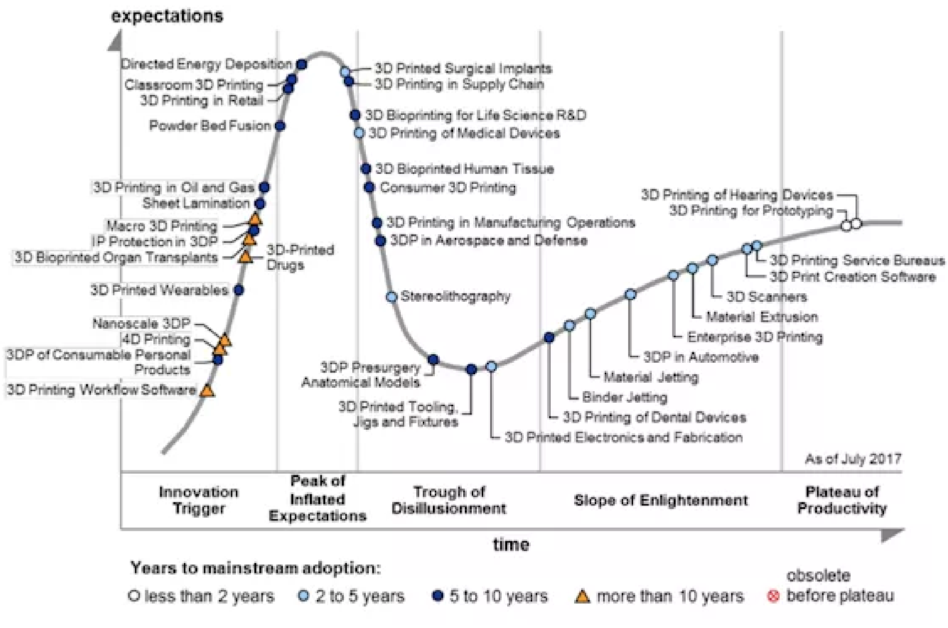

Figure 3.9: Gartner consumer 3D printing hype cycles for 2017 [64]

technology. In fact, the Compound Annual Growth Rate (CAGR) of worldwide revenues for the last 26 years is 27.3%, and that is an impressive result. Moreover, according to *Wohlers report 2017*, 97 manufacturers produced and sold AM systems in 2016, against the 62 companies in 2015 and 49 in 2014. They are all providing innovative products, spawning a never seen before competition in AM industry, which is putting pressure on the veteran AM systems producers. However, an interesting fact worth mentioning, deriving from *Wohlers report 2018*, is the incredible rise of the AM metal systems: in fact, 1768 units were sold in 2017 by 135 companies(see Figure 3.10 below) compared to 983 ones in 2016, involving instead 97 companies; hence, an increase of almost 80%. In addition, this rise has incredibly improved process monitoring and quality assurance measures in metal AM, even if there is much more work to do and at the same time, global producers are becoming aware of the benefits coming from manufacturing metal parts by applying AM technology.

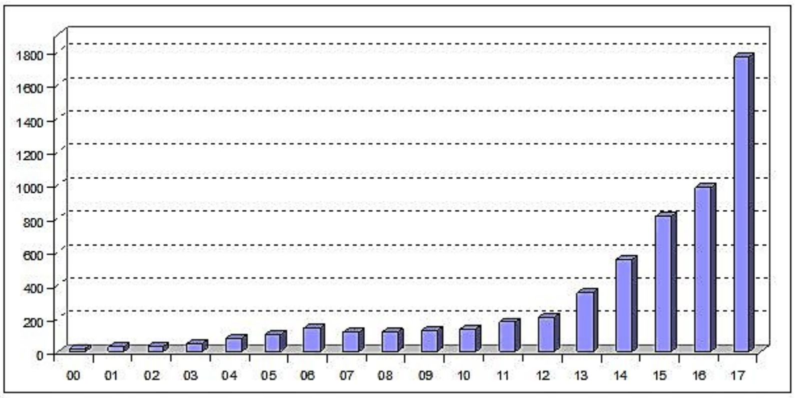

Figure 3.10: Rise of metal AM systems sold from 2000 to 2017 [67]

3.3.1 Revenues from AM

Generally speaking, in 2014, AM industry grew 35.2% to $ 4.103 billion. This is an information worth mentioning since it consists in the strongest growth in this sector in 18 years.

Digging deep in this estimate, we say that it includes all the products and services directly involved in AM, thus the primary market: AM systems, systems upgrades, materials, software, lasers for what concerns the products and system maintenance contracts, training, seminars, conferences, expositions, advertising, etc., for what concerns services. Moreover, the estimate includes both industrial systems and desktop 3D printers, while Research & Development (R&D) initiatives at OEMs are not included since it very hard (let us say impossible) to accurately quantify these kind of data.

The Table 3.1 below shows annual revenue growth percentages starting from 1989. The most relevant information emerging from the data is the incredible growth in the years 2010-2014. In terms of dollars, worldwide revenues deriving from products were $ 1.997 billion in 2014, increased of 31.6% with respect to 2013; concerning system and product upgrades, it was estimated $ 1.293 billion in 2014, increased of 32.57% from 2013. Lastly, revenues from AM services were estimated $ 2.105 billion dollars in 2014, with an increase of 38.9% with respect of 2013.

Year	Overall growth/decline	Products growth/decline	Services growth/decline
1989	153.2	153.2	
1990	25.6	25.6	
1991	32.7	32.7	
1992	18.5	18.5	
1993		28.1	
1994	99.7	59.4	139.4
1995	48.8	58.8	42.3
1996	42.6	41.0	43.9
1997	7.5	10.6	5.3
1998	4.6	6.3	3.3
1999	13.9	14.6	13.3
2000	11.5	2.1	18.9
2001	-10.5	-1.7	-16.4
2002	-10.0	-0.9	-17.2
2003	9.2	15.2	3.5
2004	33.3	48.3	17.5
2005	14.6	10.0	20.9
2006	21.7	20.0	23.7
2007	16.0	14.7	17.5
2008	3.7	0.0	7.9
2009	-9.8	-13.2	-6.2
2010	24.1	22.9	25.3
2011	29.4	28.0	30.7
2012	32.7	28.8	36.4
2013	33.4	41.3	26.3
2014	35.2	31.6	38.9

Table 3.1: Revenue growth percentages from 1989 to 2014

Concerning the Average Selling Price (ASP), we have been present at a speed falling off in the past years but then sharply rising from 2010 on, as shown in the Figure 3.11 below. We can see that the ASP was \$ 87,140 in 2014, compared to \$ 90,370 in 2013, \$ 75,000 in 2012 and \$ 73,800 in 2011. Keep in mind that in this calculation have been included only those AM systems which sell for more than \$ 5,000, hence desktop 3D are excluded.

Researchers have tried to figure out the reason of the sudden increase of ASP from 2010 on, arriving on the conclusion that high-end AM systems are selling well, combined to the fact that low-end systems are facing a bad selling period, due to the growth of the desktop 3D printers market, whose price is certainly lower.

One last point of discussion concerns the growth of material sales during the last years. In 2016, an estimated \$ 903 million was spent on materials for AM systems worldwide (see Figure 3.12 below), including both industrial machines and desktop 3D printers. Among the materials sold there are liquid photopolymers, powders, pellets, filaments, wires, sheet

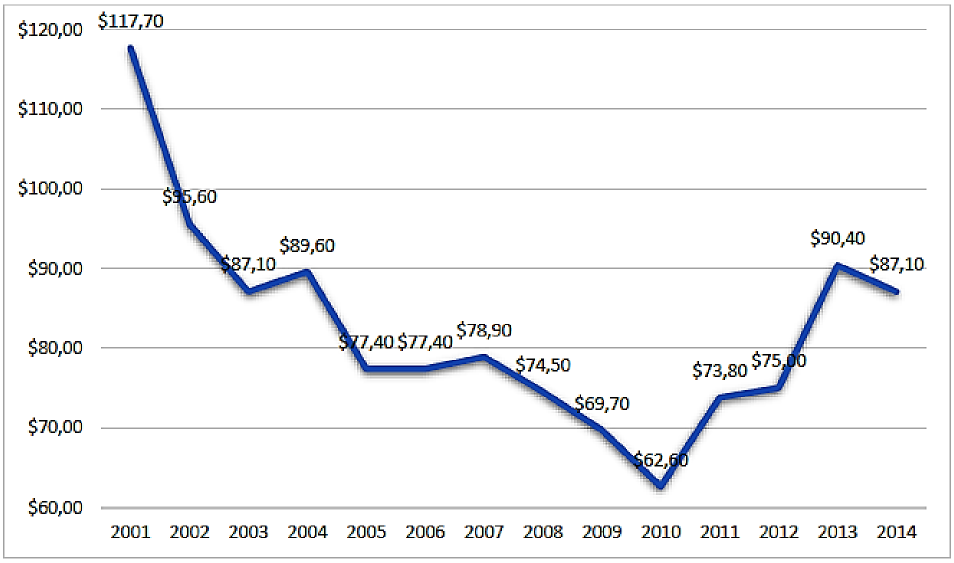

Figure 3.11: ASP trend in Additive Manufacturing from 2001 to 2014 [67]

materials and more.

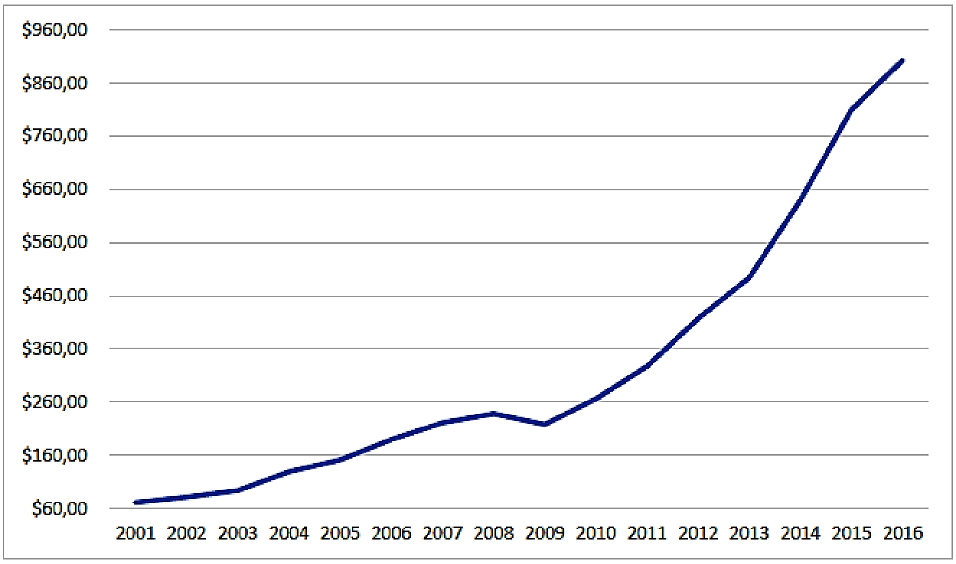

Figure 3.12: Growth of material sales from 2001 to 2016 [67]

3.3.2 Market shares

Who are the main competitors in this industry? The pie chart below (Fig. 3.13) shows the estimates of the unit sales market share among manufacturers of industrial AM systems in all the world, in 2014. Curious to say that despite *Stratasys*'s market share fell from 54.7% to 51.9%, the company still remains the leader for the 13th consecutive year.

In fact, in 2003 Stratasys became the biggest company in the AM industry and from that year it constantly expanded its lead. In 2014, Stratasys had sold around 41,869 industrial systems (cumulative estimate), and the total includes all the systems sold by Stratasys Inc., Objet (merged with Stratasys in 2012) and Solidscape (acquired by Stratasys in 2011).

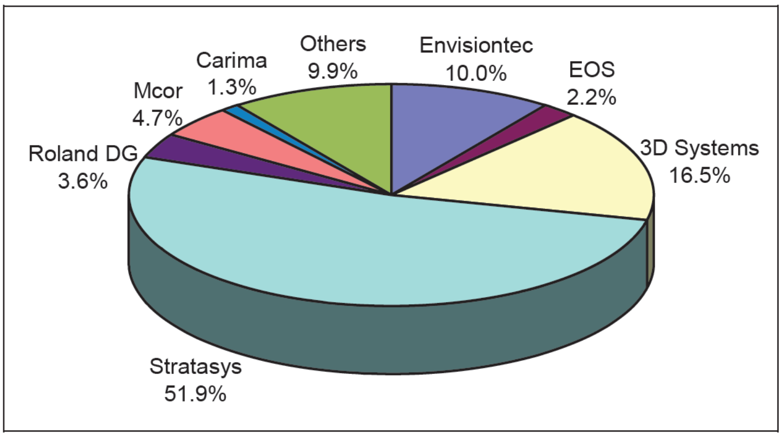

Figure 3.13: Unit sales market share estimates [67]

When it comes to market share by region, we should first say that U.S. are no longer the leader in the production and sales of AM systems, as depicted in the Figure 3.14. In fact, for 2014, Israel leads the position with 51.9% of unit sales; moreover, when Stratasys merged with the Israeli company Objet in December 2012, the new legal entity, namely Statasys Ltd., was registered as a company of Israel. This fact, indeed, provoked an incredible decline in the share of U.S. In fact, in 2012 U.S. produced around 61% of all industrial systems, falling to 18.6% in 2013 and to 17.2% in 2014.

Concerning Europe, instead, it went from 19.2% in 2012, to 21.0% in 2013 and to 22.0% in 2014. Finally, Asia's share grew from 5.7% to 9.0%.

In greater detail, the Figure 3.15 shows the cumulative total number of industrial AM systems sold from each geographic region beginning in 1988 through 2014. As depicted, U.S. system producers are responsible for 55.9% of all the machines sold over this period, which has fallen due to the fact that Stratasys became an Israeli company in 2013. Because of this, in fact, Israel's share has risen to 22.3%. Finally, Europe's share, instead, has increased from 12.9% to 14.4%.

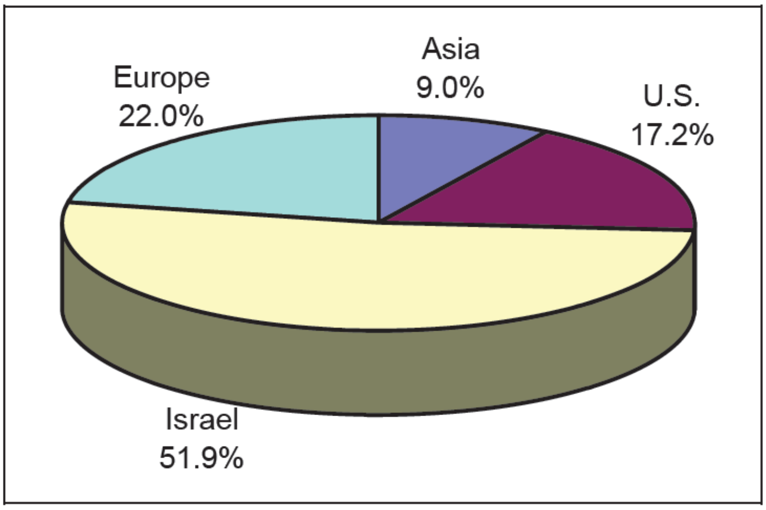

Figure 3.14: Region market share estimates [67]

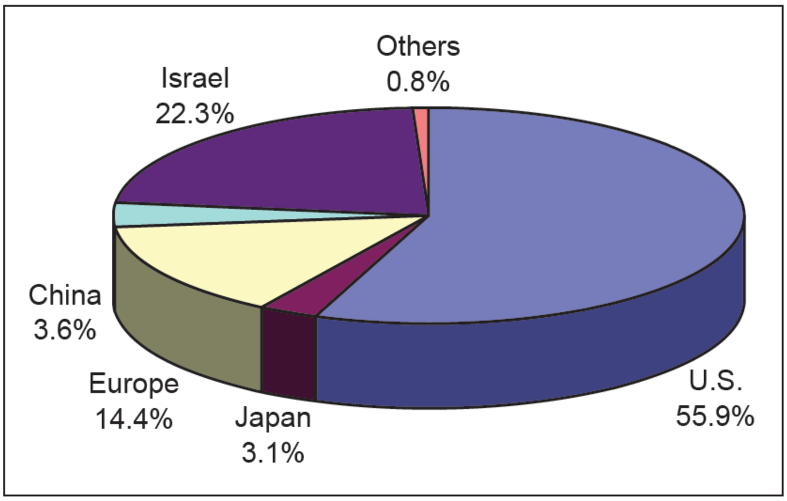

Figure 3.15: Cumulative total number of AM systems sold from each geographic region in 1988 through 2014 [67]

3.3.3 Market forecast for AM

According to Wohlers Report, which today is one of the most accurate sources in terms of reporting and market forecasts for the Additive Manufacturing world, revenues for 2016 amounted to $ 6.63 billion dollars, a sum that confirms the continuous increasing affinity between manufacturers and this technology.

However, with no doubt this number is quite far away from the $ 24 billion forecast for 2025 according to *Grand View Research*, but analysts are optimistic, given the growth of 22% for industrial printers and of 45% for desktop 3D printers. A curious and fun fact is that predictions go from $ 12 billion as forecasted by Lux Research to $ 180 billion forecasted by McKinsey. Why such discrepancy? Worth mentioning is a Deloitte report titled *"3D printing market outlook"* which was ordered by **Zortrax** (a Polish 3D printers producer); in this report, in fact, it is shown that the gap is conditioned both by the different parameters used and by the many factors that can condition the market. Reason why, Deloitte has accurately analysed the data collected in order to get a complete picture for the future of AM, involving both the estimated growth of the market by 2020 and the diffusion of the main printing technologies, as shown in the Figures 3.16 and 3.17 below.

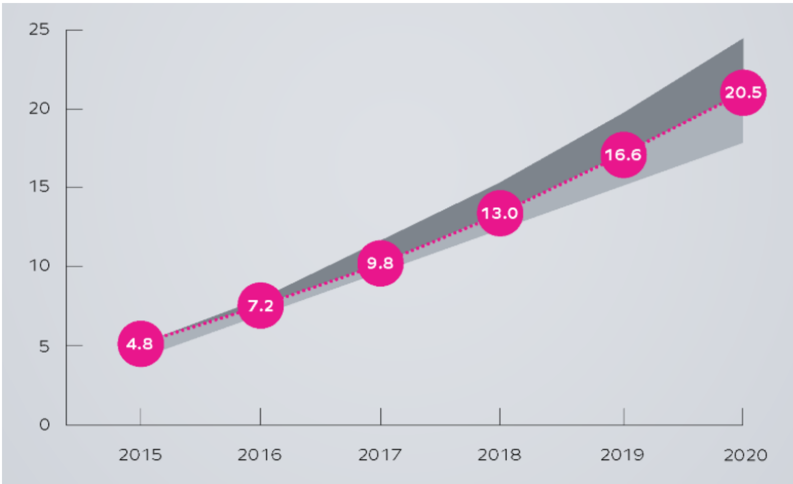

Figure 3.16: Estimated growth of the market by 2020 [47]

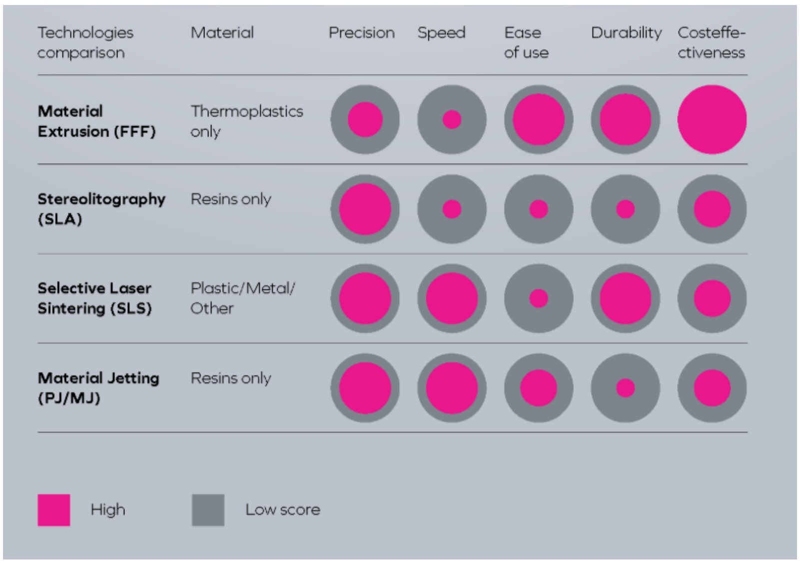

Figure 3.17: Technology overview [47]

Another reason for which we should be optimistic about the AM future is that we have finally expelled the media sensationalism related to false illusions concerning 3D printing. In fact, press did nothing but talking about 3D printing, just like we would all better have one in our home. What for? We should remember that innovation meets commercial success only if it responds to the real needs of the market. Moreover, history teaches us how stock market peaks concerning technology trends are the result of speculation instead of solid investments, and this all gives rise to unavoidable collapses.

Actualizing it, we could say that beyond all the investors who fell for it, producers like **Makerbot** bore the burnt of it, since its numbers (we talk about 90.000 printers sold in 2015) were considered disastrous since they did not respond to the predictions that presented the consumer brand **Stratasys** as the forerunner of a technology able to enter into all homes.

However, these numbers would have been anything but disappointing, if they had been evaluated according to more realist and informed parameters. After the alleged boom, the media started talking about 3D printing crisis, when this sector, even if we take into account the negative episodes we mentioned above, had recorded steady growth every year.

3.3.4 3D printing: what nowadays for?

Furthermore, another question we should answer is: what is the 3D printing nowadays for? In fact, on a side, we could say that emerging technologies create curiosity in investors, who want to build a competitive advantage for their company by adopting a new technology; on the other side, however, the same investors need to convince themselves that they are doing the right thing, and that investing in these technologies do create a real advantage and that it does not result in a mere marketing operation. Besides, what invest in? How to choose between all the products and solutions available on the market? And finally, which are the applications in which 3D printing is able to generate tangible advantages?

Indeed, thanks to an application based on AI, **Sculpteo** has processed a huge amount of data in order to propose a plausible answer to all the most frequent questions concerning 3D printing.

According to the annual report of 2017 (see Figure 3.18 below), investments on 3D printing have concerned *Rapid Prototyping* for 34% and the concept phase for 23%. These numbers add up to about 57% of the total, confirming the maturity of this technology in the design stage, and the main objectives are speeding up development (28%), customizing the product (16%) and increasing the flexibility of production (13%). Concerning the percentage linked to production, which is 22%, it is a little bit slow even if it s growing. Finally, even the market share related to 3D printing (10%) is also interesting, given its flexibility in the manufacturing of limited editions.

Another interesting interpretation is the attempt to predict the reasons why we producers should invest in 3D printing five years from 2017. An analysis that yields numbers substantially very similar to the current ones, as shown in the Figure 3.19 below.

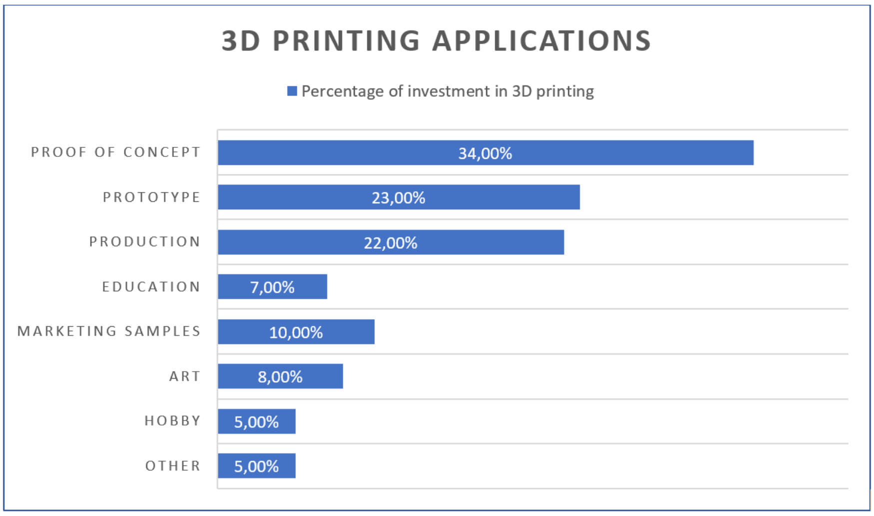

Figure 3.18: Analysis of main 3D printing applications in 2017 [47]

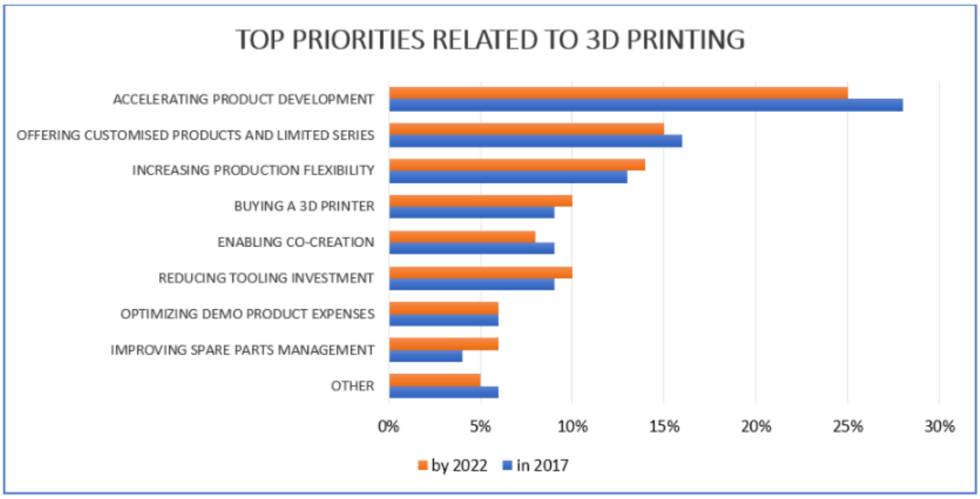

Figure 3.19: The main reasons related to investment in 3D printing from 2017 to 2022 [47]

3.3.5 Metal 3D printing

A manufacturing technology cannot be independent from the materials used to produce its creations. Indeed, people working in the industrial sector are strongly interested in the metal 3D printing and even in this case, numbers deriving from the market seem to be such encouraging. This statement has been confirmed by the American analyst **Smartech**, which talks about 950 million dollar total revenue for the 3D printing related to metallic powders; moreover, the worth mentioning fact is that this number is equivalent to about one-sixth of the total estimated volume for the entire 3D printing market.

According to an accurate forecast model, Smartech expects that Metal 3D printing may generate a volume of revenues up to 6.6 billion dollars within 2026, hence confirming its position as one of the technology areas with higher margins of potential growth.

Concerning motivations, **Sculpteo** identifies Metal 3D printing as a problem solver for the design of complex shapes which would be hard to be obtained by using conventional processes (16%) as shown in the Figure 3.20 below, for reducing cost (11%) and because it gives great flexibility in the production of limited editions (9%). Dealing with materials, analysts state that aluminium is the most used one (62%), followed by steel (22%) and titanium (8%). Low percentages, instead, belong to precious metals, confirming how the jewellery sector is currently using Metal 3D printing technologies especially for tooling and moulds manufacturing, rather than for the creation of the final product.

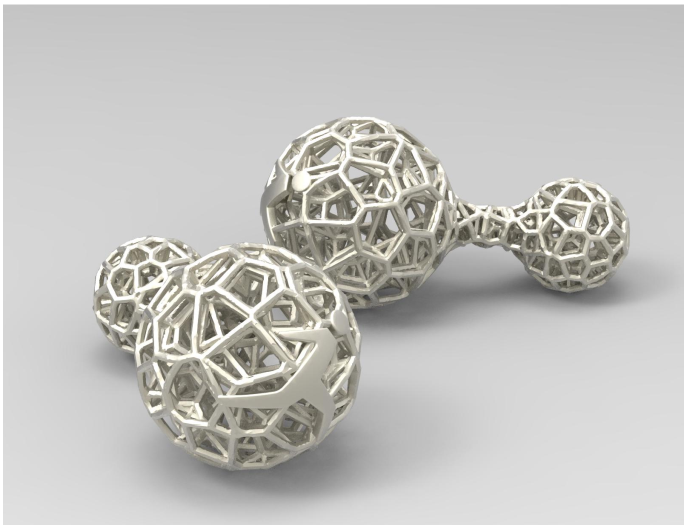

Figure 3.20: The use of additive technologies allows you to experiment with designs that are otherwise impossible to obtain [47]

Furthermore, even the volume of investments in this area confirm its future growth as a probable scenario. In fact, in 2016 General Electric entered the market by acquiring two metal additive production specialists, **Arcam** from Sweden and **Concept Laser** from Germany, for a total of about 1.4 billion dollars. With this move, followed by the opening of the Customer Experience Center in Munich, the American giant **GE Additive** intends to position itself on the European market. In the same way as GE, even **EOS**, world's leader producer of Metal 3D printing is taking similar initiatives to impose itself as a reality in the AM world.

For concluding, we can say that if progress in printing technologies and materials will create the conditions necessary to substitute conventional processes, implementing the benefits of Additive Manufacturing within companies will become a matter of expertise.

It would also be advisable to hire consultants on 3D Printing in order to evaluate and assess the effectiveness of an investment. How? Well, for instance an informed answer must be derived from a case-by-case assessment of the needs and objectives related to design, prototyping and production of a product.

3.4 3D printing and Intellectual Property rights

From batteries to human organs and even food, the boundaries of Additive Manufacturing are more and more expanding. Reason why, with larger scale adoption comes a rise in Intellectual Property (**IP**) disputes among the ones trying to obtain benefits from this technology; to best understand this, rights holders need to understand the complex legal landscape, including both opportunities and issues related to it.

3.4.1 IP Patent Law

Nowadays a lot of industries are adopting this technology with increasing frequency and even consumer use has grown, with home users who now can fabricate objects which have always been made in factories. Just to give some numbers, in the last ten years those engaged in AM filed more than 6,800 patent applications with the U.S. Patent and Trademark Office (**PTO**). In fact, many of the top patent holders are companies based in the U.S., even if inventors are not necessarily based in the same country; Japan and China take the second and third place, respectively.

Furthermore, as shown in the Table 3.2 below, the study by the U.K. Intellectual Property Office has identified some 3D printing-related patents with the most forward citations, which can be used as a measure of patent quality.

U.S. Patent number	Applicant	Publication date
5,204,055	MIT	April 20, 1993
4,863,538	University of Texas System	September 5, 1989
5,518,680	MIT	February 7, 1995
5,387,380	MIT	February 2, 1995
6,259,962	Object Geometries, Ltd.	July 10, 2001

Table 3.2: 3D printing patents with most forward citations, according to U.K. Intellectual Property Office

These patents are related to 3D printers, its components and 3D printing manufacturing processes. However, patents may also cover 3D printing raw materials as powders, filaments, liquids or sheets.

The interesting fact is that this manufacturing innovation reduces time and costs associated with all the conventional production processes, including prototyping, mould and die creation, milling, lathing, assembly and shipping. In addition, as AM keeps growing, more and cheaper supply chains try to enter the marketplace; therefore, an improved production capability combined with an increased technology accessibility and adoption, bring more players into this game, increasing also the possibility of clashes to defend their own competitive advantages. And, the focus of these fights is exactly the intellectual assets. In fact, given the large amount of articles that 3D printers can produce and the countless possible users, establishing actual knowledge of a specific, infringing patent may be hard to obtain. This is why even if consumer use of 3D printers may create multiple instances of infringement, policing and protecting patent rights in inventions copied on 3D printers may present relevant challenges for patent holders. That is why IP results vulnerable to exploitation and theft. In fact, the decreasing cost of 3D printers, scanners and 3D modelling technology together with enhancing capabilities makes the technology for IP theft more accessible to potential criminals; bear in mind that 3D printers do not need to produce a finished good in order to enable IP theft (i.e. the ability to make a wax mould from a scanned object would enable a thief to make bigger quantities of items that replicate the original).

The main consequence of these issues are the potential financial losses, according to Analyst group Gartner, which stated that 3D printing will result in the loss of at least $100 billion within this year. Stakeholders, indeed, should use the most protective means to avoid these rights disputes and their related financial drains. In fact, while in the past patent law has always provided the strongest protection for proprietary technical IP, when it comes to Additive Manufacturing, instead, the same law struggles to cover its innovations. Furthermore, after the introduction of novel rights and infringement means which have never been imagined before, AM has to face new and unexpected challenges when dealing with IP protection, leading stakeholders, as mentioned before, to understand and anticipate these vulnerabilities and hitches, trying to analyse all the available options under traditional patent law, trade secret, copyright and so on, thus determining the most cost-effective, predictable legal theories for defending their IP.

Hence, as to sum up, patent protections can help to safeguard AM's valuable inventions and each unauthorized use or replication represents an act of infringement. The main problem is that in all the technological contexts proving patent infringement can be both hard and costly, reason why patent holders should consider novel claim strategies in order to face it. Let us now move the focus on which are the main issues related to IP protection.

3.4.1.1 The "inventive concept" requirement

There is a lot of Intellectual Property in the field of AM, particularly at the level of the software that run the printers; however, while the U.S. Supreme Court is too generic in establishing software patentability, it actually requires an "inventive concept".

The main issue related to this is that finding this requirement can be difficult and expensive in most cases. In any case, generally speaking, we could say that the longer an AM software improves an existing printing process, the longer is the possibility to be patentable.

3.4.1.2 Lack of prior art

In order to obtain a patent, an IP holder must describe the art in such a way to contain all the aspects of the invention. In fact, being not too clear may put a technology's patentability at risk and this can easily happen when it comes to Additive Manufacturing.

In fact, given the transformative nature of AM and the lack of pre-existing technology in some cases, prior art may not exist and so stakeholders may face some difficulties in describing the novelty of their inventions. Furthermore, lack of prior art can also obstruct damage assessments during infringement actions.

3.4.1.3 Inherency doctrine

In U.S. patent law, the doctrine of inherency holds that, under some circumstances, prior art may be dependent not only on what it teaches but also on what is inherent, hence what derives from teachings. Indeed, under this doctrine, a single prior art reference can be found to anticipate a patented invention (an invention is said to be anticipated when it is too similar to an earlier invention to be considered novel. Since novelty is a requirement for patentability, anticipated inventions are not patentable) without declaring each feature of the earlier creation, if the inherent part of the anticipating reference is related to the missing aspect.

The issue is that, when it comes to AM, this doctrine may also impede damage assessments since, for instance, revolutionary materials can be found to depend potentially on inherent aspects of prior art.

3.4.1.4 Product-by-process inventions

Those kind of inventions may constitute another hurdle affecting AM producers. In fact, this doctrine presents some impediments when a new technology is used to make an old object; in fact, an old product does not become patentable just thanks to be made by a new process, since in assessing its patentability, the focus remains on the product rather than on the process.

Hence, the validity of a product-by-process claim keeps requiring an inventive concept, even if a novel process is used, so only the claimed process can be object of a patent infringement. Reason why, in maximizing IP protection, the holder should accurately inspect the products, materials and process involved.

3.4.1.5 Permissible repair or impermissible reconstruction

Another crucial issue related to AM patent holders is the repair and reconstruction risks created by doctrines allowing for copying of a patented object's elements admissible by law. In fact, while a complete reconstruction is such forbidden, repair is not. That is, under some circumstances, product holders could bypass the patent holder by just replicating a new part. And this is permissible by law.

Furthermore, patent holders should know that this right to some repairs may not be always contractually restricted. In fact, these restrictions may "stop" the purchaser of the product, but not the potential distributors, so they should take care about where applying the restrictions. Finally, while these repairs may represent a danger for the patent holders, patent infringement litigation for an object made on a 3D printer has yet to occur, thus stakeholders still have to face those challenges.

3.4.1.6 Novel patent strategies to consider

Since we are dealing with a challenging environment where old patent principles may no longer be suitable, AM innovators should pursue new ways for protecting their digital assets, even it could represents an hurdle in some circumstances, for example when dealing with patent law's historic uncertainty concerning patentability.

However, this uncertainty is often related with the patent acceptability of digital models. In fact, these files seem to be easy to be accessible by free riders, who are ready to freely print components and parts. If we consider it from another side, these strategies may be considered to protect assets. In fact, innovators should take into account patent claims directed at:

- the creation of distribution of digital files to be used in AM
- the scanning of products to create 3D digital files
- the importation of offshore 3D digital files

Another fact worth mentioning is that patented objects, often, include parts and components which tend to wear, thus they need to be replaced or repaired. And in this case, as mentioned before, third parties may bypass the patent holder and create their own replacement parts, which is allowed by law. However, if these parts are subject to utility or design patents, the third-party repair may result protected and so the reconstruction considered an infringement. Reason why, patent holders are struggling to extend the scope of their rights to cover replacement parts or components.

3.4.2 IP Trade Secret Law

Given the uncertainties, hurdles and expenses faced in protecting and defending patents, AM innovators should consider other ways to protect their products, potentially more predictable but more cost-effective and convenient. For instance, **trade secret law** could be a valid alternative. In fact, it provides easier burdens of proof and no filing requirement and it is able to protect designs, compilations, instruments, formulas and practices, hence, newer innovators ca use it to protect AM's adaptations, changes and processes to adapt their technologies for commercial applications, as long as patents become older. Furthermore, it also provides a valid alternative for protecting files and software in case the Supreme Court notes that it lacks an element of technological improvement and so cannot be sufficient to qualify for patent protection. Finally, differently from patent law, a trade secret holder is not required to prove usefulness, novelty or non-obviousness; it simply applies when whatever is declared as a secret is not known in the industry, and a secret represents a competitive advantage. For claiming misappropriation of a trade secret, the holder must prove that someone other than him has acquired the trade secret by improper means of duty breach.

Unfortunately, Trade Secret protection has its limitations. First of all, the kind of protection it provides results to be less strong than the one available under patent law. Moreover, proving misappropriation in the rapidly changing environment of Additive Manufacturing can turn to be challenging.

3.4.3 IP Copyright Law

Apart from patent law and trade secret law, another available source of AM Ip protection is **Copyright Law**. In fact, stakeholders can rely on this law to protect their assets from being unlawfully printed by customers, consumers or competitors. It results very helpful as kind of protection, since in the last years digitalization has completely transformed the world of illicit reproductions, making the replication of copyrighted works much easier.

Copyright surely covers design-oriented objects reproduced by a 3D printer, which would probably infringe the original work and also a scan of the copyrighted object would be considered an infringement. Another issue arises when stakeholders try to protect object including design elements; in fact, while functional works cannot be protected by copyright, courts apply a test after which if a useful article incorporates a design element that is physically or conceptually separable from the underlying product, the element is eligible for copyright protection. However, even if this test may provide some protection to AM copyright holders, it is not well defined and litigation may result to be costly.

As the previous ways of IP protection, even Copyright has its limitations. A significant example comes from the fact that copyright protection may not preclude others from producing or printing objects from a copyrighted build file if the objects being considered are functional and non-architectural. And, given that AM build files often regards functional products, especially in the industrial field, this may represent a relevant disadvantage.

In conclusion, it is evident to say that understanding the rapidly changing legal environment of Additive Manufacturing is crucial to protect the intellectual assets which constitute the focus of the technology evolution. As it was for previous disruptive innovations, AM will challenge existing legal IP principles. In fact, while traditional laws strongly strives to keep up with revolutionary innovations, litigations will keep pushing the boundaries of the current legal scope. In this sense, the main issue of stakeholders is to understand and anticipate this legal climate and always try to consider both advantages and disadvantages of the IP protection they are pursuing (patent, trade secret or copyright). In addition, the same stakeholders must recognize that despite the most strategic moves to protect their IP, the outcomes in this risky and continuously changing environment remain unpredictable. Given these preconditions, AM stakeholders can choose the most cost-effective and protective means for safeguarding the Intellectual Property of this disruptive technology.

3.5 AM & ethics

Notwithstanding all the possible benefits that could derive from the diffusion of AM, there are some issues needed to be addressed for what concern ethics. For the latter reasons this section will first analyse the environmental impact of AM offering some possible solutions to reduce inefficiencies according to some publications found in the database of scientific researches like ScienceDirect. In the second subsection, instead, we will discuss about the implications of 3D printing on the production of weapons taking a cue from an event already happened that created a great stir.

3.5.1 The environmental impact

Despite the current positive evolution of additive manufacturing technologies that is progressing from rapid prototyping to the production of final products, there are still a lot of questions about the possible negative externalities regarding the environment. Moreover, it could be thought that the latter are just caused by the resources consumption or by the energies required in the printing process itself, but actually a great impact is given by the feedstock production and the post treatment as well. In what follows, it will be analysed each of this phase reporting their impact on the environment.

As discussed above, each AM machine requires a specific raw material, that in many cases changes also from one printer to another, even if both embody the same technology. This results in an ulterior production process needed in order to obtain the feedstock material, that surely impact on the environment.

Unfortunately, nowadays there is a little documentation about these environmental performances, even if looking at Figure 3.21, it is possible to have an idea of how many steps are necessary to obtain metal AM powders (no data found for polymer or photopolymer). Furthermore, the Figure 3.22 shows the estimations about the additional energy needed to obtain one kilogram of metal powder starting from simple material shapes.

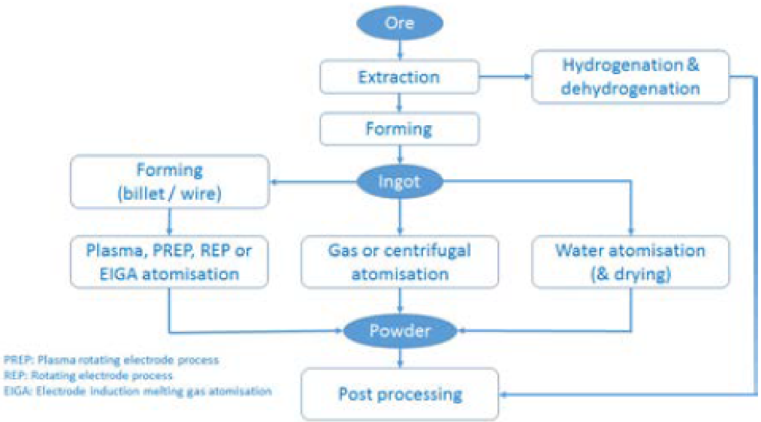

Figure 3.21: Metal atomization routes [30]

Material	SEC (MJ/kg)	Others	Reference
Ti_6Al_4V	7.02	Argon: 0,18m³/kg	[5]
$AlSi_{10}Mg$	8.1	n/a	[16]
Ti_6Al_4V	31.7	n/a	[17]
Ti_6AlV	23.8	Argon: 5,5m³/kg Process Efficiency: 97%	[18]

Figure 3.22: Metal atomization consumptions [30]

Concerning the production processes' environmental impact, so the resources needed to effectively print the final part, here is provided an idea for the 5 most common AM technologies:

- *Selective Laser Sintering*: as already discussed previously, this technique uses a laser to sinter the powder and requires a level of energy that goes from 107 to 145 MJ/Kg. However, as depicted in Figure 3.23, the biggest impact for the environment is represented by the waste powder fraction, around 45%;

- *Selective Laser Melting*: this technique uses a laser too as energy source, which requires from 83 to 588 MJ/Kg. Contrary to SLS, here the biggest environmental impact is represented by the printing process energy with a fraction of 66 to 75%, instead the powder production just account for 10-12% of the total impact. The other resources such as argon gas consumption, waste material and machine transportation have negligible impact;

- *Electron Beam Melting*: printers with this technology use an electron beam as energy source that uses from 60 to 375 MJ/Kg. As for SLM, the biggest impact is given by the process with a fraction of 74% on the total environmental impact;
- *Fused Deposition Modeling*: here the material is extruded through a nozzle and the specific energy consumption values varies between 83 and 1247 MJ/Kg. Unluckily, no more information are available, however has been estimated that 60% of the energy is deployed in order to warm up the system, consequently the overall consumption could be reduced if parts are produced consecutively;
- *Stereolithography*: in this process a photopolymer contained in a vat is cured with a laser and the only data available regards some model produced by 3D Systems with a specific energy consumption that goes from 50 to 150 MJ/Kg;

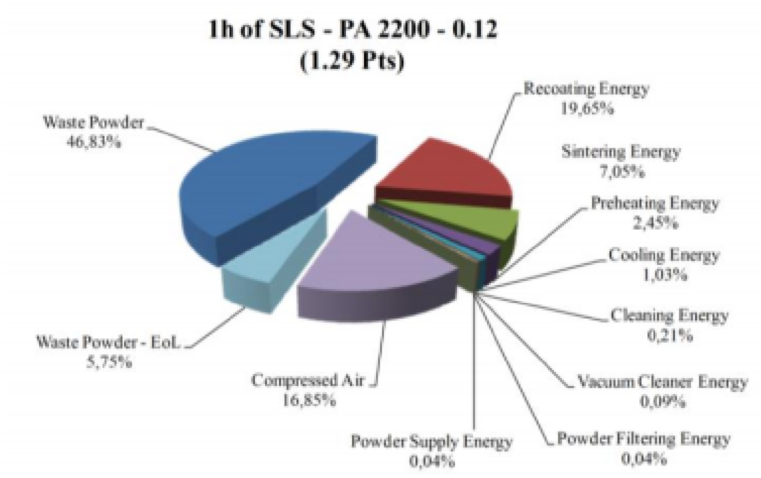

Figure 3.23: Environmental impact (ReCiPe Europe H/A method) distribution of 1 hour of SLS of PA2200 with a layer thickness of 120 µm. [30]

Finally, let us analyse the refinement process necessary after the printing phase for many technologies under the AM umbrella.

A common post treatment for laser based powder bed fusion systems is represented by the Electrical Discharge Machining. This is a wire erosion process used to separate parts from the build platform with a consumption of 142 MJ per printed product, that represent the 25% of the total energy used for the part production. Another post treatment, necessary to remove the support structures after the Fused Deposition Modeling printing, is the ultrasonic cleaning, which needs a power level of 250 Watt/hour on average.

Generally, both feedstock production and post processing are overlooked or neglected in the comparison with traditional manufacturing processes from an environmental point of view. In fact, taking into account all the phases, AM processes require an energy value 1

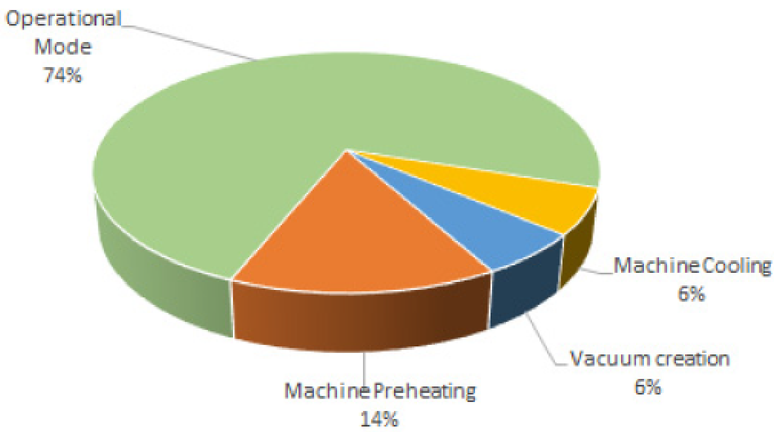

Figure 3.24: Distribution of energy consumption for the EBM production of an aeronautical turbine with a volume of 53.56cm^3. [30]

to 2 orders of magnitude higher than conventional ones. However, the additional impact of AM is compensated during the part use phase, since the introduction of lightweight components in some industries, such as automotive or aerospace, reduces the fuel consumption with a lower impact on the environment, as shown in Figure 3.25.

For concluding, another possible amount of environmental impact could be compensated increasing the reuse market. Indeed, customizing an old product could increase its value modifying the aesthetic and functional properties at the point of reuse. In such a way, in the long term the new material requirements for the global production will be reduced as well as the energy that will be saved for a new part production and the related transportation cost.

Transport system	Energy source	FRC [26]	Service life	Eco-Impact (ReCiPe H/A)	Life time savings (ReCiPe H/A)	Equivalent electrical energy
Gasoline car	Gasoline	0.5 l / (100kg*100km)	200000km	0.121 Pts/l	1.21 Pts/kg	85 MJ
Diesel car	Diesel	0.24 l / (100kg*100km)	200000km	0.141 Pts/l	0.68 Pts/kg	48 MJ
Short distance train	Electricity	300 kJ / (1000kg*km)	3.5*10^6 km	0.051 Pts/kWh	14.88 Pts/kg	1050 MJ
Long distance train	Electricity	100 kJ / (1000kg*km)	10*10^6 km	0.051 Pts/kWh	14.17 Pts/kg	1000 MJ
Short distance aircraft	Kerosene	12.5 ton / (100kg*year)	25 year	0.134 Pts/l	335 Pts/kg	23647 MJ
Long distance aircraft	Kerosene	103 ton / (100kg*year)	25 year	0.134 Pts/l	2760 Pts/kg	194852 MJ

Figure 3.25: Fuel consumption reduction coefficients for different vehicle types. [30]

3.5.2 3D printing & weapons production

The deployment of 3D printing technology for the production of weapons it is not for sure the first thought a person could do when speaking about additive manufacturing. However, this technological paradigm results suitable also for this purpose and it could represent a serious risk for the society at all.

In 2012, the firm producer of 3D desktop printers, MakerBot, shifted from open source capability to proprietary control, caused by differences between the founders. This created a lot of hate in their open source community or, more in general, in people who believe that technology should be completely free. It was probably this reason to push Cody Wilson (see Figure 3.26), an anarchist law student from Texas, to start sharing the blueprints of a 3D printable gun on thingiverse.com, MakerBot's online repository of digital designs. As a counter move, Bre Pettis MakerBot's founder, pulled the files, showing himself inconsistent with the previously statement "We are all collaborating together and we are a community of equals". The reaction of Wilson was to found Defense Distributed, a no-profit organization with the purpose of developing and publishing open source weapon designs through the 3D search engine Defcad, which was created exactly for this purpose. After this episode, Stratasys seizes some uPrint SE Plus Printer from Wilson, subsequently to his further attempt to print guns. In few weeks he decided to answer again publishing *Liberator*, the world's first fully printed gun. However, 4 days after Wilson released his video, Makerbot published a new video where RoboHand prosthetic was advertised, printable with just 5 dollars in building material (see Figure 3.27). The winner at the end, at least for the Internet, was Liberator with 3.7 million views against the 484,000 of Robohand.

However, after a while, the State Department demanded that Cody Wilson take down his gun files.

Figure 3.26: Cody Wilson with a 3D printed gun. [14]

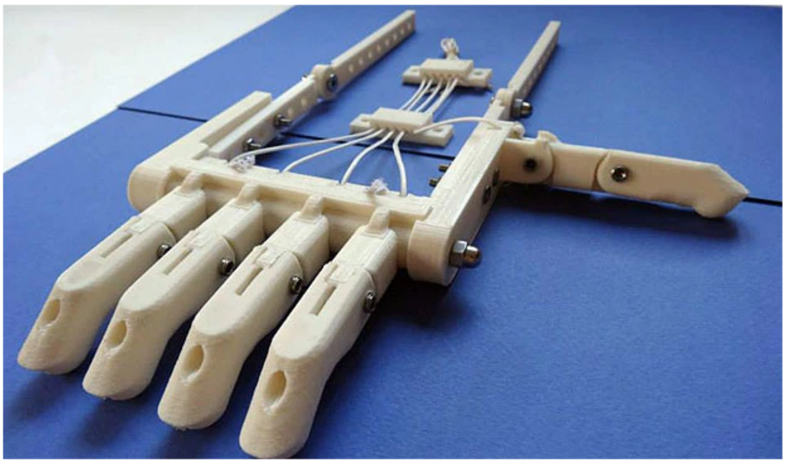

Figure 3.27: Robohand from MakerBot. [64]

Even if this topic is probably far from the engineering and management interest, it has been included in this thesis with the aim of emphasizing the potentiality of this technological paradigm that could transform itself in something that goes against community's welfare. In fact, 3D printers allows to manufacture even worst weapons than a gun without the serial number, examples are represented by major military hardware, new concepts in war-making equipment and weapons of mass destruction, just think about chemical and biological weapon which could be easier to produce thanks to nanoscale 3D printing or in general with AM machines.

Hence, in the light of the prediction that one day in the future everyone will own a 3D printer, the formulation of appropriate regulation is necessary.

Chapter 4

Italian Orthopaedic Sector Analysis

4.1 Introduction

In this chapter has been analysed the Italian orthopaedic sector, however given the specificity of the latter, there are not many data available, for this reason most of the informations reported in this chapter regards the wider Italian sector of medical devices taken from the consultancy firm Assobiomedica, which annually release a report on production, research and innovation of the medical devices. Analysing these reports it is possible to understand that the Italian medical device sector has the following features:

- it is a wide sector extremely heterogeneous which hardly fits with numbers and statistics given its undefined borders;
- it is a landing sector for technologies coming from different fields;
- it is highly innovative and constantly evolving where the relations between clinical world, companies, start-ups and research centres are very close and traceable to a dynamic framework;
- product(service)-oriented which tends to coincide with the orientation to social welfare generating positive externalities.

4.2 A general background on prostheses

A prosthesis is intended as an artificial device, customized or mass-produced, used to substitute partially or completely a part of the body (limbs, organs or tissues) not entirely formed for congenital causes or damaged after a traumatic event, in order to return to patient a better body aesthetics or functionality. Nowadays different types of prosthesis are available on the market, nevertheless most of the firms, belonging to the merchandise class 325030, manufacture and sell hearing aids(small percentage) and orthopaedic prostheses. The latter kind could be further divided into two subcategories:

- *Exoskeletal Prosthesis*: these devices provide a support thanks to a structure placed outside the body, with the intent to returning the functionality of a missing limb. Usually these prosthesis are customised on the patient by prostheticians, whom use craft techniques or, lately, even 3D printers. A further classification divide these prosthesis in traditional or modular, the latter replicates better the skeleton contrary to the traditional which is only a rigid structure (figures 4.1 and 4.2).

- *Endoprosthesis*: these are orthopaedic implants placed entirely inside the body through surgical operations with the aim of returning joint functionality. The materials used to manufacture these devices are generally titanium alloys and stainless steel, to give strength at the framework, and plastic to replicate the cartilage (figure 4.3).

Figure 4.1: Traditional prosthesis with a rigid structure [45]

Figure 4.2: Modular prosthesis [42]

Figure 4.3: Total hip replacement [59]

4.3 Medical devices Industry

The focus of this chapter is on all the Italian firms belonging to the orthopaedic sector. In order to define this market segment has been considered the 2007 ATECO code 325030 corresponding to the *manufacture of orthopaedic prosthesis, other prosthesis and aids (including repairs)*. ATECO stands for ATtività ECOnomiche (in English Economic Activities) and is an automatic coding tool adopted by the Italian statistical institute ISTAT for national statistical surveys with economic nature.

However, after some research it emerged the unavailability of many data regarding this specific sector, for this reason each of the following sections firstly reports informations about the wider Italian Medical Devices Industry, subsequently it compares the latter to the orthopaedic prostheses segment, when is possible.

Assobiomedica, a federation belonging to the General Confederation of Italian Industry (Confidustria), annually releases a report about the production, research and innovation in the medical devices' Italian sector. From the report released in 2017 with data related to 2016, it emerges that, the Italian Medical Devices industry (64,5% public and 35,5% private sector) worth 11,4 billions of euros and that, the 7,7% of total Italian Health Expenditure is invested in medical devices.

Regarding the medical devices industry (Assobiomedica report 2017), there is a total of 3.883 firms, 95% of these SME, plus 349 start-up with a total of 76.000 of employees, 36% graduates engineers or researchers. Moreover the 51% of the firms is represented by manufacturers, 44% are distributors and 5% service companies. The 25% of 349 start-ups has been founded in the last 4 years and the 2% work using 3D printers.

As shown in figure 4.4 the prostheses manufacturing segment is to include in the biomedical sector, that accounts for the 45% of total medical devices industry dimension, around 5,13 billions of euros, and 1.755 firms. Nevertheless the Italian biomedical sector includes all the single user devices, aside orthopaedic prosthesis there are also patches,needles and syringes, pacemakers, stents (tubular supports placed temporarily inside a blood vessel) and defibrillators. Moreover the biomedical sector includes also the eye-wear market(frames, corrective lenses, sun lenses and contact lenses), which represents the 7% of this segment, and companies operating in the dental market (4% of biomedical segment).

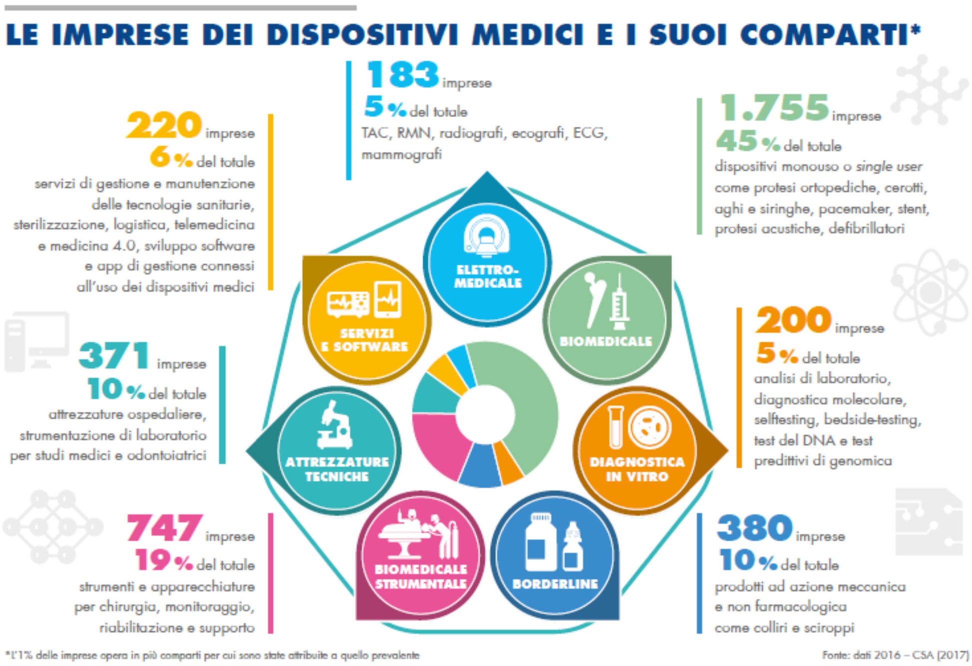

Figure 4.4: Segments' division of the italian medical devices' industry [5]

Focusing on the 2016 Assobiomedica report, which analyses mainly data relative to 2014 in a more complete way than 2017 version, it arises that the number of firm was 4.480 (13% more) with a total of 68.000 employees (10% less), with a domestic demand of 9,2 billions of euros (23% less than 2016). For what concern biomedical sector, it was the same, around 45% of total with 1.961 firms, 87% of these were small enterprises, 10% medium and 3% were big companies. Moreover the 52% of the firms in the biomedical segment were distributors and 48% manufacturers.

Comparing the report of 2016 with the 2017's one it is possible to say that the number of manufacturers is slightly decreased during last years, in fact in 2014 they represent the 53% (2.374 firms) of total, 87,9% of these is represented by direct manufacturers, the others are manufacturers for third parties. On contrary the number of distributors and service providers is increased from, respectively, 43% (1908 companies) and 4% (198 firms). The multinational companies are the 13%, 60% are foreigners and 40% from Italy (so the 8%, corresponding to 342 of the total firms in the sector had a foreign ownership), nevertheless their revenues accounts for 60% of total.

Taking into account the Assobiomedica report released in 2014 it is possible to extrapolate mainly informations about 2012, when in Italy the medical devices' sector consisted of 3.025 firms which employed 54.000 workers, with a domestic demand of 9,2 billions of euros. As for the most recent versions, the biomedical sector accounted for 44% of the total industry, 89% of these were small enterprises and 11% medium size, however the 17% of the industry's companies did not exclusively deal with medical devices. Moreover the 67% of the firms in the biomedical segment were distributors and 33% manufacturers. For what concern the kind of firms in the industry, 56% of these it is a distributor (13 percentage points more than 2014), the 40% of the firms are manufacturers (13 percentage points less than 2014), 81% of the latter were direct manufacturers and the 18% manufacturers for third parties, while the remaining part of service providers it was always at 4%. In 2014 the multinational companies were 477, around 16% of total„ nevertheless their revenues accounts for 60% of total, instead the 84% had Italian origins. The 11% (329) of sector had foreign ownership and the remaining 89% had Italian origins.

The census of 2011, described in the 2013 Assobiomedica report, recorded 3037 firms in the medical device sector. For what concern the sub-sectors of this industry, the biomedical one accounts for the 45% both in number of firms and revenues on the overall. The 90% of the firms in the biomedical sector were small size, the 8% was medium and the remaining 2% was big. Talking about the activities performed by the firms in the medical device sector, for 2011 is reported that 59% of these were distributors (3 percentage points more than 2012), 37% were manufacturers and services stuck at 4%. In 2011 the number of multinational companies was 519, 17% of total, which generated the 70% of all the revenues. Similarly, it is noted that 10% of the companies in the sector are controlled by foreign capital, but considering their revenues, it represents 49% of the total. This is what emerges considering the ultimate owner, or the ultimate shareholder - be it a person or a company - to whom the control of the various companies can be traced back. Most of these companies are attributable to ultimate US, German or Swiss owners.

The first edition of the report released by Assobiomedica in 2012 and conducted on 2009 data, reports that there were 2,735 companies, over 52 thousand employees, and total Italian revenues of 16.8 billion euros, compared to an internal market for medical devices estimated at 8.6 billion euros, of which about 6.3 billion (73%) to public demand, equal to 5.7% of the total public health expenditure and to 19.1% of public health expenditure in goods and services (respectively equal to 110.219 and 32.846 billion euros). The 90% is represented by micro (60.8%) and small enterprises (27.4%), these percentages are even higher in the southern and insular regions; the large companies are 2.4% (or 62) and of these almost 70% have their registered offices in Lombardy (36) and Tuscany (7). In the 2012 version of the report there are not information about the dimension of the sub-sectors, instead there was yet the distinction of firms considering the activities performed, indeed in 2009 the amount of distributors was around 65%, quite 6 percentage points more than 2012), the 30% were manufacturers (7 percentage points less 2012) and the remaining 4% was constituted by service providers. Moreover in 2009 the multinational firms were the 10,8% of the total and that 8,2% of the companies in the sector were controlled by foreign capital.

Talking about start-ups, these are all that innovative and technological companies, currently active in the industry, or with applications in it, which, having not yet developed all the organizational processes necessary to be on the market, are presumably looking for strategic partners.

The census, updated to June 2016 (Assobiomedica report 2016), recorded 328 start-ups with activities of interest for the manufacture of medical devices. The 58% of these start-ups is concentrated in four regions: Lombardy always leading, followed by Emilia-Romagna, Piedmont and Tuscany. After these, even if with a much lower number, there are Friuli-Venezia Giulia, Veneto, Sardinia and Campania, coming to represent over 80% of the total. The 45% of start-ups has been originated as a spin-off of public research, this percentage has decreased in the last years; 31% is incubated. The average age is higher than 5 years, but the 33% percent was born for less than 48 months, 87% of these are registered in the Register of innovative start-ups introduced by the so-colled "Decreto Sviluppo bis"(DL 179/12). Start-ups born in the most recent period are mostly active in the services and software sector, that is also the segment in which the start-up defined as innovative, according to the law 221/2012 of the DL 179/12, are more active. The 29% of start-ups work in the field of advanced diagnostics, in line with the trend "personalized approach and therapy-diagnosis integration", which is intended to be followed at European level for the competitive development of the member countries of the Union.

The census, updated to June 2014 (Assobiomedica report 2014), recorded 255 start-ups (so in 2 years the number has increased by 28%) with activities of interest for the manufacture of medical devices. The 61% (3 percentage points more than 2016) is concentrated in the same 4 regions listed for 2016. The 55% (10 percentage points more than 2016) was generated as a spin-off of public research and the 36%(3 percentage points more than 2016) is incubated.

The report released in 2013 by Assobiomedica says that the number of firms in the same year was 214 and these were concentrated in the same amount and in the same regions reported for 2014. The 67% (6 percentage points more than 2014) over all the start-ups was generated as a spin-off of public research, the remaining part instead constituted atypical company spin-offs, or start-ups created by processes of outsourcing of research activities by consolidated companies. Unlike the following years, most of the surveyed start-ups are not incubated in science and technology parks or other structures dedicated to promoting innovation; under this profile, start-ups in Tuscany and above all in Piedmont are the exception. In 2011 (Assobiomedica report 2012) 146 start-ups were registered (of which 95 university spin-offs, equal to 65%); of these, 68 were start-ups with a secure and exclusive biomedical or diagnostic vocation born between 2001 and 2011 (of which 52 university spin-offs, equal to 76%).

The business network contract, governed by law 33 of 9 April 2009, is a legal instrument, through which the member companies mutually undertake to implement shared projects and objectives to expand their innovative capacity and competitiveness on the market, without having to renounce its independence, autonomy and specialities. Any company, regardless of its form of organization (corporations, persons, etc.), size (large, small or medium), and the scope of activities (manufacturing, commercial, services, etc.) can subscribe to the related contract and thus become part of a business network. Since 2009 this regulatory instrument has been progressively spreading. According to the latest update in May 2016, networks involving companies in the medical devices sector are 33, with 66 companies in the sector out of a total of 195 companies. The regions with the highest number of companies participating in the networks are: Emilia Romagna, Lombardy and Friuli Venezia Giulia, with 18, 15 and 10 companies respectively involved. Also in the field of medical devices, the network contract confirms the same characteristic aspects that have emerged in consideration of its overall diffusion:

- strong territoriality: 65% of the medical device companies involved in a network are concentrated in three regions (Emilia-Romagna, Lombardy and Friuli-Venezia Giulia) and 76% of the networks are uni-regional;
- relatively small size of networks and businesses: 52% of networks are composed of fewer than four companies and 85% of no more than six; there are large (3%) and above all medium-sized enterprises (19%) even if the weight of micro and small size companies is prevalent (in 77% of cases these are companies with less than 50 employees);
- transversality of each network with respect to the sectors involved and the nature of the enterprises: 54% of the networks of which medical device companies belong include firms that also operate in other sectors, moreover for 73% of the cases are involved in the same network manufacturing, commercial and service companies.

4.3.1 Medical Devices Supply Structure

In this subsection is reported the number companies in 2016 (Assobiomedica 2017), their respective plants and the amount of people employed in the medical device segment, for each region that has identified the health sector as a development driver, divided by northern Italy (figure 4.5), central Italy (figure 4.6), south Italy and islands (figure 4.7). In northern Italy there is a total of 2.655 companies and start-up (67% of the total), 50.426 employees(70% of total), 2.400 plants with Lombardy in first place, where are active 1.179 firms, 67 start-ups, 28.555 employees and 1.050 plants. In central Italy there are 683 firms and start-ups (17% of the total) , 17.066 people employed (24% of total), 522 plants and Lazio leading with 417 enterprises, 18 start-ups, 13.136 people employed and 301 plants and buildings. Finally in south Italy are in business a total of 624 companies(16% of the total), whom employ 4.262 workers (6% of total) and 440 plants. Here the bigger is Campania with 221 firms,16 start-ups, 1.825 people employed and 179 active plants.

Analysing the 2016 report of Assobiomedica (with information about 2014) it is possible to say that 69% of all Italian medical devices' firms and the 83% of revenues are concentrated in five Italian regions: in first place there is Lombardy, then Emilia-Romagna, Lazio, Veneto and Tuscany. The most relevant case is represented by Lombardy, where

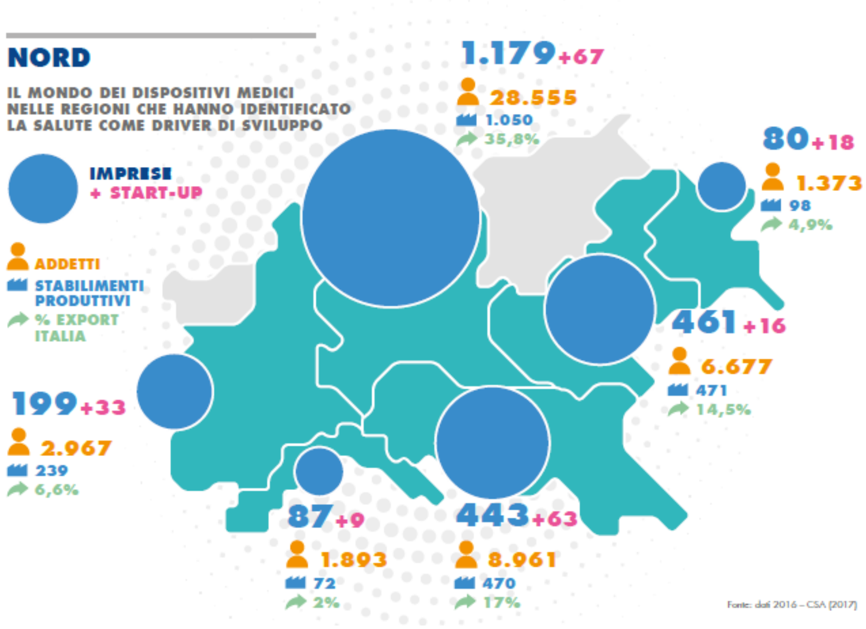

Figure 4.5: Companies, plants and people employed in northern Italy [5]

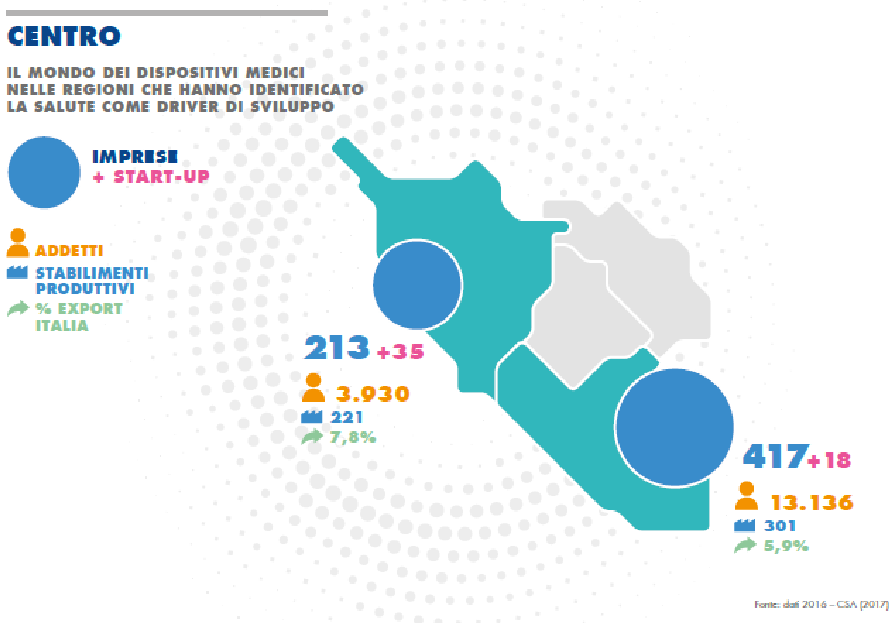

Figure 4.6: Companies, plants and people employed in central Italy [5]

are located 29% of the companies belonging to the medical devices' sector, with 47% of the total revenues as is depicted in figure 4.8. In figure 4.9, taken from Assobiomedica report released in 2014, is shown that in 2012 the percentage of revenues and firms was

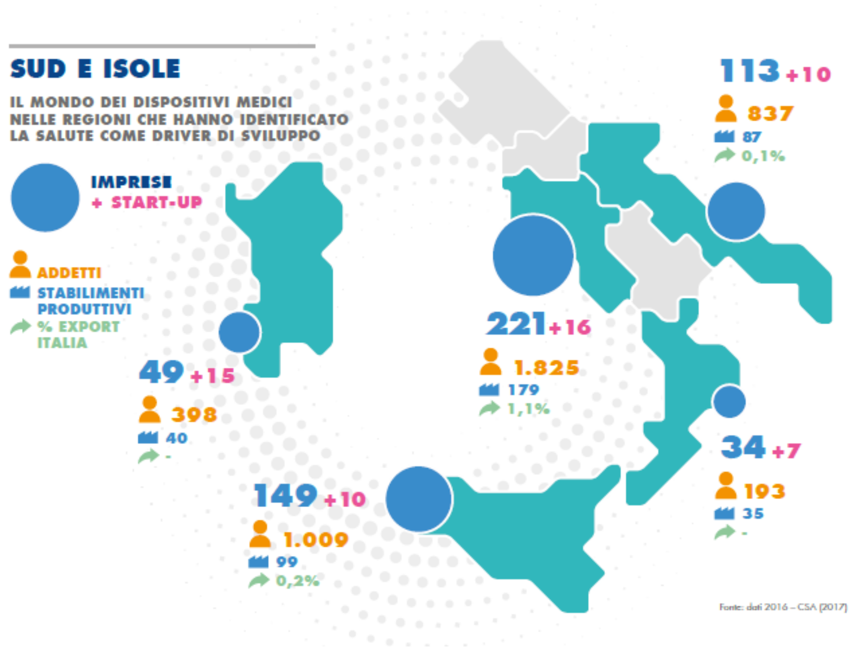

Figure 4.7: Companies, plants and people employed in south Italy[5]

concentrated in the same amount and regions reported for 2014 (Assobiomedica 2016 report), with Lombardy leading on all the other regions. In 2011 (Assobiomedica report 2013) the situation was practically the same for both number of firms and revenues per region, for these reason have been omitted the relative graphs. Conversely, in 2009 (2012 report), the market share of Emilia-Romagna, both in terms of revenues (figure 4.10) and number of firms, it was twice the size of 2012, instead Lombardy in 2009 had the same number of firms of 2012 with half of the earnings. Moreover, in 2009 the 60% of firms were concentrated in four regions: Lombardy (25.7%), Emilia-Romagna (12.8%), Lazio (11.9%), and Veneto (11.2%).

4.3.2 Import & export of medical devices

In what follow are exposed available data about the import and export of the Italian companies belonging to the medical devices industry. As depicted in figure 4.11 (Assobiomedica report 2017), Italy imports medical devices mainly from Germany, Netherlands and Belgium for a total value of 6,8 billion Euro. For what concern export, Italy is in the thirteenth position in this industry with a total of 4,9 billion Euro. The first country where Italy exports is France, then there are the United States and in third place Germany.

The analysis of data related to patenting and trade flows highlights interesting developments in the sector worldwide. Technological innovation in the sector remains high and mainly concentrated in the advanced countries, to which, however, there is a continuous growth in the role of new markets, not only as importers, but also as exporters.

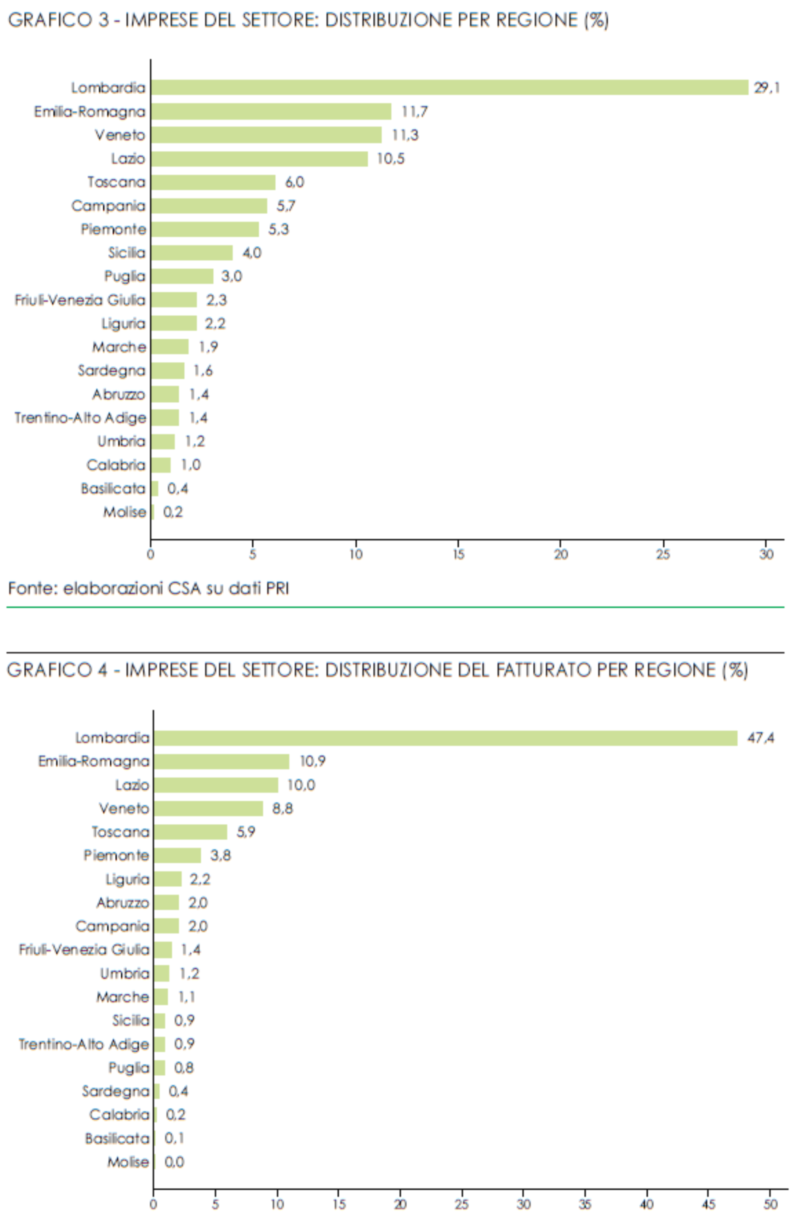

Figure 4.8: Number of firms and revenues per region in 2014[5]

Tanking into account the 2016 Assobiomedica report, with information related to 2014 mainly, it emerges that Italy has substantially confirmed its non-leading position on the international scene. More precisely, in the rankings of the main patents, exporters and importers, Italy maintains the positions acquired, without losing or gaining. In 2014, its share of patents on the global total decreased slightly, while that relative to exports and imports remained practically unchanged. The fact that the share of exports on the total

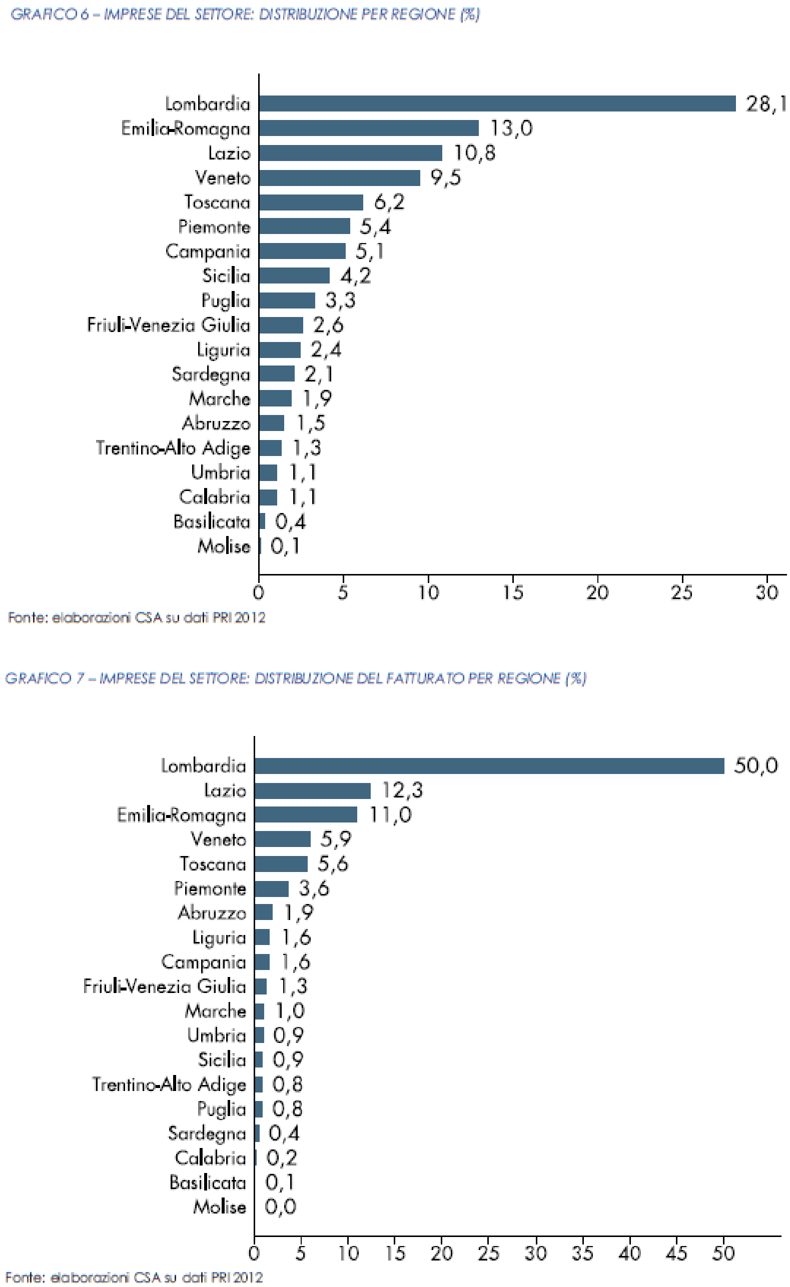

Figure 4.9: Number of firms and revenues per region in 2012 [5]

remains higher than that relating to patents, would suggest that the Italian patenting activity is effectively selective and that Italian companies are particularly active on the side of incremental innovation. In 2014, the main market was the United States that amounted for 1 billion euros, about 15.4% of Italian exports. Followed by France, Germany, Spain

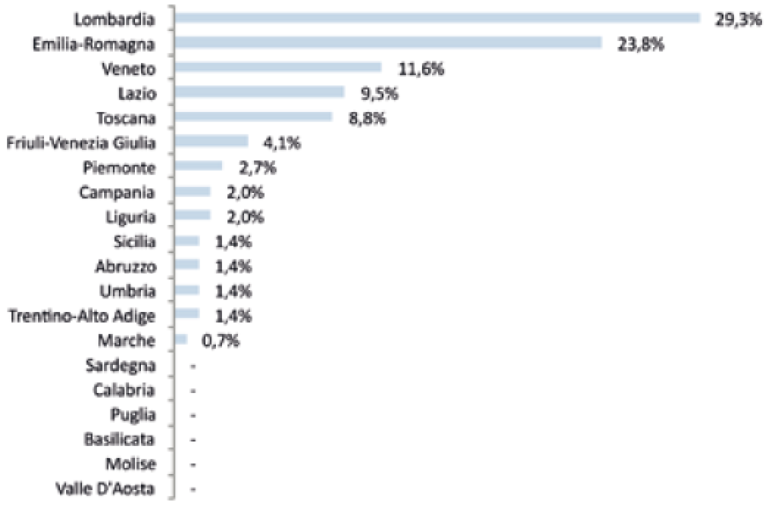

Figure 4.10: Revenues per region in 2009 [5]

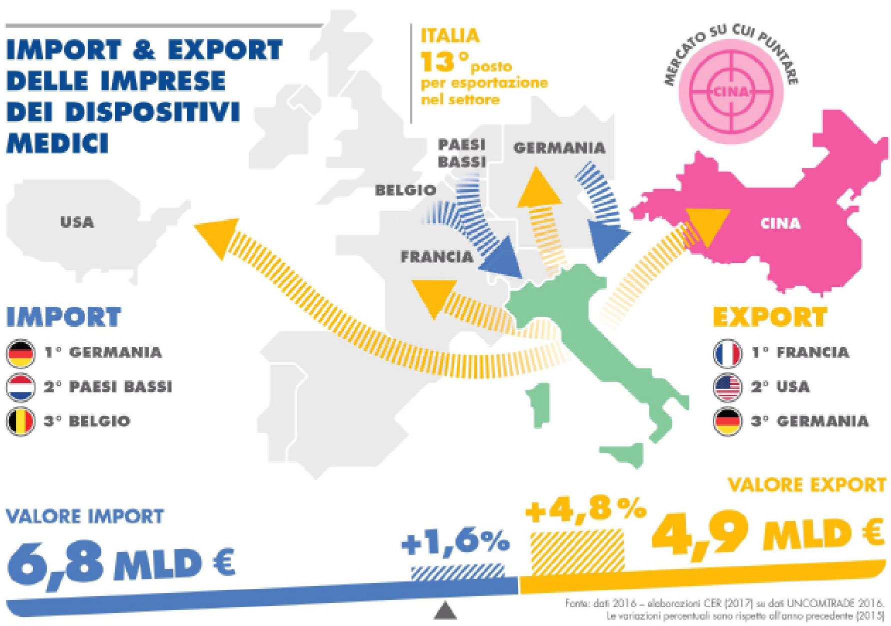

Figure 4.11: The amount of medical devices imported and exported from Italy [5]

and the United Kingdom, which together absorb over 2 billion Euro, about 31.6% of Italian exports. In 2015 Italian exports amounted to 7 billion Euro, an increase of 8.1%. The electro-medical diagnostic and the biomedical are driving the exports, which for over 23% have headed to the United States and the United Kingdom. Imports, in turn, amounted to 7.3 billion Euro, an increase of 6% over the previous year. Furthermore, Italian exports show a significant degree of territorial diversification, which allows the country to be less exposed to geopolitical risks. On the other hand, the weight on foreign markets important for size and prospects is still too low: it would be important, from this point of view, to hook emerging economies both as outlet markets and to start collaborative relationships also during the production phase. Considering instead, the 2014 Assobiomedica report with information related to 2012, the amount of exports, was less than in 2015, around 6 billion of euros. For what concern imports in 2012 amounted to 6,7 billion of euros, slightly less than in 2015. From the Assobiomedica report released in 2013 emerges that in 2011 the amount exports was 5,2 billion Euro, instead the imports were 6,8 billions. In 2010 instead, the imports were 7 billions and the exports 5 billions.

By virtue of these trends, Italy recorded a negative trade balance in 2015 of approximately 300 millions of euros (figure 4.12), equal to 2.3% of the total trade (standardized trade balance). This is the lowest value recorded in the period considered, with a reduction of over 100 million euros compared to the previous year. After the peak recorded in 2009 (1.5 billion euros), the deficit fell almost constantly both in absolute terms and in standard terms, with the sole exception of a slight increase in 2014. Going down a little more in detail, Italy in 2015 maintains a positive trade balance in technical equipment and biomedical, where it increases in absolute value and as a percentage of the overall trade, and in the diagnostic electro-medical, where in 2014 it was even negative, figure 4.13. It remains negative and worsens, in absolute terms and in standardized terms, in the remaining sectors.

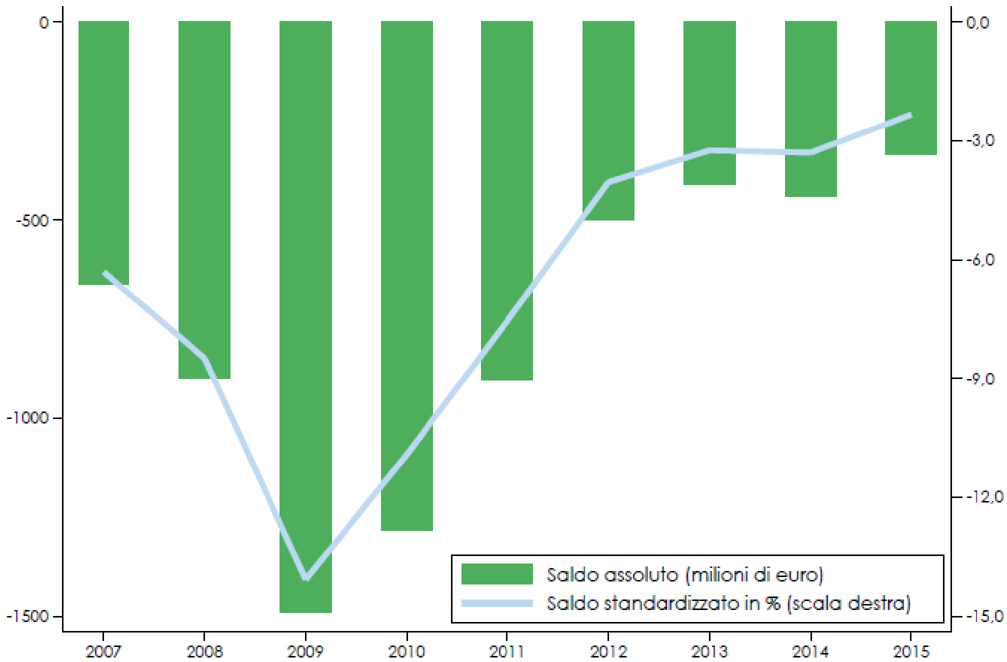

Figure 4.12: Trade balance of Italian medical devices in 2015 [5]

COMPARTO	2007	2008	2009	2010	2011	2012	2013	2014	2015
Attrezzature tecniche	47,7	48,3	40,0	33,2	35,0	48,8	54,0	49,1	49,9
Biomedicale	3,1	-0,5	-7,1	-3,5	-0,5	1,7	1,1	1,9	4,2
Biomedicale strumentale	-16,2	-15,4	-17,5	-17,7	-13,9	-11,8	-10,9	-10,4	-12,4
Diagnostica in vitro	-35,3	-34,9	-36,2	-33,5	-27,9	-23,1	-19,3	-23,2	-30,1
Elettromedicale diagnostico	-6,6	-17,8	-26,1	-13,1	-15,6	-2,4	2,7	-3,3	6,2
TOTALE	-6,3	-8,5	-14,1	-10,9	-7,5	-4,0	-3,2	-3,3	-2,3

Fonte: elaborazioni CER su dati UNCOMTRADE

Figure 4.13: Trade balance of Italian medical devices, divided by sub-sectors in 2015 [5]

4.3.3 Synthesis

In this subsection is just presented a summary table of the most relevant information gathered until this moment from Assobiomedica. In reading the results it must be taken into account that the informations reported are the most up-to-date possible with the last version available of the reports. The table is depicted in figure 4.14. In figure 4.15 instead is shown the evolution of the medical devices industry in terms of revenues from 2008 to 2016, the total growth in this time frame has been 36%, however the growth peak (16%) is between 2015 and 2016, probably because the 2016 revenues have been estimated due to data incompleteness. Indeed if we consider just the time span that goes from 2008 (8,39 billions of Euro) to 2015 (9,86 billion of euros) the total growth has been around 18%, that in any case underlines a positive trend with an average growth rate of 2,4%.

YEAR	2008	2009	2010	2011	2012	2013	2014	2015
TOT. REVENUES MED DEV	€ 8.398,0	€ 8.773,0	€ 8.996,0	€ 9.486,7	€ 9.245,5	€ 9.051,2	€ 9.267,5	€ 9.869,8
GROWTH TOT REV		4,5%	2,5%	5,5%	-2,5%	-2,1%	2,4%	6,5%
PUBLIC DEMAND	€ 6.307,0	€ 6.580,0	€ 6.738,0	€ 6.991,7	€ 6.740,0	€ 6.891,9	€ 7.137,4	€ 7.324,1
PRIVATE DEMAND	€ 2.091,0	€ 2.193,0	€ 2.258,0	€ 2.495,0	€ 2.505,5	€ 2.159,3	€ 2.130,1	€ 2.545,7
# FIRMS		2.735		3.037	3.025		4.480	
# EMPLOYEES		52.000			54.000		68.000	
MANUFACTURE REVENUES	7.144,0	7.349,0	7.228,0	6.803,4	7.157,0	7.111,1	7.269,1	7.962,1
IMPORT	6.263,0	6.412,0	6.917,0	6.794,4	6.728,4	6.538,9	6.878,6	7.290,6
Import_GROWTH		2,4%	7,9%	-1,8%	-1,0%	-2,8%	5,2%	6,0%
EXPORT	€ 5.009,0	€ 4.988,0	€ 5.149,0	€ 5.269,0	€ 5.768,3	€ 6.128,7	€ 6.439,7	€ 6.958,2
Export_GROWTH		-0,4%	3,2%	2,3%	9,5%	6,2%	5,1%	8,1%
# START-UPS				146		214	255	

Figure 4.14: Summary table in million Euro [5]

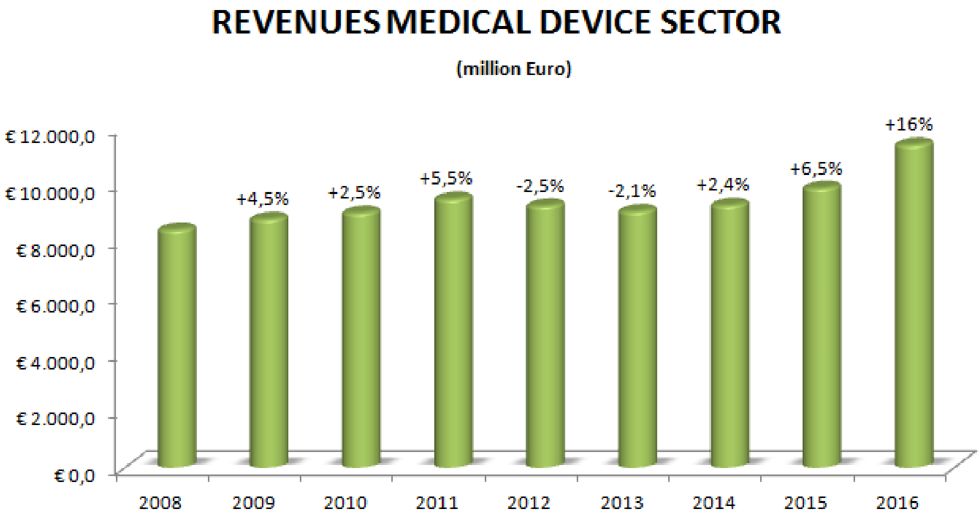

Figure 4.15: Medical devices' sales revenues [5]

4.4 Definition of the orthopaedic Sector & growth

In this subsection is shown how the 325030 ATECO sector has changed from 2008 to 2016 in terms of sales revenues, sales growth and employees; the last year available (2017) has been omitted for incompleteness. All the informations have been obtained performing analysis on AIDA, gathering the yearly segment dimensions in terms of revenues and number of players. As is depicted in figures 4.16 and 4.17 there is a positive trend in both. The total sale growth from 2008 to 2016 has been 64% and 34% for the number of firms. In 2015 was registered the highest peak for both, with an increase of 10% for sales and 7% for the number of firms.

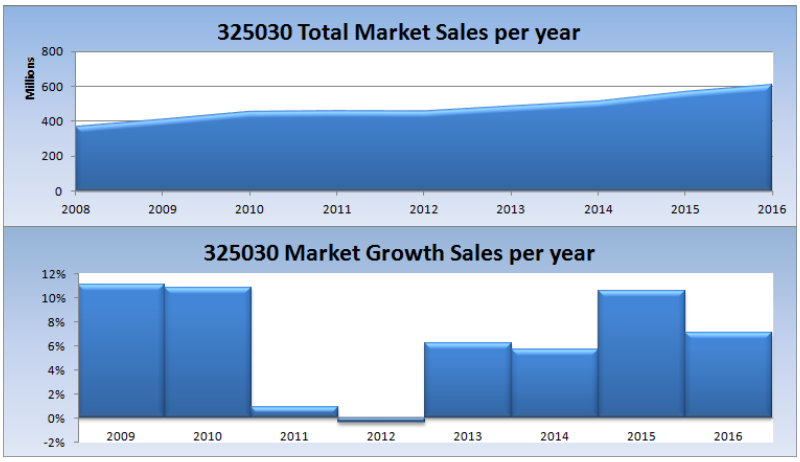

Figure 4.16: Sales and growth rate in the sector from 2008 to 2016[4]

Figure 4.17: Number of players from 2008 to 2016[4]

Going more in detail for 2016, crossing the data from Aida and Assobiomedica, arise that the prosthesis manufacturing sector worth 606 millions Euro (11,8% of the biomedical sector and 5,3% of the medical device sector) generated by 316 firms (figure 4.18), these latter represent the 18% of the firms working in the biomedical sector.

In 2014, the orthopaedic prosthesis sector gathered revenues for 512 millions Euro (12,28% of the biomedical sector and 5,5% of the medical devices' industry) with a total of 295 firms (31% of the biomedical sector). In 2012, the revenues of the orthopaedic sector were 456 million Euro (34% of the biomedical sector and 4,9% of the medical devices' industry) with a total of 272 firms (61% of manufacturers in the biomedical sector).

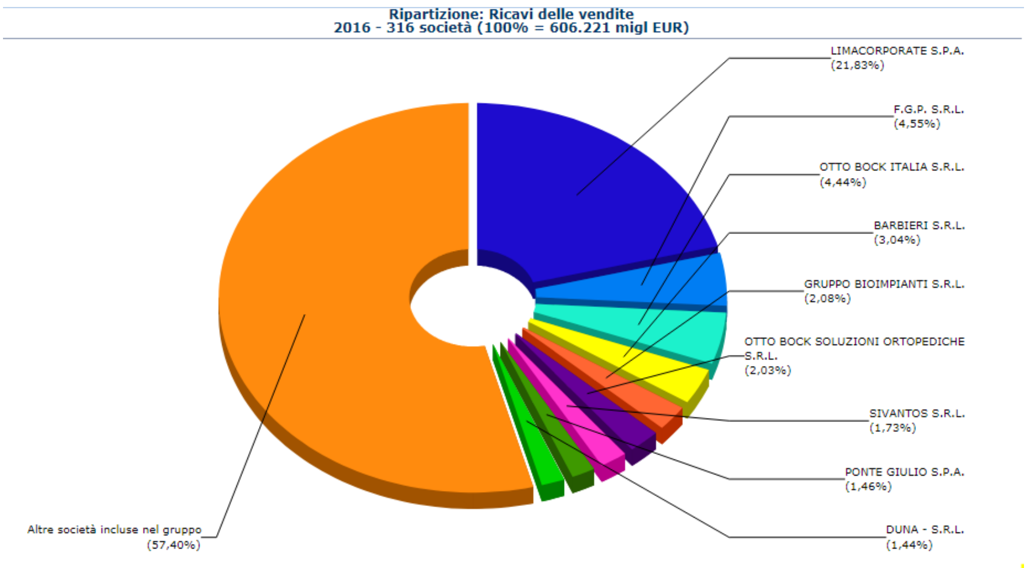

Figure 4.18: Prosthesis manufacturing sector's market shares in 2016 [4]

In figure 4.19 is illustrated the percentage value of the orthopaedic sector with respect to the medical device industry. The peak here has been in 2015, where the orthopaedic segment were 5,7% of the wider industry.

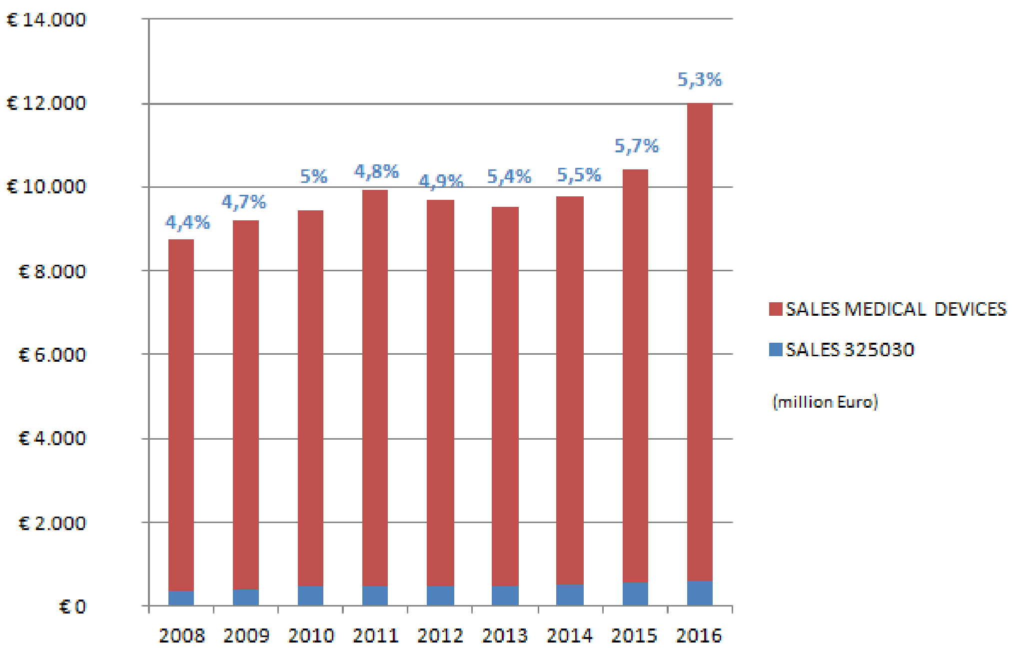

Figure 4.19: Comparison of the orthopaedic sector' dimension with medical devices dimension per year[4] [5]

4.4.1 Major Players & concentration ratios

Looking at the Italian orthopaedic sector, this section firstly describe the major firms in business, subsequently are computed some concentration indexes such as the Herfindahl–Hirschman Index (HHI), or just Herfindahl index, CR_4 and CR_8.

The Herfindahl index is a statistical measure of market concentration, used to understand the firms' size and the level of competition in a particular market segment. To compute this index we first need the market shares of each firm (MS_i) by dividing its sales by the market's total sales:

$$MS_i = \frac{Sales_i}{\sum_{i=1}^{n} Sales_i}$$

Where n is the total number of firms in the segment.

Once market shares are determined the HHI is defined as the sum of their squares:

$$HHI = (MS_1 * 100)^2 + (MS_2 * 100)^2 + (MS_3 * 100)^2 + ... + (MS_n * 100)^2$$

The value obtained ranges between 0 and 10.000. If is 0 means that there is perfect competition, otherwise the closer to 10.000 it is the higher the concentration, and consequently the closer a market is to a monopoly. For example, with just one firm in the market, HHI would be 10.000. The U.S. department of Justice (source Investopedia) consider a marketplace:

- *Competitive:* if HHI < 1.500
- *Moderately concentrated:* if 1.500 < HHI < 2.500
- *Concentrated:* if HHI > 2.500

Taking into account the market in analysis (ATECO 325030), by using the sales and revenues of 2016 the Herfindahl–Hirschman Index is equal to 573, indicating a competitive market, even if the firms placed in first position clearly dominate the segment.

The concentration ratio instead, is another index used to understand the market power of the first firms, so whether are in business many small firms or few large firms. For example CR_4 is market shares percentages' sum of the four largest firm in that industry. As for Herfindahl index, the lower the concentration index the higher the degree of competition. Indeed from 0 to 50% the industry is perfectly competitive. For what concern our analysis as depicted in figures 4.20 and 4.21

$$CR_4 = 33{,}86$$

and

$$CR_8 = 41{,}16$$

These results confirm the state of perfect competition given by HHI for 2016.

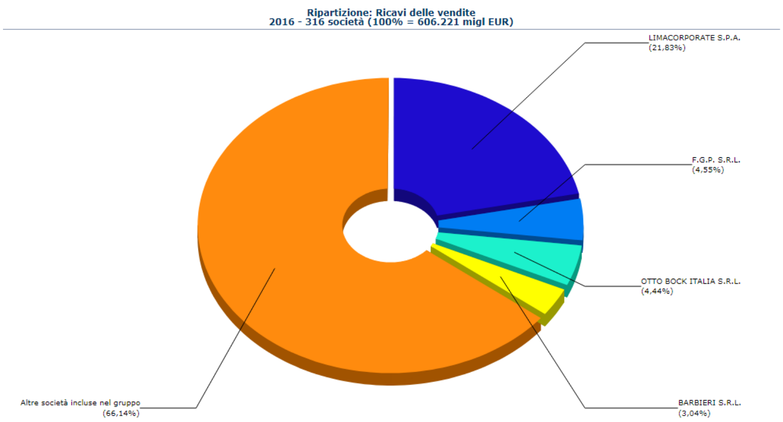

Figure 4.20: The Four-Firm Concentration Ratio for ATECO sector 325030 in 2016 [4]

4.4.2 Orthopaedic sector's supply structure

The aim of this subsection is to understand if the orthopaedic sector reflects the proportions, in geographic distribution, exposed previously for the wider medical device sector.

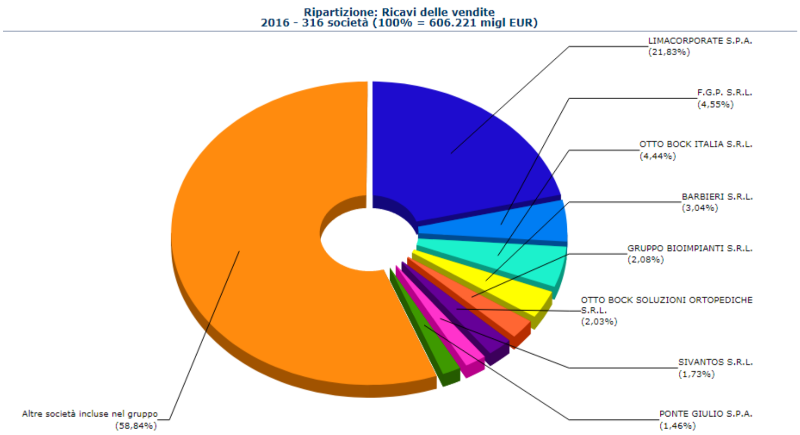

Figure 4.21: The Eight-Firm Concentration Ratio for ATECO sector 325030 in 2016 [4]

It was decided to use the AIDA's database to compare the orthopaedic sector's situation in 2014 with the informations reported by Assobiomedica, figure 4.8. As is illustrated in figure 4.22, for what concern the percentage of companies for each region there is a correspondence for Lazio, Lombardy, Emilia-Romagna and Veneto, whom are in the first four positions (47% the cumulated percentage) with Piemonte in fifth position, despite the seventh position in the medical device industry, moreover Lazio leads (14%) gaining 3 three positions. The geographic positioning reflects the revenues one (figures 4.22 and 4.23) with the only exception constituted by Friuli-Veneza Giulia, that was fifteenth in number of firms, but is in second place for percentage of sales after Emilia-Romagna. In total the first four regions (Emilia-Romagna, Friuli-Venezia Giulia, Lombardy and Veneto) accounts for the 65% of total revenues.

In figure 4.24 are reported the percentage of revenues and firms for each region in 2016. Unfortunately, given the unavailability of data about the medical device sector in 2016 it is not possible any comparison with the wider industry. However has been decided to include these informations, first to have the most update possible picture of the orthopaedic segment, second to compare these data with the previous in figure 4.22. Focusing on the number of firms per region, the situation remain perfectly unchanged (from 2014 to 2016), figure 4.25. Conversely, for what concern the percentage of revenues for each region in 2016 (figures 4.26 and 4.24), there is Friuli-Venezia Giulia leading, who exchanged positions with Emilia-Romagna. Following, there are Lombardy and Veneto that, in total with the first two, accounts for the 66% of total revenues.

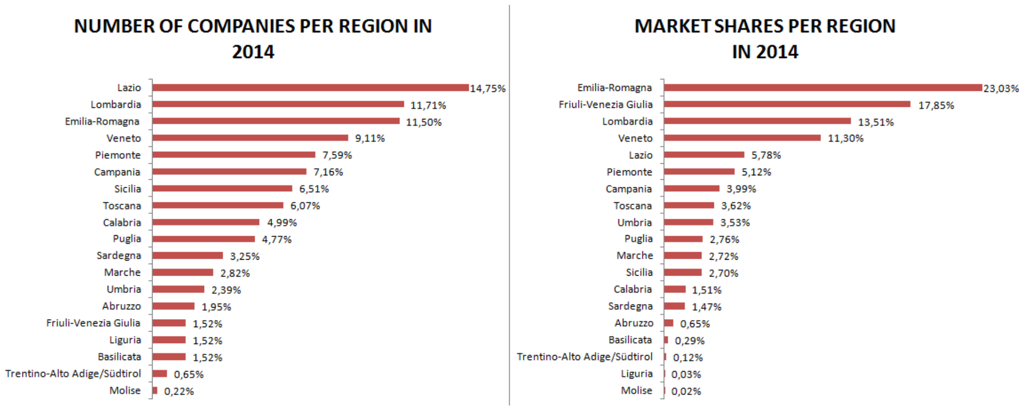

Figure 4.22: Number of companies and revenues per region in 2014 (%), ATECO 325030 [4]

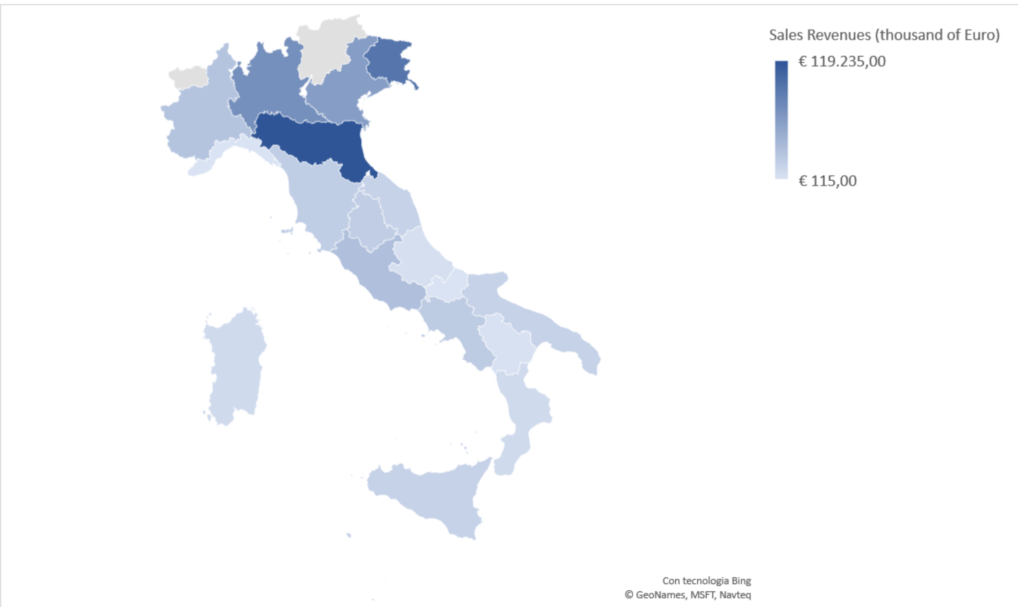

Figure 4.23: Revenues per region in 2014 (%), ATECO 325030 [4]

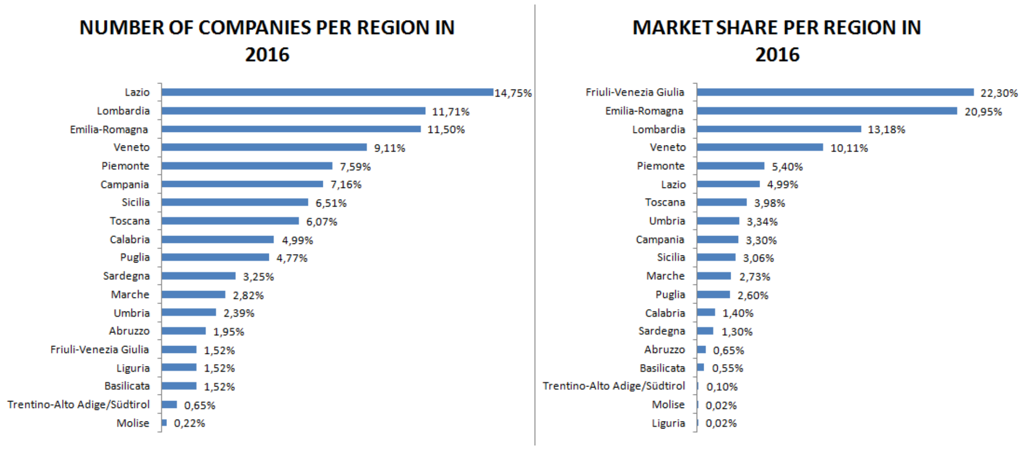

Figure 4.24: Number of companies and revenues per region in 2016 (%), ATECO 325030 [4]

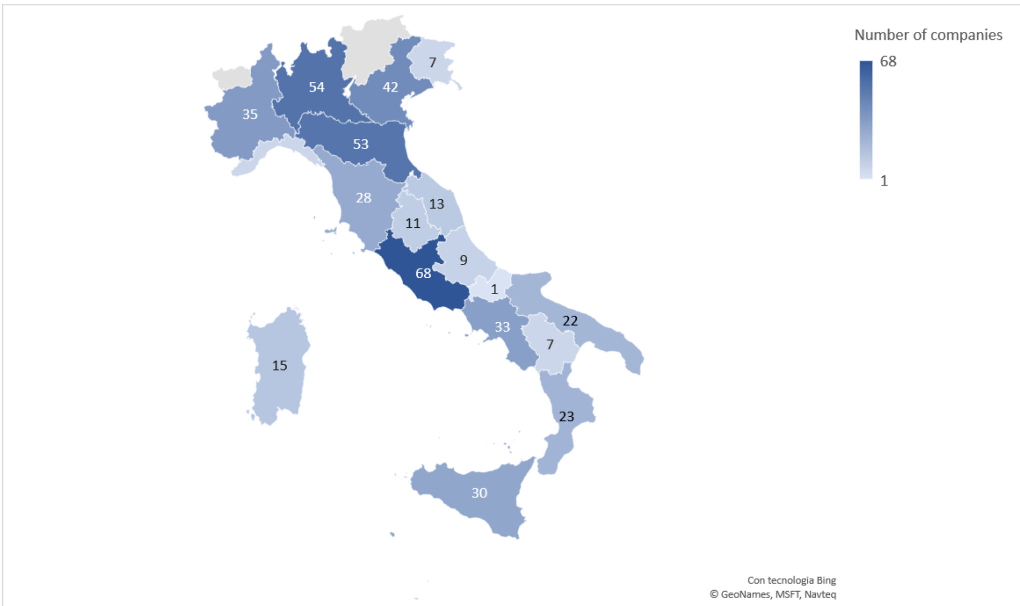

Figure 4.25: Number of companies per region in 2014 & 2016 (%), ATECO 325030 [4]

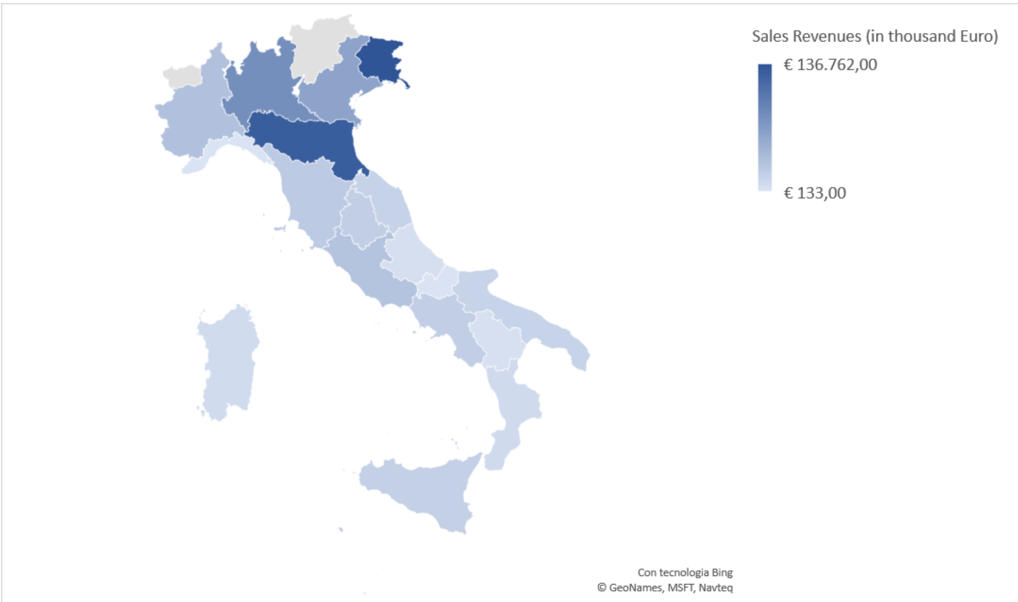

Figure 4.26: Revenues per region in 2016 (%), ATECO 325030 [4]

Chapter 5

AM impact on the Italian Orthopaedic Sector

5.1 Introduction

In the previous chapter has been extrapolated the orthopaedic prostheses manufacturing sector, from the wide Medical devices Industry, highlighting its main features.

It is now time to move to the core of this thesis describing the results obtained after submitting a survey, about the adoption of Additive Manufacturing, to the first 100 firms (in terms of revenues) belonging to the Italian orthopaedic manufacturing sector. In order to do this, the first section of this chapter just explains the sample characteristics through graphs obtained with STATA (a software for Statistics and Data Science). Subsequently the questions asked to the participants of the survey will be analysed and commented. Finally will be exposed the results going more into details and explaining the evolution in time, on who actually replied. Particular attention will be paid for the respondents that have already adopted one of the technologies belonging to the additive manufacturing umbrella.

5.2 The sample

As already said above the sample of interest is constituted by the first 100 companies belonging to the orthopaedic sector. All the informations about these firms have been downloaded from the AIDA database [4] using as research strategy the 2007 ATECO code 325030. Subsequently all the data have peen processed with the statistic software STATA in order to have a big picture of the sample features and where the latter are congruent with the informations reported by Assobiomedica.

Before to start it is necessary to state some general premise. The time span considered goes from 1999 to 2016 for many of the firms in the sample. Then, important to say that, was essential to clean the data through STATA. For this reason some variables relative to the first years have been recalculated, where was clear that the balance sheet information was related to a smaller period than one year. After these changes, the lack of few years it has been noticed and as a consequences has been decided to compute the average of the previous year and of the following year. Finally the variables of interest have been recalculated taking into account the price and salary indexes.

In figures 5.1 and 5.2 are depicted respectively the total sample sales revenues and their growth for each year starting from 2007. It has not been considered the entire time span because the firms has been founded or simply registered to AIDA in different years. Moreover, even cutting half of the observations, there was still a different number of firms each year. For this last reason the sales have been standardized taking as reference year 2015, when it has been registered the maximum number of firms equals to 93.

The sales revenues (figure 5.1) have a positive trend with a peak in 2016 with 522 millions, however the biggest jump in terms of growth, 12%, has been in between 2009 and 2010 (figure 5.2), instead the lowest in 2012, when has been registered a growth of -1.16%. The negative result in 2012 is confirmed by the average return on assets (figure 5.3) and the average return on sales (figure 5.4), which have both a negative trend from the time period considered.

In figure 5.5 instead is depicted the average number of employees for each year and it emerges the the minimum number has been registered in 2010 with an average of 18 employees, successively it is observed a positive trend that goes form 26 employees in 2011 to 30 in 2016. The increase in terms of employees number, as could be expected, reflects the increase in the average total personnel costs (5.6), that goes from 1,097,933 Euro in 2011 to 1,215,755 Euro in 2016. For what concern this last computation, all the values have been deflated using a salary index downloaded from ISTAT. In figure 5.7 is illustrated the average added value for each year from 2007 to 2016, here is confirmed the overall positive trend observed for the previous variables analysed.

The last variable of interest is about the geographic distribution of the firms belonging to this sample. In figure 5.8 are depicted the companies distributions in 2014 and 2016. Focusing first on the sample companies, in 2016 the 56% of the firms were distributed in four regions: Emilia-Romagna, Lombardy, Veneto and Lazio. Moreover it is possible to see that in this time frame the ranking is practically not changed, meaning that the relative power of each firm is the same. However some region has increased its absolute power, in particular Piedmont (the only one that increased also its relative power from twelfth position to fifth), has doubled its share from 3,41% in 2014 to 6,52% in 2016, and Sicily that increased from 4,55% to 5,43%. Comparing instead the information reported by Assobiomedica (figure 4.8) with this graphs, the main difference appreciable in 2014 is in the first two positions, where Lombardy and Emilia-Romagna practically exchange their market share, probably due to the high specialization of the last in prostheses. The other difference is constituted by Piedmont that was in seventh position for what concern the medical devices but only twelfth for orthopaedic prostheses. Surprisingly the comparison of the sample distribution does not reflect properly the one of the orthopaedic sector exposed in the previous chapter (figure 4.22), where, Emilia-Romagna, was in third position accounting for 11% of the total firms and Lazio was at first place. As for the previous reports, the 2016 geographic distribution it is not comparable with Assobiomedica reports but has been included to have an idea of the last data available.

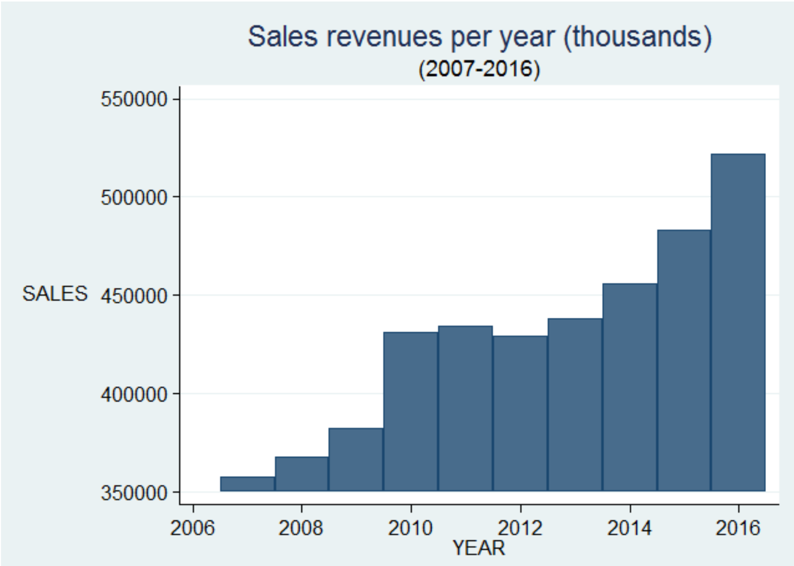

Figure 5.1: Sales Revenues of the sample per year, ATECO 325030 [4]

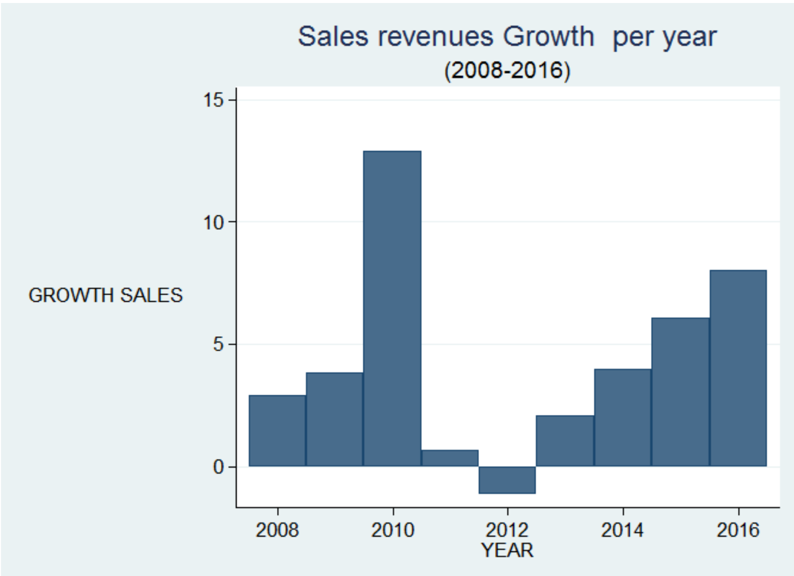

Figure 5.2: Growth Sales Revenues of the sample per year, ATECO 325030 [4]

5.3 The survey questions: analysis and comments

After the description of the sample selected from AIDA we can move to the analysis of the questions and relative answers of the survey. The latter have been obtained first gathering the contacts of all the firms, successively a marked letter signed by the supervisor coupled with the survey has been sent to present the project. The final step was the calling activity, where we have tried to convince all the companies to take part in the investigation.

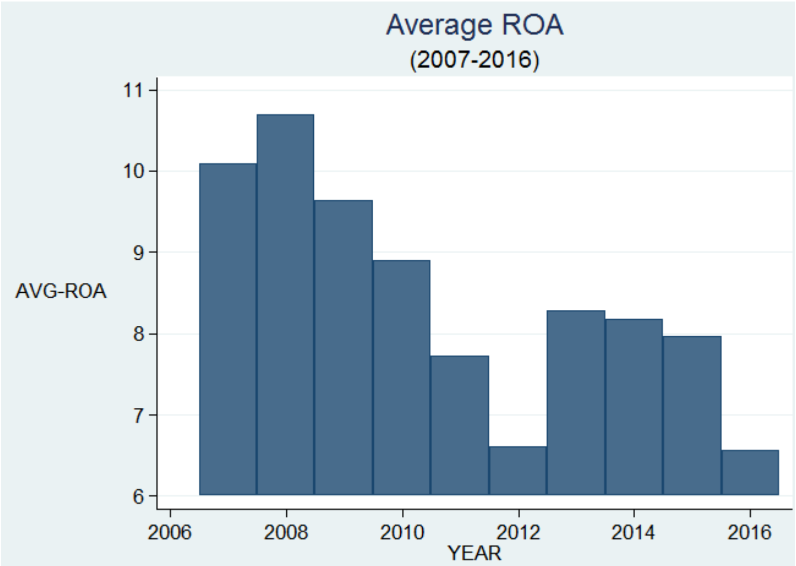

Figure 5.3: Average return on assets of the sample per year, ATECO 325030 [4]

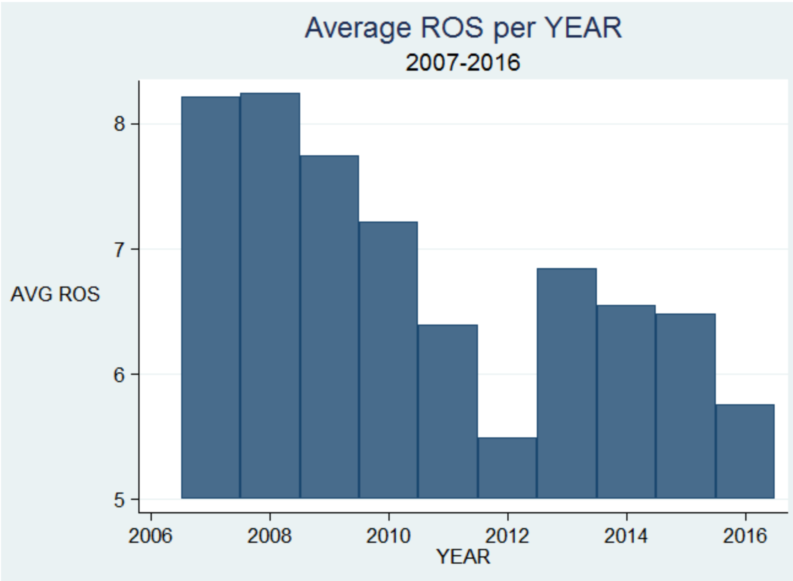

Figure 5.4: Average return on sales of the sample per year, ATECO 325030 [4]

After a deeper analysis of the single firms it emerges that 3 of the 100 firms belong to the same group, moreover 5 companies do not manufacture orthopaedic prostheses, 6 firms in this time span have failed or changed owner/segment and 2 companies did not want to take part in the survey. However has been added to the list one start-up, because it is in a partnership with one of the sample firms. At the end of this skimming the sample size goes to 86, 34 of these actually answered to the questions resulting in a response rate of

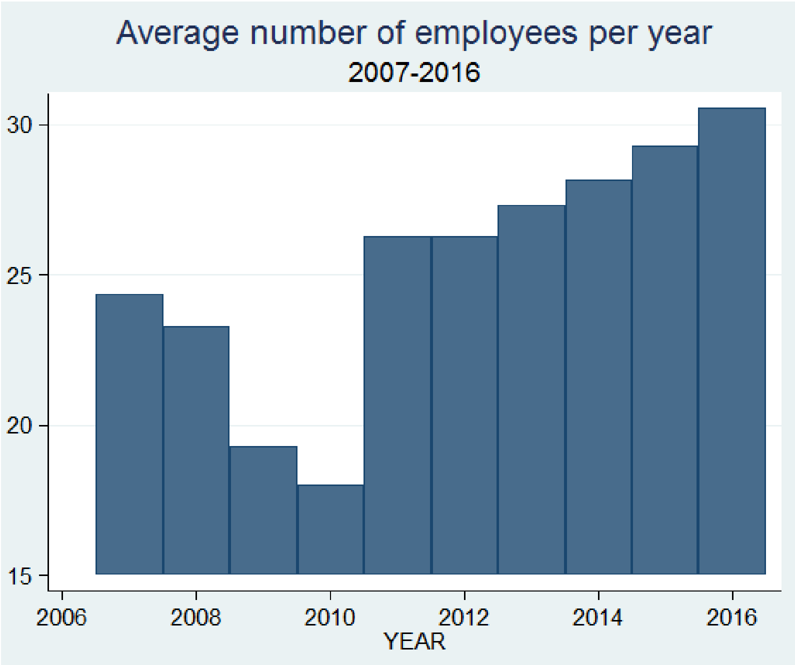

Figure 5.5: Average number of employees of the sample per year, ATECO 325030 [4]

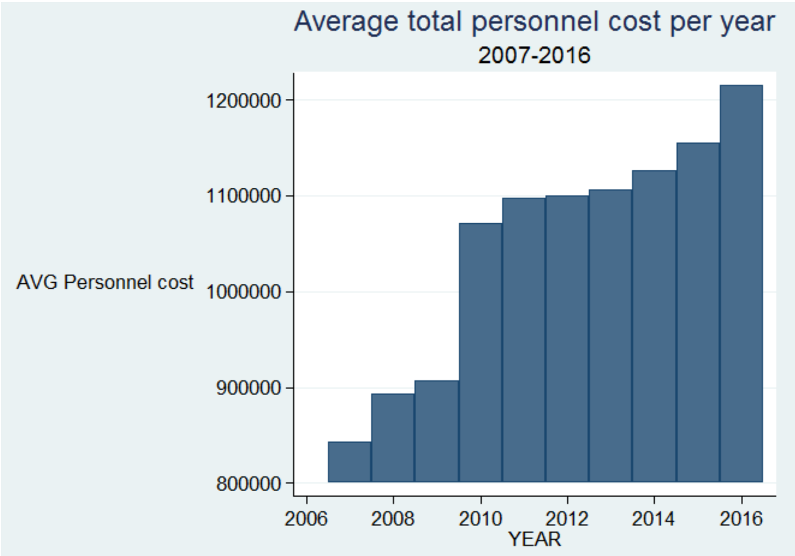

Figure 5.6: Average total personnel cost of the sample per year, ATECO 325030 [4]

39.53%. Moreover during the calling activity it has been possible to extrapolate the most important answer (if they have already adopted additive manufacturing systems or not) for 11 additional firms, for a total of 45 answers, resulting in a response rate of 51,13%. The entire questionnaire sent to each company is exposed in Appendix A.

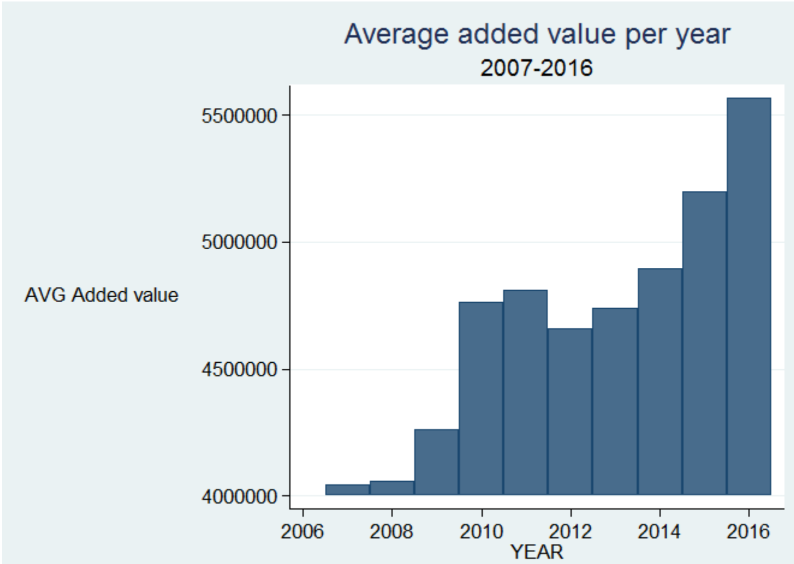

Figure 5.7: Average added value of the sample per year, ATECO 325030 [4]

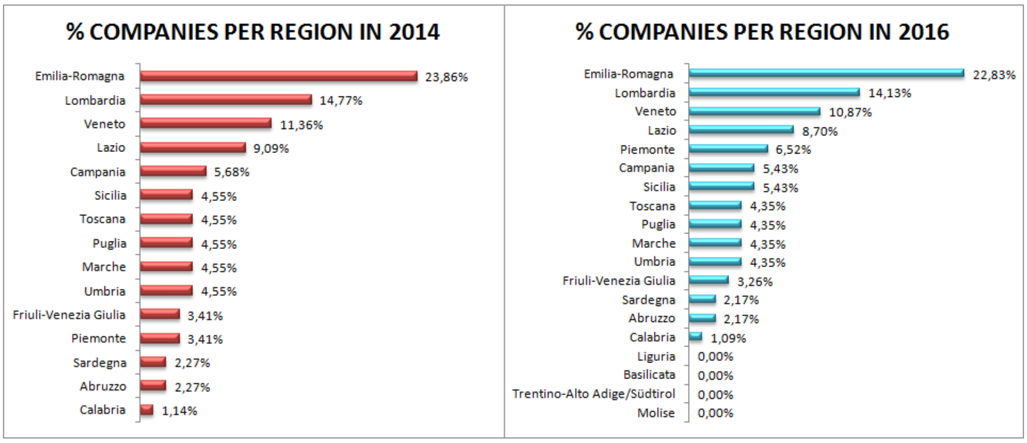

Figure 5.8: Geographic distribution of the sample in 2014 and 2016, ATECO 325030 [4]

The first question asks if the firm belongs to a group of companies or not and as is shown in the left side of figure 5.9, the 32.4% belongs to a group while the remaining 67.7% does not. The intriguing discovery is that who said yes cover the highest positions in the ranking. At these latter it has been asked whether the ownership of the company was Italian or not (right side of figure 5.9). The 54.5% said to be Italian and the remaining 45,5% said to have a foreign ownership. This high percentage of foreign firms could be explained with a 2015 research released by ISTAT, which says that in Italy there are 14 thousands of foreign holdings that produce revenues for 530 billion if euros with an added value of 104 billions.

The second question concerned the legal institution of the enterprise, in particular if it

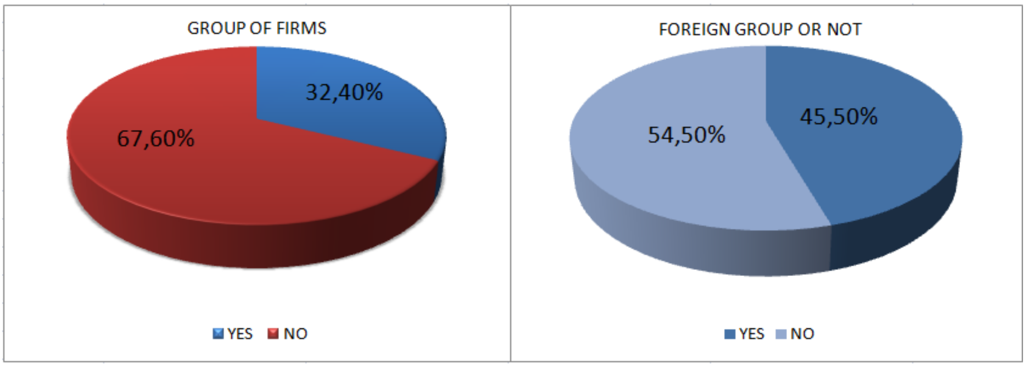

Figure 5.9: Question 1 and 6: "Does the company belong to a group of companies?"& "Is the company part of a group whose property is not Italian?"

is a family business or not. The aggregate responses in percentages are depicted in figure 5.10 and says that in this sector companies tend to be in a partnerships, with a percentage of 64,7, against the 35,3% which settled a family business. One of the biggest advantages of being a family business is the total freedom and independence from investors in taking important decisions, as could be to adopt or not a technology like additive manufacturing. However just the 40% of who conduct a family business has adopted, against the 60% of adopters that doe not have a family business.

The third question wonder where the production is located mostly and, not surprisingly, as shown in figure 5.11, almost all companies (55.9%) allocate their production in Northern Italy, the 20.6% in South Italy, the 14.7% in central Italy. The 2.9% of the firms instead allocate the production all over Italy, with the same rate firms allocate the production in Asia and in other areas of the European union.

The fourth question was about the production strategy used, i.e. if it is centralized (a single production site) or decentralized. It emerges that the 70.6% works in a single site, instead other part, which have more than one production site amount to 29.4%, figure 5.12. Probably the reason why firms decide to work in one single site is given by the nature of the product purchased. Indeed, as already said in the previous chapters, prostheses in general are highly customized, consequently it is necessary to be next to the final customer in order to achieve the best wear-ability possible, moreover outsourcing the production has some critical threads such the ones related to the transfer of know-how, the increase of logistic costs and the loss of quality control. However, as said in the second chapter, the adoption of additive manufacturing technologies could enhance the decentralization. For the latter reason, should be particular interesting to know which will be the evolution in the following years in parallel with 3D printing diffusion.

The following question asked where the firms suppliers are mostly located. The results are illustrated in figure 5.13: the great majority, as for the third question about the production location, works with suppliers in Northern Italy (58.9%), 11.9% of the suppliers instead are in Central Italy, the 2.9% of the total in South Italy and the 17.6% abroad, but in the European Union. Of The the three remaining interviewees (each of them accounts for the 2.9% of the total) one have suppliers located in Asia, another in Italy &

European Union, instead the last one in EU & United States. In the end, quite the 75% of the respondents prefer Italian suppliers, probably for the same reasons outlined for the previous question about the production strategy.

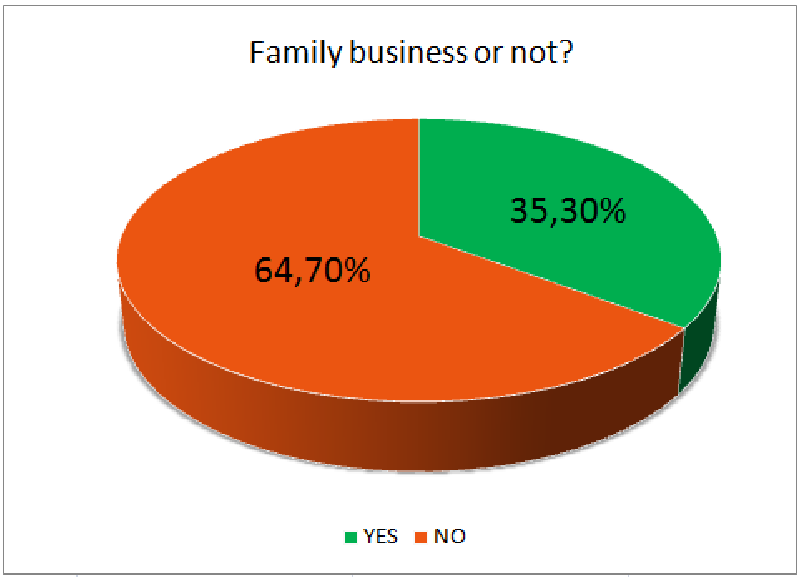

Figure 5.10: Question 2:"Is the company a family business?"

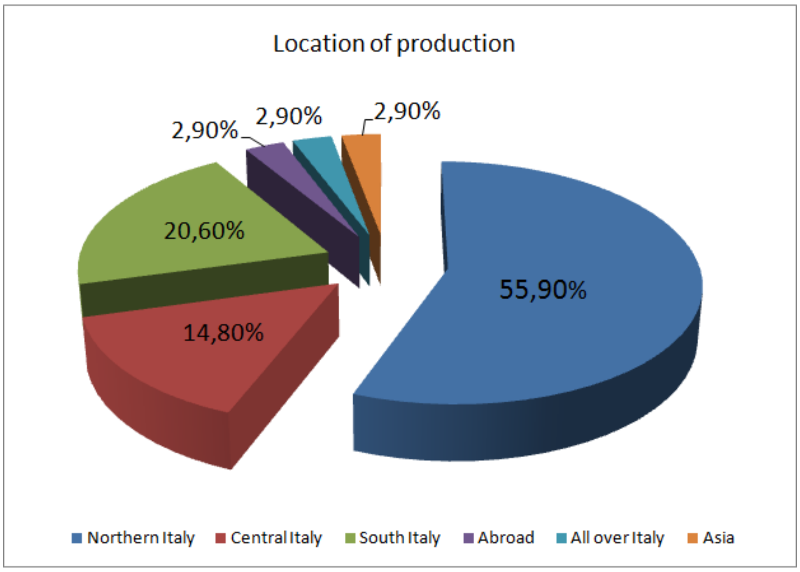

Figure 5.11: Question 3: "Where is the production mainly allocated?"

The seventh question, deserves particular attention, inasmuch it has been made to ask whether the firm have invested in additive manufacturing or not. It emerges that, over 34 respondents, more than half (52.9%, so 18 firms) have actually adopted one of the

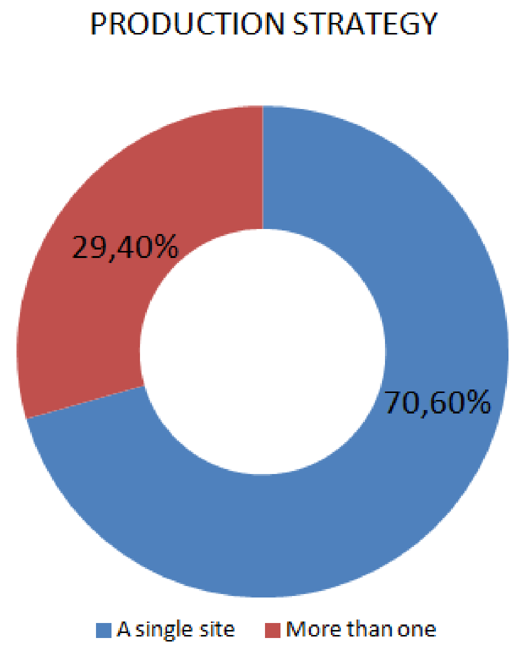

Figure 5.12: Question 4: "Which is the production strategy currently adopted?"

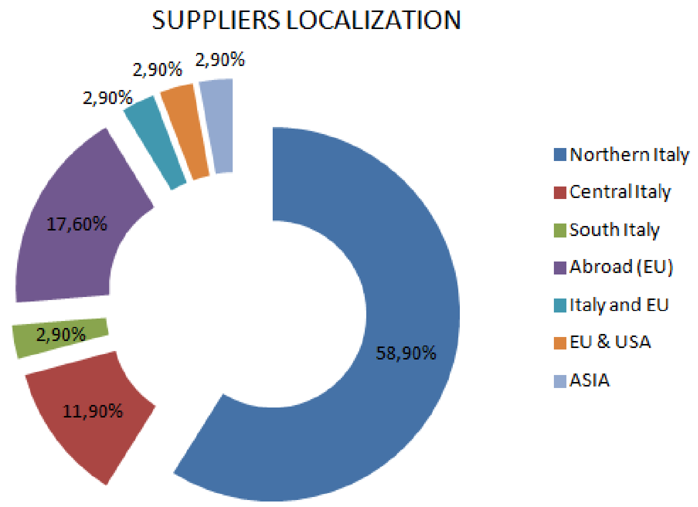

Figure 5.13: Question 5: "Where is most of the company's suppliers located?"

additive manufacturing technologies available, while the other 47.1% have not, figure 5.14. The distinction of these two groups is important in the context of our survey, indeed the following questions (from 8 to 15) have been addressed just to the firms that have already adopted 3D printing technologies, so to whom said yes. Instead, the last three question until the eighteenth have been asked just to who answered negatively. Moreover, as said at the beginning of this section, from the calling activity has been intuited the position of eleven other companies with respect to this topic. Ten of the latter admitted they do not have a 3D printer, while just one probably have already adopted. However there are no additional information about these eleven.

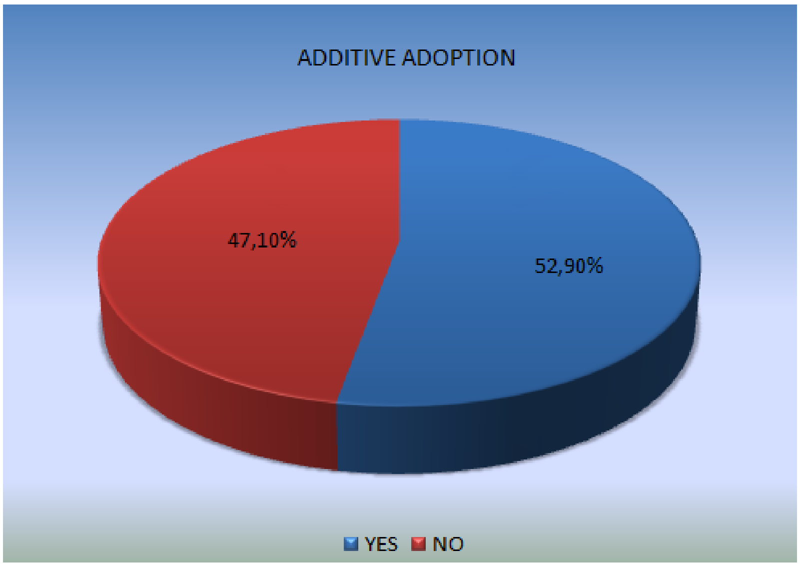

Figure 5.14: Question 7: "Has the company made investments in additive technologies?"

The eighth question has been answered from 17 over 18 respondents which have adopted and it asked about the kind of feed material used to produce with AM. As depicted in figure 5.15, the 70.6% use additive technologies to work polymers, 17.6% metals and, with the same percentage rate (5.9%) the adopters that work with Carbon & Titanium and the ones that instead use latex derivatives. The reason why the majority of them uses polymers has been understood during the calling activity, where it was possible to talk with the chiefs of production. The latter generally said that, in this particular moment the use of polymers is suitable for production, but just for accessories or in general not functional part, specially for what concern the prostheses. Other reason for the choice of polymers have been:

- adequate adhesions to other resins or alloys;
- good dimensional stability;
- ease of processing;
- ease of repair;

The next has been an open question, where was asked which technology they adopted and the 17% says to use just a 3D system detection CAD CAM, 47% instead only say 3D

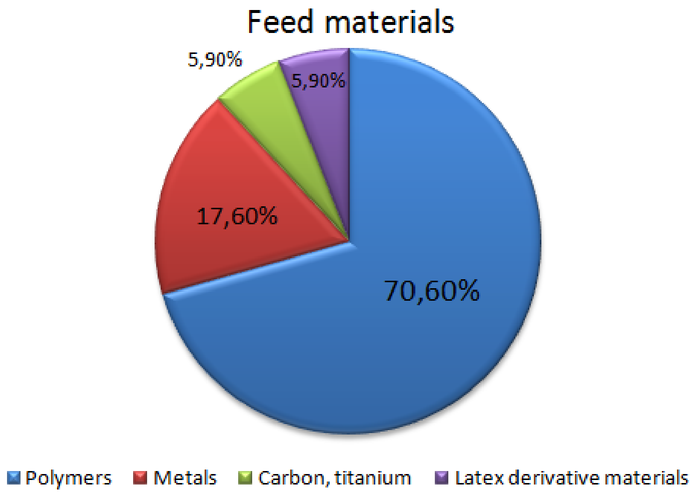

Figure 5.15: Question 8: "Which materials do you use additive technologies for?"

printer without specifications, 23% admitted to use FDM, 6.5% SLS and the remaining 6.5% uses Electron Beam Melting.

The tenth question is really important because concerned about the first year in which firms have made their first investment in additive manufacturing technologies. This is important for the comparison of the performances before and after the adoption that will be discussed in the last section. Looking at figure 5.16 it is possible to state that practically the 41% of the respondents have invested for the first time in the last three years, so these will quite useless to understand differences in performance. The 29.5% is the sum of the respondents percentages that have as first adoption year 2003, 2004, 2008, 2013 and 2015. The 11.8% respectively adopted in 2007 and 2010. The one who invested in 1995 actually is the result of a misunderstanding because it does not use a 3D printer but just a CAD CAM system.

The following question is strongly related to the tenth because it wonder the amount invested in 3D technologies in each year starting from 2014 to 2017. Analysing figure 5.17 is possible to say that most of the firms have invested each year an amount included in the lowest range that goes from 0 to 15,000 Euro, but in these is surely included some firm who did not invest. Moreover just one firm has invested more than 200,000 Euro in each year oh this time frame and just few companies made little investments that goes from 15,000 to 40,000 Euro. After a deeper analysis it emerges that these investments are all proportional to the amount of total fixed assets owned by each adopter the year before their first investment.

After the question concerning the amounts invested for each year, has been asked what were the main objectives that the company has proposed to achieve with investments in additive technologies. In detail, the questions asked to rank from 1 to 5 a series of possible objectives:

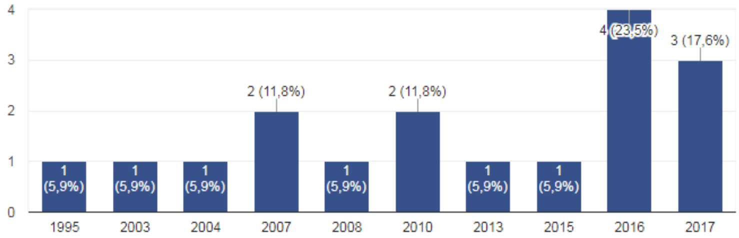

Figure 5.16: Question 10: "When did you make the first investment in additive technologies?"

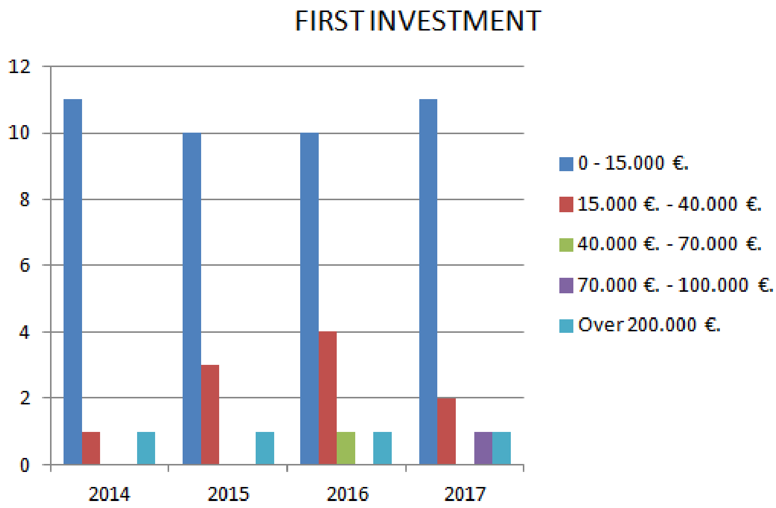

Figure 5.17: Question 11: "Which is the amount of investment in additive technologies in each year from 2014 to 2017?"

- reduction of production costs;
- to increase the product range variety;
- approach the needs of costumers;
- reduction of transition time to design to mass production;

Now it is going to be analysed each of the objective and the respective score assigned by each respondent, figure 5.18. For what concern the cost reduction 4 firms ranked it as most important and the same quantity said the opposite, 3 give a level of 2, one assigned 3, three respondents say 4. In the previous chapters we stressed about the main advantages achievable trough additive manufacturing and production costs reduction was one of those, especially in sectors like medical applications. In fact, the process automation helps to reduce labour costs, involving less machining steps so cycle time and factory footprint are reduced.

The second and the third objectives are strongly connected with the main feature embodied in 3D printers: customization. Indeed 7 of the respondents ranked as most important target the one to be the closest possible to customer needs, the others quite homogeneously ranked it from 2 to 5. The same could be said for the increment of product variety. Instead, definitely lower the percentage of firms who believe additive manufacturing could help to reduce the production times.

The thirteenth question has been done to understand what use companies make of the 3D printers. It emerges that 6 of the respondents use additive manufacturing technologies exclusively for rapid prototyping, 7 only to manufacture and 5 for both. In figure 5.19 are shown aggregated values saying that in total 11 of the respondents use AM for rapid prototyping and 12 for production. A related question is the number fourteen, depicted in figure 5.20, which says that 61.1% of the adopter believe that AM has partly solved the issues concerning their supply chain, 11.1% states that it did not change anything, while just the 27.8% says that AM solved all the problems.

The last question addressed to who already adopted on of the additive manufacturing technologies was about the impact of the adoption on their supply chain. Looking at figure 5.21 it emerges that the 60% of adopters believe that Am technologies enhance the efficiency in terms of logistics, indeed as stressed much in the previous chapters, 3D technologies could help in reduce the lead times and simplify the warehouse management. The 36% say to increase the flexibility, another feature highlighted of AM. The 32% answered that the adoption helps to diversify raw material and technologies, while 24% of adopters has reduced its number of suppliers. The remaining 8% has increased its product variety after the adoption.

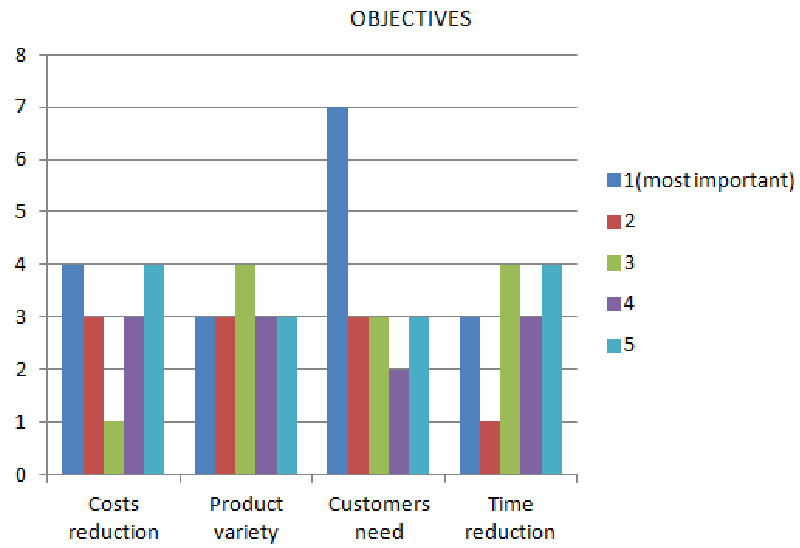

Figure 5.18: Question 12: "Which have been the main objectives that the company has proposed to achieve with the investments in additive technologies carried out in 2014-2017?"

It is finally time to move to the 47.10% that have not already adopted any technology

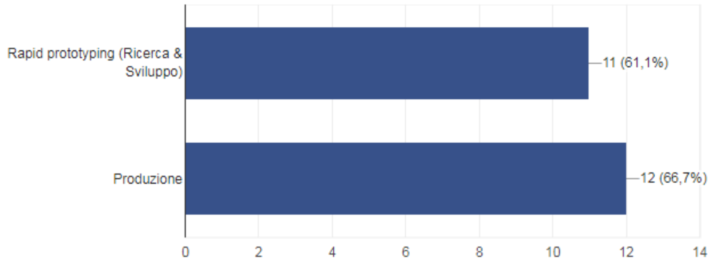

Figure 5.19: Question 13:"Which process do you use AM technologies for?"

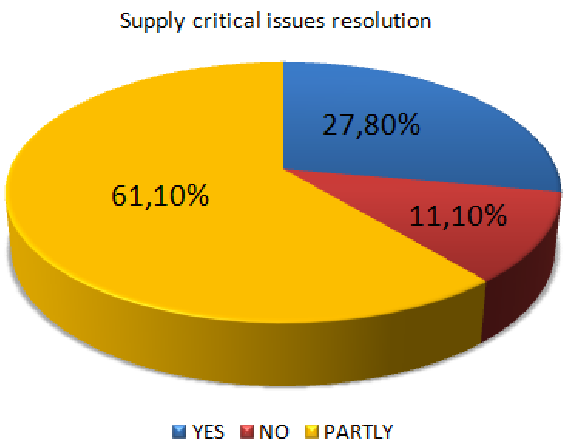

Figure 5.20: Question 14: "Do you think that a production supported by additive technology could solve or at least mitigate the critical issues of its Supply Chain?"

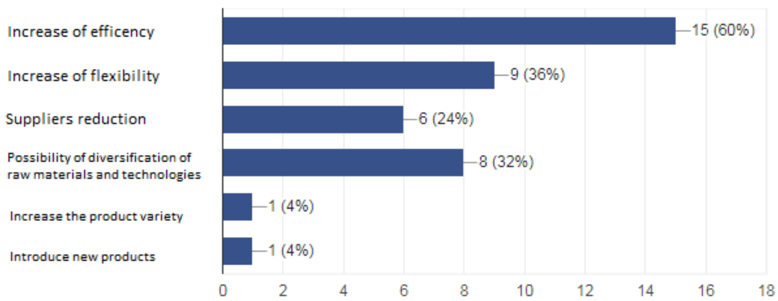

Figure 5.21: Question 15: "Which are or could be the impacts of additive technological solutions on your Supply Chain?"

under the AM umbrella. The first question addressed to this group had the purpose to understand the reason why the firms have decided to continue to produce using the old paradigm. Nine firms over 16 has answered to an open question saying:

- "scarcity of the materials available and the excessive time in the manufacture of the devices";
- "longer production times";
- "production does not require the use of these technologies";
- "For the type of product we make (orthopedic insoles) there are still no tires with low hardness (around 30 shore A) and moreo er the time of realization is still too long",
- "The dimensional tolerances currently guaranteed by additive processes are not compatible with the small size of our products";
- "financial reasons";
- "it does not fit with mass production";
- "we are in a partnership with an adopter";
- "do not fall within the business plan";

To summarize, 2 say no to AM for quality issues, 3 for not suitability with production, 2 for the production times, 1 for financial issues and anther for a strategic partnership.

The seventeenth question would like to understand if and when the non adopters are planning to invest in additive. As illustrated in figure 5.22 just the 6.2% of total has already planned to invest in additive manufacturing in the short term (within 1 year), the 25% in the medium term (within the next 5 year), instead the remaining 68.8% have not planned any investment.

Finally, the last question is the same of the one addressed to AM adopters about the critical issues (question 14). However the version for non adopters asks just to imagine if the adoption could mitigate or not the issues related to their supply chain. The results, depicted in figure 5.23 explain even why in the previous question there was an high percentage of firms that have not any plan. Indeed just the 12.5% of the 16 respondents trust this new paradigm, while the 43.8% says that could partly solve the issues and another 43.8% that do not trust these new technologies at all.

5.4 STATA analysis on the respondents & conclusion

After the description of the sample and the analysis of the answers gathered, it is now time to expose the results coming from a statistical analysis performed on STATA, where have been crossed the informations downloaded from AIDA databases (related to

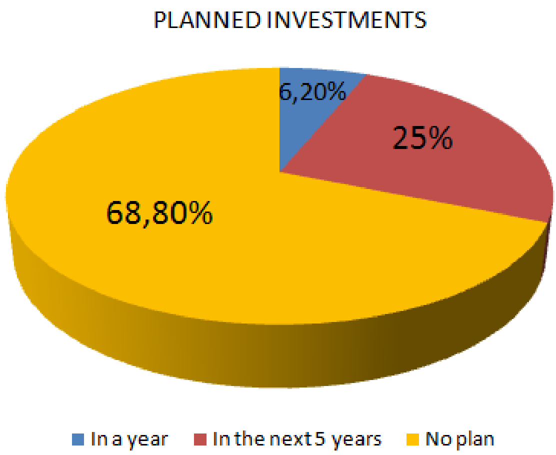

Figure 5.22: Question 17: "Have you already planned future investments in additive technologies?"

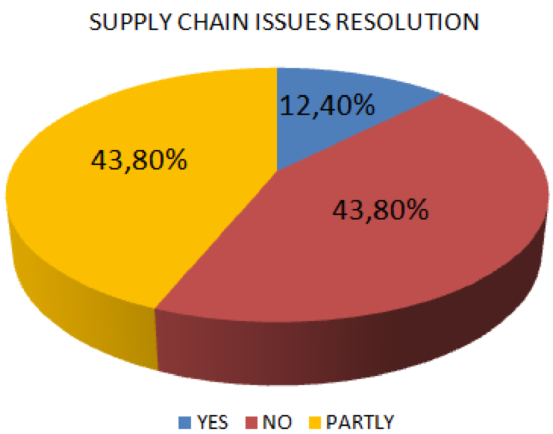

Figure 5.23: Question 18: "Do you think that a production supported by additive technology could solve or at least mitigate the critical issues of its Supply Chain?"

the balance sheets of the companies belonging to the market segment corresponding with the ATECO code 325030) and from the questionnaire submitted to the sample.

For most of the variables of interest has been built a regression linear model. Generally speaking, a linear model for panel data has the characteristic of comprising differentiated intercepts (constants) for each observation belonging to the panel. These, interpreted as specific effects of single individuals, can be considered unknown but fixed, which are added to others to be estimated. This last model is called "fixed effects model" and it is the one we used for the variables above mentioned. In its simplest formulation, the model coincides with the estimation of a linear regression in which to the set of regressors are added as many dummy variables as the units of the panel. More specifically, the dummy we used are referred to years, in order to capture any time-related effects that are not already in the model.

The first interesting finding derives from the dimension of the respondents. Indeed splitting in two half the sample of 100 firms (in figure 5.24 on the x axes, 1 if it is big, 0 for small) emerges that the 64.71% (22 over 34) of the bigger firms have taken part to the investigation, against the 35.29% (12) of small size enterprises. The other eleven observation depicted in figure 5.24 refers to the ones who just give some information by phone, as explained before. The other result that cross the dimensions and the adoption, on who actually filled the questionnaire (34 firms), says that there is no association between these two variables, in fact the number of big companies represent the majority (around 56%) for both adopters and proponents of the older paradigm, figure 5.25.

Subsequently has been performed an analysis to understand the association between the adoption and the localization of the ownership. Looking at figure 5.26 we can state that the number of foreigner are 5 over the 34 respondents and that, half of both Italian and foreign companies have adopted, while the other half have not. Then even for these two variables we can appreciate a low degree of association.

1 if yes, 0 if not	grande 0	1	Total
0	8	3	11
	72.73	27.27	100.00
	40.00	12.00	24.44
1	12	22	34
	35.29	64.71	100.00
	60.00	88.00	75.56
Total	20	25	45
	44.44	55.56	100.00
	100.00	100.00	100.00

Pearson chi2(1) = 4.7166 Pr = 0.030

Figure 5.24: Firms size and response rate [4]

Let now move to more interesting testes on how the relevant variables has changed before and after the adoption on productivity indexes. In particular a linear regression with fixed effects has been built on the following variable:

- labour productivity (sales/number of employees);
- return on sales, determined by the ratio between operating profit and net sales, it is useful to understand the firm operational efficiency;
- value added per employee;
- market shares;

It is important before to start to premise the all the testes have been performed looking at the evolution, over the time frame available, year by year.

addititive	grande 0	1	Total
No	7	9	16
	43.75	56.25	100.00
	58.33	40.91	47.06
Sì	5	13	18
	27.78	72.22	100.00
	41.67	59.09	52.94
Total	12	22	34
	35.29	64.71	100.00
	100.00	100.00	100.00

Pearson chi2(1) = 0.9462 Pr = 0.331

Figure 5.25: Firms size and AM adoption [4]

addititive	prop_for 0	1	Total
No	14	2	16
	87.50	12.50	100.00
	48.28	40.00	47.06
Sì	15	3	18
	83.33	16.67	100.00
	51.72	60.00	52.94
Total	29	5	34
	85.29	14.71	100.00
	100.00	100.00	100.00

Pearson chi2(1) = 0.1172 Pr = 0.732

Figure 5.26: Foreign ownership and AM adoption [4]

For what concern the labour productivity, after preliminary analysis (a parametric t-test and a non-parametric test) is emerged that going forward with the years from the one of adoption, we reject the null hypothesis, on the equality of the expected values before and after the adoption (in favour of the latter), with always greater degree of confidence. This last statement is partially confirmed by a linear regression test with fixed effects, indeed for the first year after the adoption (table 5.27) the adopters labour productivity was lower than the one of non-adopters and we strongly reject the null hypothesis. However the adopters labour productivity grows every year, becomes richly positive seven years after the adoption (but still lower than non-adopters) where we can not reject the null hypothesis in significant terms. At the end of the eighth year, finally the adopters productivity becomes better and we strongly reject the null hypothesis. These results are partially confirmed after a robust regression analysis (which considers the variables auto-correlation) and strongly confirmed for a regression analysis with fixed effects which introduces the year dummies, to capture any time-related effect that is not already in the model. However in the robust version of the last model we reject with a lower degree of confidence.

Variable	post	post_1	post_2	post_3	post_4	post_5	post_6	post_7
post	-37546.25							
	10200.16							
	0.00							
post1		-30397.74						
		10365.31						
		0.00						
post2			-21236.99					
			10716.25					
			0.05					
post3				-23079.21				
				10992.62				
				0.04				
post4					-10223.72			
					10797.79			
					0.35			
post5						-186.32		
						11009.07		
						0.99		
post6							13496.74	
							11720.24	
							0.25	
post7								29889.51
								12046.42
								0.01
_cons	209064.67	204999.05	200873.89	200676.34	196256.04	193543.93	190983.93	188855.42
	5175.74	4952.06	4819.82	4587.44	4244.61	3987.63	3782.72	3575.17
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N	193	193	193	193	193	193	193	193

Figure 5.27: Regression analysis with fixed effects from the first year after the adoption to the eighth [4]

The second variable of interest is constituted by the return on sales. For this variable we performed a linear regression analysis with fixed effects(figure 5.31) that partially confirms what said before for the labour productivity, indeed even if ROS value remains negative, during the years there is a decreasing gap between pre and post adoption. The same trend is observed for the robust analysis even if with a lower degree of confidence. Subsequently we have performed the same analysis introducing the year dummies and the results confirms what said before, as depicted in figures 5.33 and 5.34, with the only difference that, in these two last analysis the ROS value becomes positive already in the fourth year after the adoption.

The next variable analysed is represented by the value added for each employee, which is a measure of employees' effort usage. Performing the same 4 analysis used for the other two variables the positive trend for the adopters is confirmed, as shown in figures: 5.35, 5.36, 5.37 and 5.38. Focusing the attention on the last figure indeed, it emerges that after eight years we can reject the null hypothesis significantly.

Finally one of the most interesting variable examined is the market share evolution of the adopters. This variable confirms the previous graphs too, with a positive growth over time as shown in figures 5.39, 5.40, 5.41 and 5.42.

In conclusion, after the examination of these data it is possible to state that who invest in additive manufacturing technology actually increases its productivity and market share.

Variable	post	post_1	post_2	post_3	post_4	post_5	post_6	post_7
post	-37546.25							
	9905.62							
	0.00							
post1		-30397.74						
		11976.38						
		0.02						
post2			-21236.99					
			14524.58					
			0.16					
post3				-23079.21				
				15600.16				
				0.16				
post4					-10223.72			
					17049.20			
					0.56			
post5						-186.32		
						19332.86		
						0.99		
post6							13496.74	
							21838.58	
							0.55	
post7								29889.51
								21152.81
								0.18
_cons	209064.67	204999.05	200873.89	200676.34	196256.04	193543.93	190983.93	188855.42
	4105.96	4529.93	5042.21	4849.79	4593.57	4407.49	4073.52	3288.00
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N	193	193	193	193	193	193	193	193

Figure 5.28: Robust regression analysis with fixed effects from the first year after the adoption to the eighth [4]

Nevertheless the benefits are not immediate, meaning that it takes three or four years after the investment to start to appreciate all the advantages that these technologies could bring.

In the end, even if there are positive effects, the collection of new data from the balance sheets of the following years will allow more complete analysis, which could confirm or reject the truthfulness of the results exposed in this thesis.

Variable	post	post_1	post_2	post_3	post_4	post_5	post_6	post_7
post	-36389.38 12257.17 0.00							
post1		-27652.68 12488.20 0.03						
post2			-16199.56 12838.37 0.21					
post3				-19126.31 13116.08 0.15				
post4					-1400.97 12956.51 0.91			
post5						10271.75 13075.50 0.43		
post6							27001.62 13499.34 0.05	
post7								44153.70 13557.57 0.00
N	193	193	193	193	193	193	193	193

Figure 5.29: Regression analysis with fixed effects and year dummies from the first year after the adoption to the eighth [4]

Variable	post	post_1	post_2	post_3	post_4	post_5	post_6	post_7
post	-36389.38 15134.85 0.03							
post1		-27652.68 17184.12 0.13						
post2			-16199.56 19013.66 0.41					
post3				-19126.31 20102.64 0.36				
post4					-1400.97 14753.46 0.93			
post5						10271.75 17722.56 0.57		
post6							27001.62 21928.11 0.24	
post7								44153.70 22466.41 0.07
N	193	193	193	193	193	193	193	193

Figure 5.30: Robust regression analysis with fixed effects and year dummies from the first year after the adoption to the eighth [4]

Variable	post	post_1	post_2	post_3	post_4	post_5	post_6	post_7
post	-5.33							
	1.16							
	0.00							
post1		-4.97						
		1.18						
		0.00						
post2			-4.52					
			1.23					
			0.00					
post3				-3.78				
				1.24				
				0.00				
post4					-3.23			
					1.21			
					0.01			
post5						-2.59		
						1.24		
						0.04		
post6							-2.02	
							1.34	
							0.13	
post7								-1.52
								1.40
								0.28
_cons	10.04	9.71	9.40	9.03	8.72	8.44	8.23	8.09
	0.59	0.56	0.54	0.52	0.48	0.45	0.43	0.42
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N	192	192	192	192	192	192	192	192

Figure 5.31: ROS regression analysis with fixed effects from the first year after the adoption to the eighth [4]

Variable	post	post_1	post_2	post_3	post_4	post_5	post_6	post_7
post	-5.33							
	1.24							
	0.00							
post1		-4.97						
		1.42						
		0.00						
post2			-4.52					
			1.51					
			0.01					
post3				-3.78				
				1.85				
				0.06				
post4					-3.23			
					1.92			
					0.11			
post5						-2.59		
						2.14		
						0.24		
post6							-2.02	
							2.28	
							0.39	
post7								-1.52
								2.14
								0.49
_cons	10.04	9.71	9.40	9.03	8.72	8.44	8.23	8.09
	0.51	0.53	0.52	0.58	0.52	0.49	0.43	0.33
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N	192	192	192	192	192	192	192	192

Figure 5.32: ROS robust regression analysis with fixed effects from the first year after the adoption to the eighth [4]

Variable	post	post_1	post_2	post_3	post_4	post_5	post_6	post_7
post	-2.59							
	1.32							
	0.05							
post1		-1.89						
		1.35						
		0.16						
post2			-1.09					
			1.39					
			0.43					
post3				0.01				
				1.39				
				0.99				
post4					0.74			
					1.36			
					0.59			
post5						1.58		
						1.37		
						0.25		
post6							1.88	
							1.43	
							0.19	
post7								2.30
								1.46
								0.12
N	192	192	192	192	192	192	192	192

Figure 5.33: ROS regression analysis with fixed effects and year dummies from the first year after the adoption to the eighth [4]

Variable	post	post_1	post_2	post_3	post_4	post_5	post_6	post_7
post	-2.59 1.99 0.21							
post1		-1.89 1.97 0.35						
post2			-1.09 1.91 0.58					
post3				0.01 2.05 1.00				
post4					0.74 2.29 0.75			
post5						1.58 2.50 0.53		
post6							1.88 2.48 0.46	
post7								2.30 2.41 0.35
N	192	192	192	192	192	192	192	192

Figure 5.34: ROS robust regression analysis with fixed effects and year dummies from the first year after the adoption to the eighth [4]

Variable	post	post_1	post_2	post_3	post_4	post_5	post_6	post_7
post	-1.65 0.23 0.00							
post1		-1.20 0.25 0.00						
post2			-1.06 0.26 0.00					
post3				-0.92 0.27 0.00				
post4					-0.69 0.26 0.01			
post5						-0.40 0.27 0.14		
post6							-0.16 0.29 0.59	
post7								0.18 0.30 0.55
_cons	5.69 0.12 0.00	5.46 0.12 0.00	5.38 0.12 0.00	5.29 0.11 0.00	5.19 0.10 0.00	5.10 0.10 0.00	5.04 0.09 0.00	4.98 0.09 0.00
N	193	193	193	193	193	193	193	193

Figure 5.35: Value added per employee regression analysis with fixed effects from the first year after the adoption to the eighth [4]

Variable	post	post_1	post_2	post_3	post_4	post_5	post_6	post_7
post	-1.65 0.36 0.00							
post1		-1.20 0.33 0.00						
post2			-1.06 0.38 0.01					
post3				-0.92 0.42 0.04				
post4					-0.69 0.39 0.10			
post5						-0.40 0.39 0.31		
post6							-0.16 0.41 0.71	
post7								0.18 0.40 0.66
_cons	5.69 0.15 0.00	5.46 0.12 0.00	5.38 0.13 0.00	5.29 0.13 0.00	5.19 0.10 0.00	5.10 0.09 0.00	5.04 0.08 0.00	4.98 0.06 0.00
N	193	193	193	193	193	193	193	193

Figure 5.36: Value added per employee, robust regression analysis with fixed effects from the first year after the adoption to the eighth [4]

Variable	post	post_1	post_2	post_3	post_4	post_5	post_6	post_7
post	-1.05 0.25 0.00							
post1		-0.50 0.27 0.07						
post2			-0.31 0.27 0.27					
post3				-0.16 0.28 0.58				
post4					-0.01 0.28 0.97			
post5						0.36 0.28 0.20		
post6							0.60 0.29 0.04	
post7								0.92 0.29 0.00
N	193	193	193	193	193	193	193	193

Figure 5.37: Value added per employee regression analysis with fixed effects and year dummies from the first year after the adoption to the eighth [4]

Variable	post	post_1	post_2	post_3	post_4	post_5	post_6	post_7
post	-1.05							
	0.48							
	0.04							
post1		-0.50						
		0.32						
		0.14						
post2			-0.31					
			0.34					
			0.38					
post3				-0.16				
				0.37				
				0.68				
post4					-0.01			
					0.29			
					0.97			
post5						0.36		
						0.27		
						0.20		
post6							0.60	
							0.30	
							0.06	
post7								0.92
								0.33
								0.01
N	193	193	193	193	193	193	193	193

Figure 5.38: Value added per employee, robust regression analysis with fixed effects and year dummies from the first year after the adoption to the eighth [4]

Variable	post	post_1	post_2	post_3	post_4	post_5	post_6
post	-0.07						
	0.37						
	0.86						
post1		-0.12					
		0.34					
		0.72					
post2			0.55				
			0.29				
			0.06				
post3				0.72			
				0.28			
				0.01			
post4					0.63		
					0.28		
					0.03		
post5						0.58	
						0.29	
						0.04	
post6							0.71
							0.30
							0.02
_cons	2.68	2.70	2.41	2.38	2.43	2.48	2.48
	0.20	0.18	0.14	0.13	0.12	0.11	0.10
	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N	126	126	126	126	126	126	126

Figure 5.39: Adopters' market share, regression analysis with fixed effects from the first year after the adoption to the eighth [4]

Variable	post	post_1	post_2	post_3	post_4	post_5	post_6
post	-0.07						
	0.35						
	0.85						
post1		-0.12					
		0.43					
		0.78					
post2			0.55				
			0.77				
			0.48				
post3				0.72			
				0.91			
				0.44			
post4					0.63		
					0.90		
					0.49		
post5						0.58	
						0.87	
						0.51	
post6							0.71
							0.93
							0.46
_cons	2.68	2.70	2.41	2.38	2.43	2.48	2.48
	0.18	0.20	0.32	0.34	0.30	0.25	0.21
	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N	126	126	126	126	126	126	126

Figure 5.40: Adopters' market share, robust regression analysis with fixed effects from the first year after the adoption to the eighth [4]

Variable	post	post_1	post_2	post_3	post_4	post_5	post_6
post	-0.35						
	0.40						
	0.39						
post1		-0.44					
		0.38					
		0.25					
post2			0.40				
			0.34				
			0.24				
post3				0.64			
				0.33			
				0.06			
post4					0.55		
					0.33		
					0.10		
post5						0.49	
						0.33	
						0.15	
post6							0.60
							0.35
							0.09
N	126	126	126	126	126	126	126

Figure 5.41: Adopters' market share, regression analysis with fixed effects with year dummies from the first year after the adoption to the eighth[4]

Variable	post	post_1	post_2	post_3	post_4	post_5	post_6
post	-0.35						
	0.48						
	0.48						
post1		-0.44					
		0.55					
		0.44					
post2			0.40				
			0.59				
			0.50				
post3				0.64			
				0.84			
				0.46			
post4					0.55		
					0.82		
					0.51		
post5						0.49	
						0.79	
						0.55	
post6							0.60
							0.83
							0.48
N	126	126	126	126	126	126	126

Figure 5.42: Adopters' market share, robust regression analysis with fixed effects with year dummies from the first year after the adoption to the eighth[4]

Appendix A

Questionnaire

The following pages show the questionnaire submitted to a sample of 100 Italian companies operating in the orthopaedic prostheses manufacturing sector.

As discussed in the previous chapter, the data extracted from the answers have been analysed and used to understand if, and in which measure, these companies use additive technologies to manufacture their products.

Later, as main point of focus, we have tried to understand the economical impact on the Italian market, deriving from this way of producing.

Questionario sulle tecnologie additive

1. **Indirizzo email** *

2. **L'impresa fa parte di un gruppo di imprese? (per gruppo si intende un insieme di più imprese controllate - direttamente o indirettamente - dalle medesime persone fisiche o dalla medesima impresa)**
   Contrassegna solo un ovale.
   - Sì *Dopo l'ultima domanda in questa sezione, passa alla domanda 6.*
   - No *Dopo l'ultima domanda in questa sezione, passa alla domanda 7.*

3. **È un'impresa a conduzione a familiare?**
   Contrassegna solo un ovale.
   - Sì
   - No

4. **Dove è allocata principalmente la sua produzione?**
   Contrassegna solo un ovale.
   - Nord Italia
   - Centro Italia
   - Sud Italia
   - Estero (Unione Europea)
   - Altro: ____________

5. **Qual è la strategia produttiva attualmente adottata?**
   Contrassegna solo un ovale.
   - Su sito unico
   - Su più siti produttivi

6. **Dov'è localizzata la maggior parte dei fornitori dell'impresa?**
   Contrassegna solo un ovale.
   - Nord Italia
   - Centro Italia
   - Sud Italia
   - Estero (Unione Europea)
   - Altro: ____________

Interrompi la compilazione del modulo.

Gruppo imprese

7. **L'impresa fa parte di un gruppo la cui proprietà non è italiana?**
   Contrassegna solo un ovale.
   - Sì
   - No

Interrompi la compilazione del modulo.

Adozione tecnologie additive

8. **L'impresa ha effettuato investimenti in tecnologie additive?**
   Contrassegna solo un ovale.

   - Sì *Passa alla domanda 8.*
   - No *Passa alla domanda 16.*

Interrompi la compilazione del modulo.

Adozione di tecnologie additive: Sì

9. **Utilizzate tecnologie additive per la lavorazione di:**
   Contrassegna solo un ovale.

   - Polimeri
   - Metalli
   - Altro: __________

10. **Quali tecnologie additive avete adottato? (lista di diverse tecnologie)**

11. **Quando ha effettuato il primo investimento in tecnologie additive? (Specificare anno)**

12. **Qual è l'ammontare di investimento in tecnologie additive in ciascun anno dal 2014 al 2017?**
    Contrassegna solo un ovale per riga.

	0 - 15.000 €.	15.000 €. - 40.000 €.	40.000 €. - 70.000 €.	70.000 €. - 100.000 €.	100.000 €. - 200.000 €.	Oltre 200.000 €.
2014						
2015						
2016						
2017						

13. **Quali sono stati i principali obiettivi che l'azienda si è proposta di raggiungere con gli investimenti in tecnologie additive effettuati nel periodo 2014-2017?**
    Indicare in ordine decrescente, 1 il più importante
    Contrassegna solo un ovale per riga.

	1	2	3	4	5
Riduzione dei costi di produzione					
Aumento della varietà della gamma dei prodotti					
Maggiore corrispondenza con i bisogni dei clienti					
Riduzione dei tempi di passaggio dalla progettazione alla produzione in serie					

14. **Utilizza le tecnologie additive per:**
Seleziona tutte le voci applicabili.

- [ ] Rapid prototyping (Ricerca & Sviluppo)
- [ ] Produzione
- [ ] Altro: ____________________

15. **Ritiene che un produzione supportata da tecnologia additiva potrebbe risolvere o, per lo meno attenuare, le criticità della sua Supply Chain?**
Contrassegna solo un ovale.

- ( ) Sì *Passa alla domanda 15.*
- ( ) No *Interrompi la compilazione del modulo.*
- ( ) In parte *Passa alla domanda 15.*

Interrompi la compilazione del modulo.

Criticità Supply Chain

16. **Quali sono o potrebbero essere gli impatti delle soluzioni tecnologiche additive sulla vostra Supply Chain?**
Seleziona tutte le voci applicabili.

- [ ] Aumento dell'efficienza (es. riduzione del tempo ciclo dell'ordine, riduzione dei livelli di scorta, etc.)
- [ ] Aumento della flessibilità
- [ ] Riduzione del numero dei fornitori
- [ ] Possibilità di diversificazione delle materie prime/tecnologie utilizzate
- [ ] Altro: ____________________

Interrompi la compilazione del modulo.

Adozione di tecnologie additive: No

17. **Quali sono i motivi per non aver ancora investito in tecnologie additive?**

____
____
____
____
____

18. **Avete già pianificato investimenti futuri in tecnologie additive?**
Contrassegna solo un ovale.

- ( ) Sì, a breve (entro 1 anno)
- ( ) Sì, a medio termine (entro i prossimi 5 anni)
- ( ) No, non abbiamo pianificato nessun investimento

19. **Ritiene che un produzione supportata da tecnologia additiva potrebbe risolvere o, per lo meno attenuare, le criticità della sua Supply Chain?**
Contrassegna solo un ovale.

- ( ) Sì *Passa alla domanda 15.*
- ( ) No *Interrompi la compilazione del modulo.*
- ( ) In parte *Passa alla domanda 15.*

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