POLITECNICO DI TORINO

Master Degree in Engineering and Management

Master's Degree Thesis

The adoption of Additive Manufacturing in the dental 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 analyzing 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 two chapters we examine in depth the 3D printing related to the dental prostheses 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

ASP Average Selling Price

CAD Computer Aided Design

CAGR Compound Annual Growth Rate

CFL Cubital Facet List

CLIP Continuous Liquid Interface Production

CMM Coordinate Measuring Machine

CNC Computer Numerical Control

COM Cost Of Manufacturing

CT Computer Tomography

CT Nuclear Magnetic Resonance

DED Direct Energy Deposition

DIY Do It Yourself

DLC Direct Labour Cost

DLP Direct Light Processing

DMC Direct Material Cost

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
IDLC	InDirect Labour Cost
IDMC	InDirect Material Cost
IP	Intellectual Property
JT	Jupiter Tessellation
KPI	Key Performance Indicator
LBL	Layer By Layer
LENS	Laser Engineered Net Shaping
LOM	Laminated Object Manufacturing
MC	Marketing Cost
MOC	Manufacturing Overhead Cost
MP	Market Price
OEM	Original Equipment Manufacturer
PBF	Powder Bed Fusion
R	Revenue
RDC	Research and Development Cost
RM	Rapid Manufacturing
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
SVRT	Sustainable Value Roadmapping Tool
T	Taxes
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.

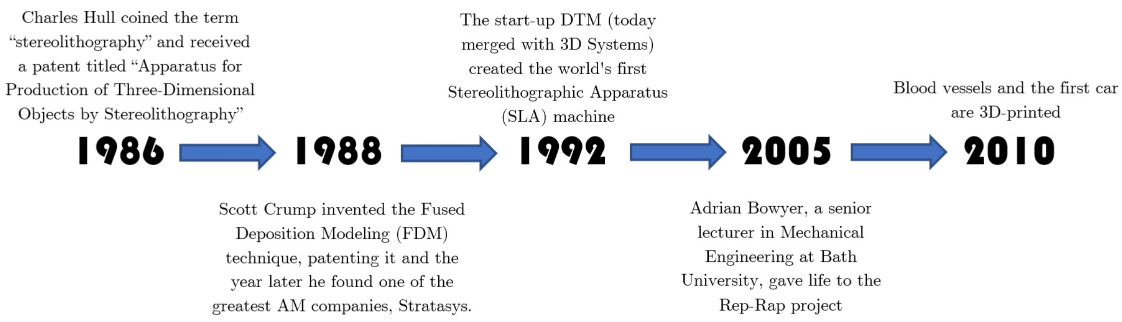


Figure 1.1: Timeline of the most important years in 3D printing history [63]

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.

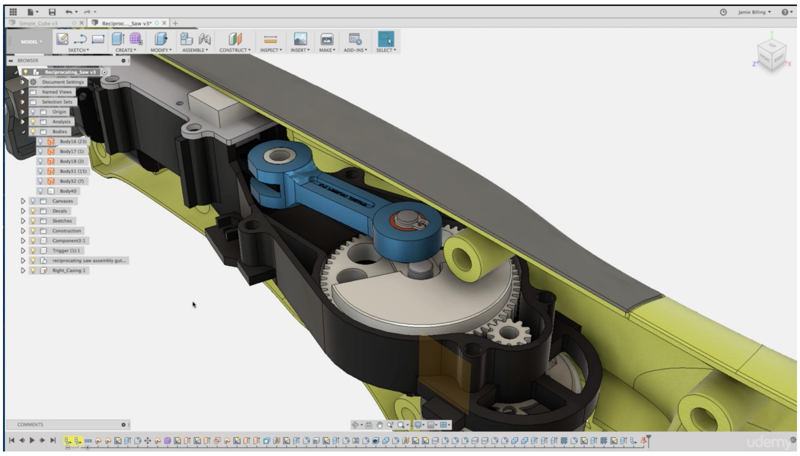


Figure 1.2: Solid Modeling [13]

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.

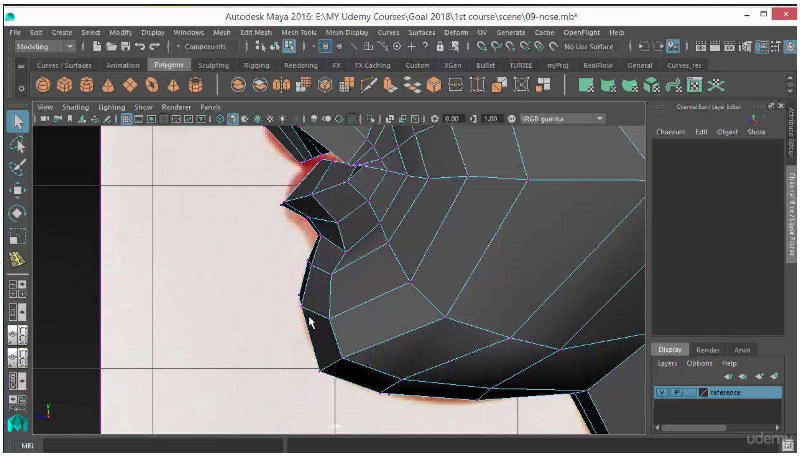


Figure 1.3: Surface Modeling [13]

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*.

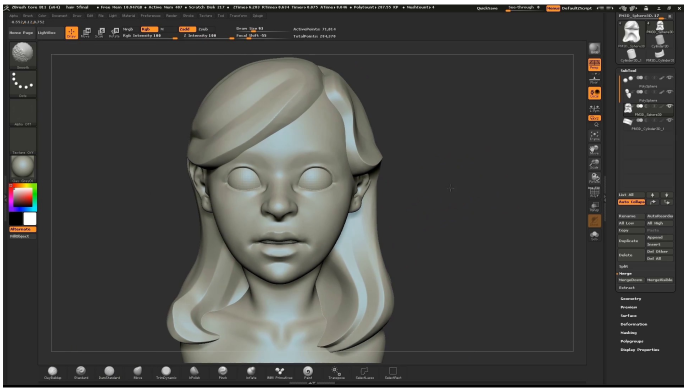


Figure 1.4: Sculpting [66]

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 [36]

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

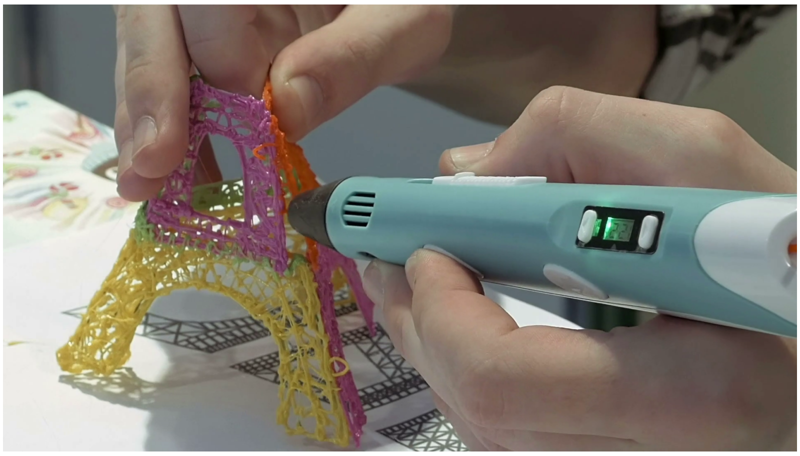


Figure 1.8: How Manual Measurement works [59]

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).

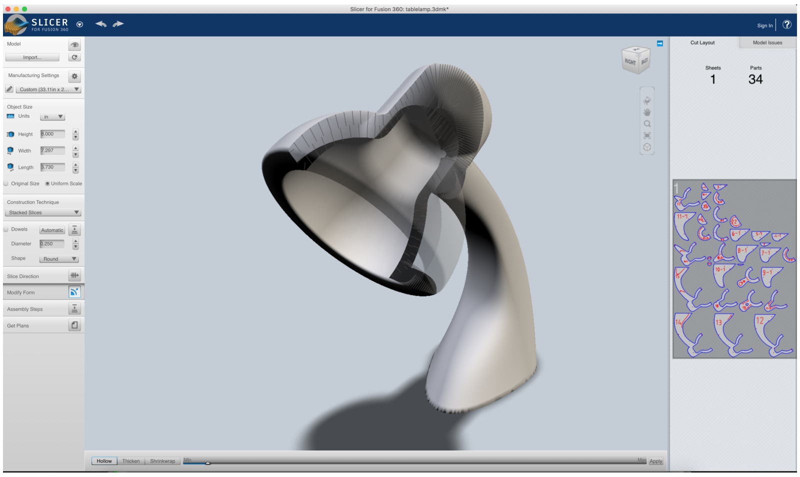


Figure 1.9: Slicer, a tool for Autodesk Fusion 360 [7]

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.

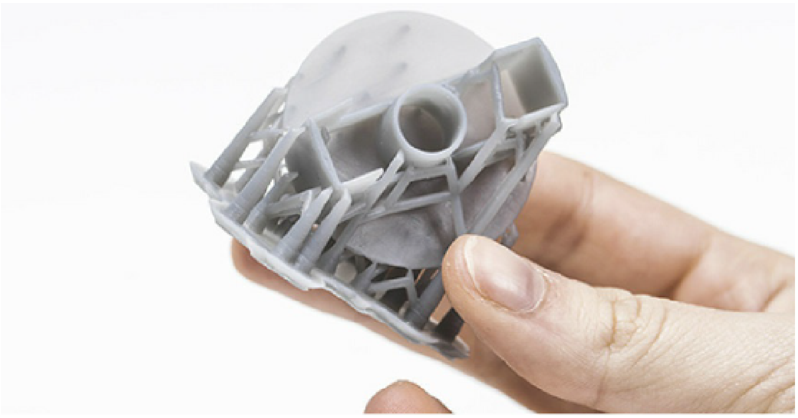


Figure 1.10: The shaft end cap after being removed from the build platform with support structures still attached [48]

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 [32]

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.

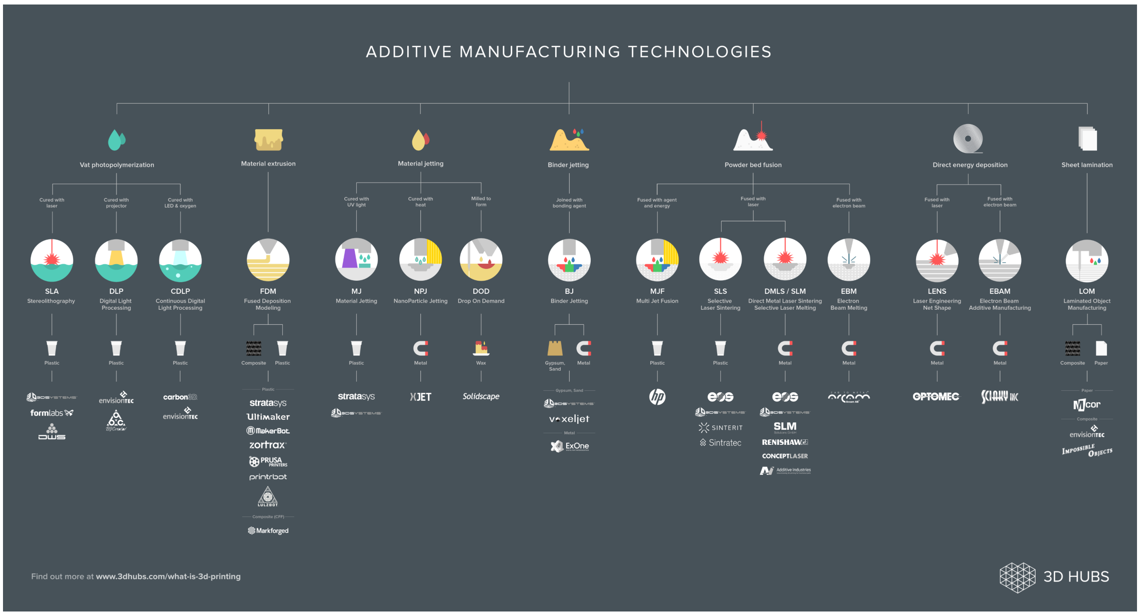


Figure 1.12: Map of all the existing AM processes and related technologies [1]

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).

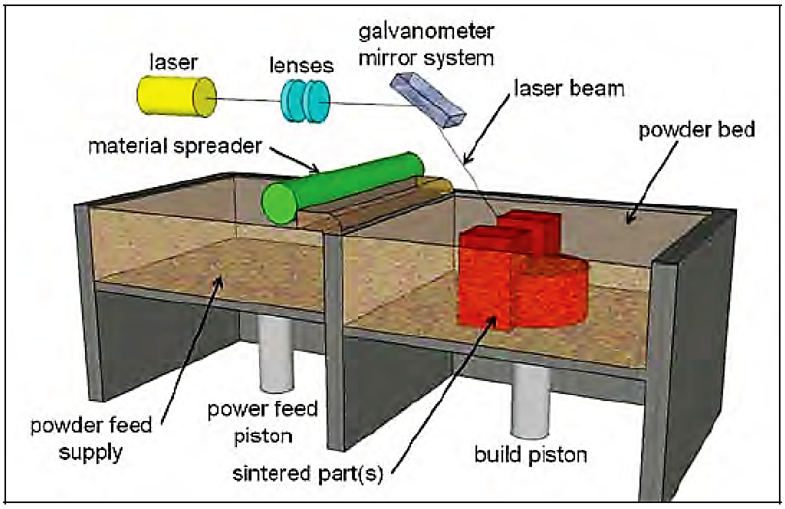


Figure 1.13: Powder bed fusion process [63]

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

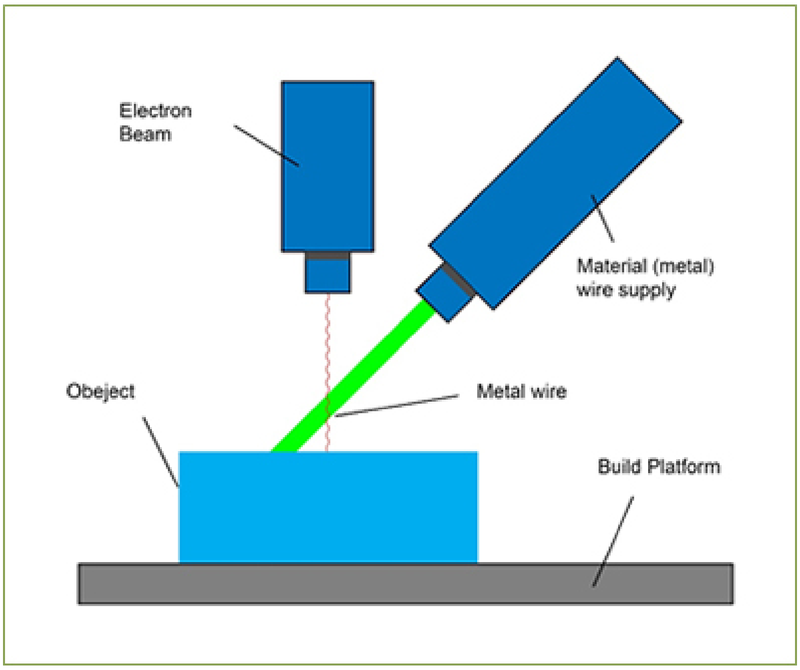


Figure 1.14: Direct Energy Deposition process [23]

- 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

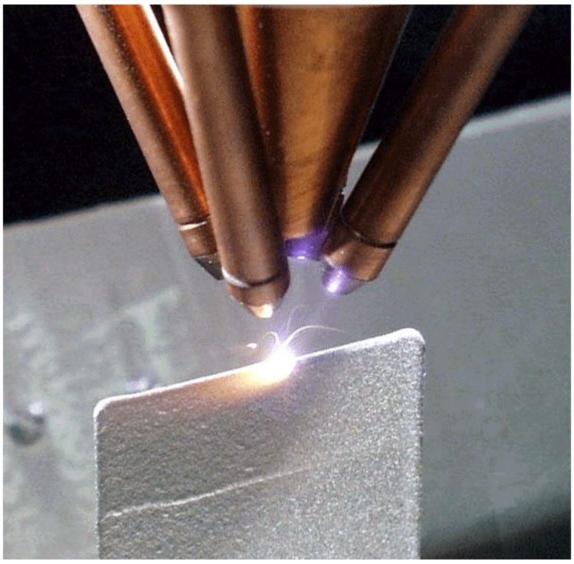


Figure 1.15: Laser Engineered Net Shaping [57]

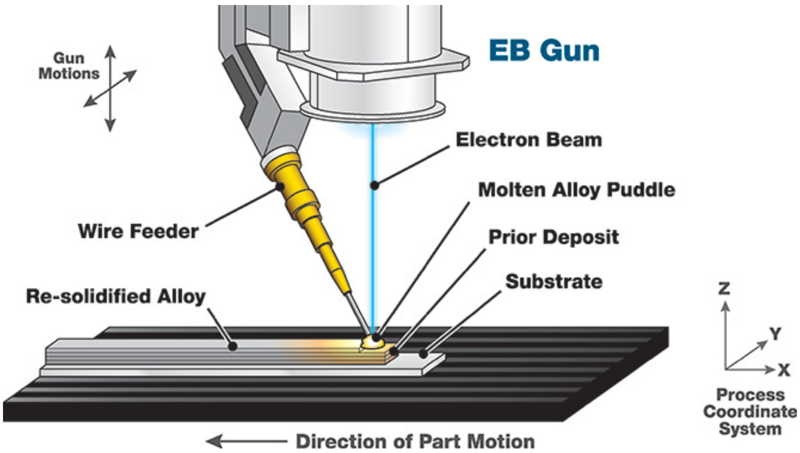


Figure 1.16: Electron Beam Direct Manufacturing[51]

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

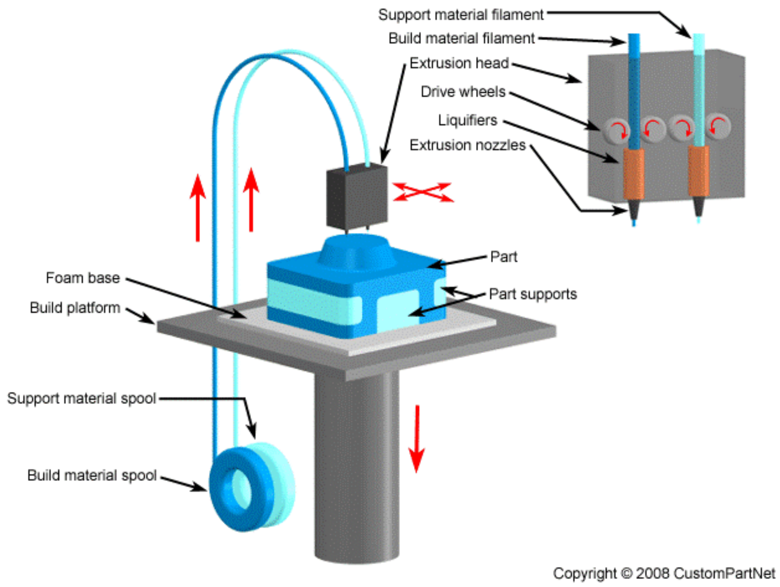


Figure 1.17: Fused Deposition Modeling or Material Extrusion process [15]

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

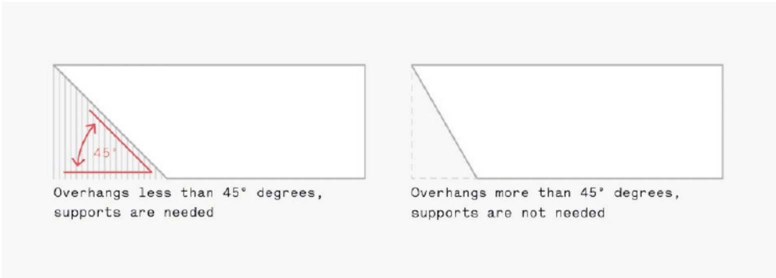


Figure 1.18: FFF support requirements [48]

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.

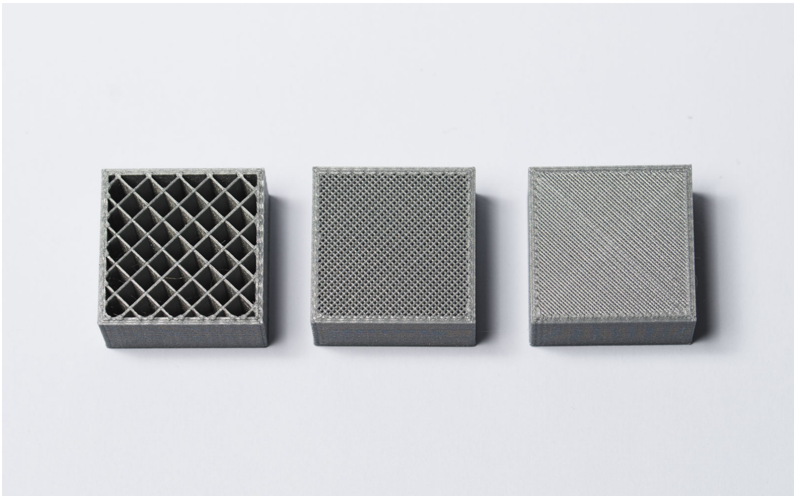


Figure 1.19: Infill percentage ranging from 10% (left), 50% (center) and 80% (right) [48]

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.

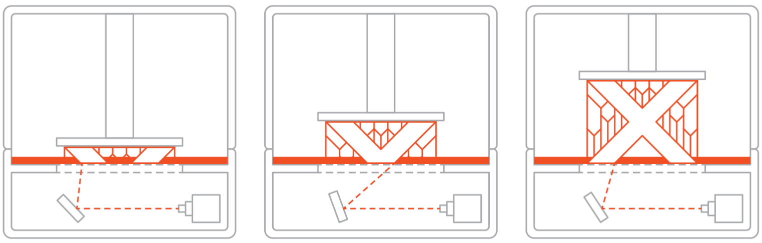


Figure 1.20: The Vat photo polymerization priting process [48]

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.

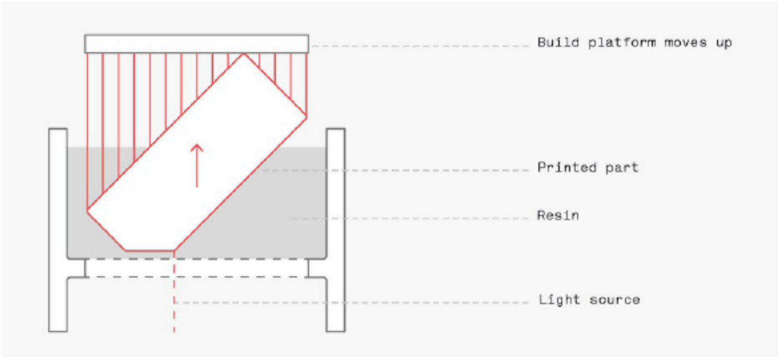


Figure 1.21: The Bottom-up approach [48]

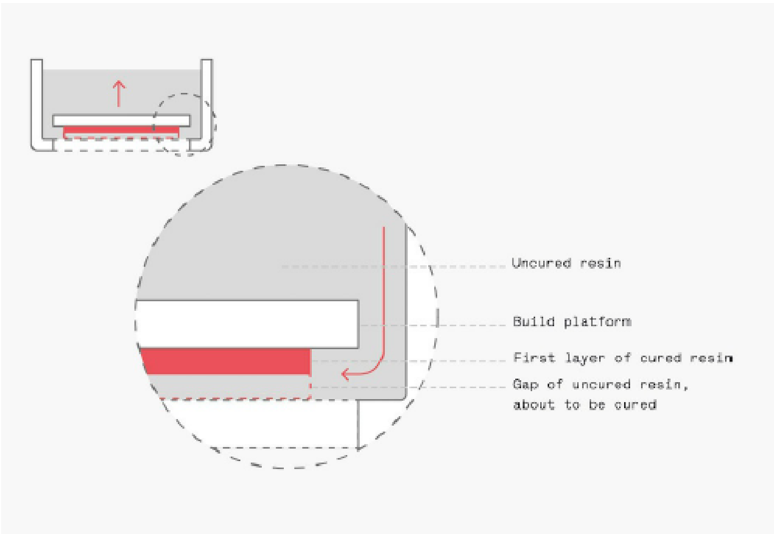


Figure 1.22: Bottom-up printer configuration [48]

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.

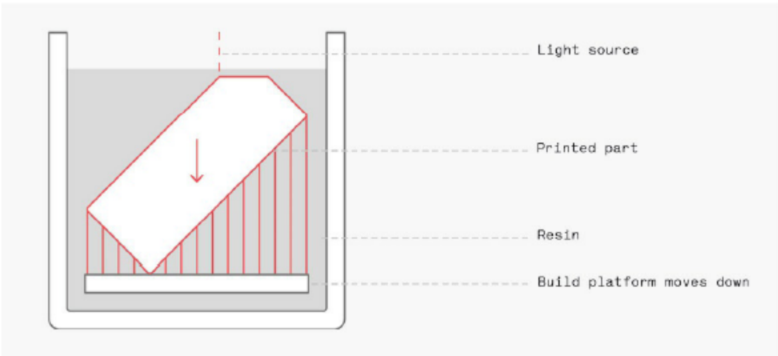


Figure 1.23: The Top-down approach [48]

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

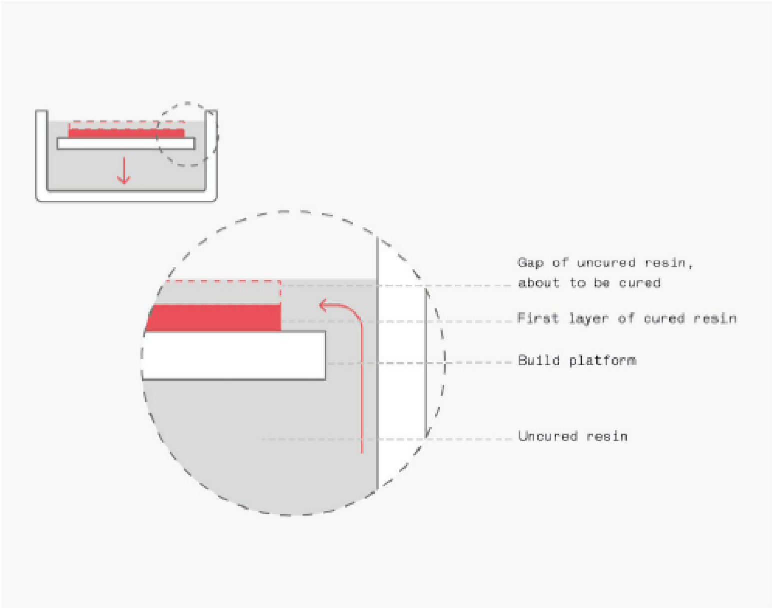


Figure 1.24: Top-down printer configuration [48]

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.

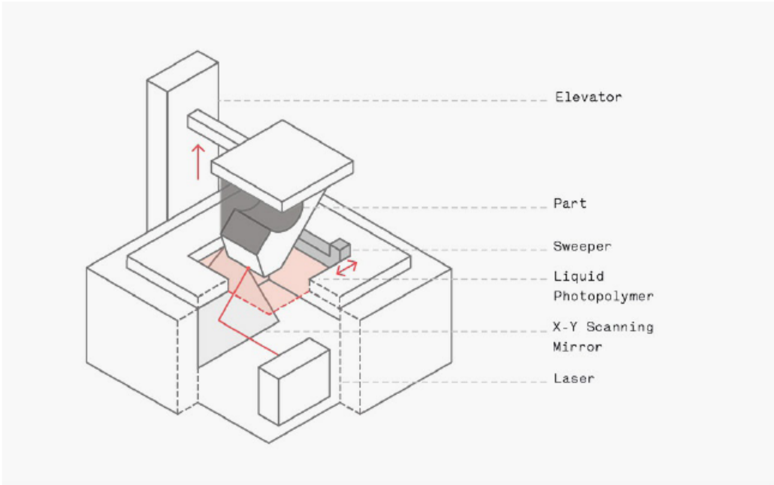


Figure 1.25: Schematic of a SLA printer [48]

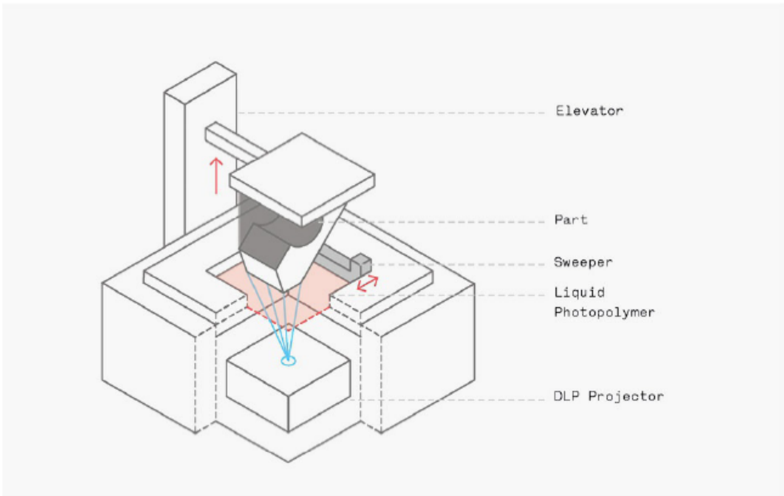


Figure 1.26: Schematic of a DLP printer [48]

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

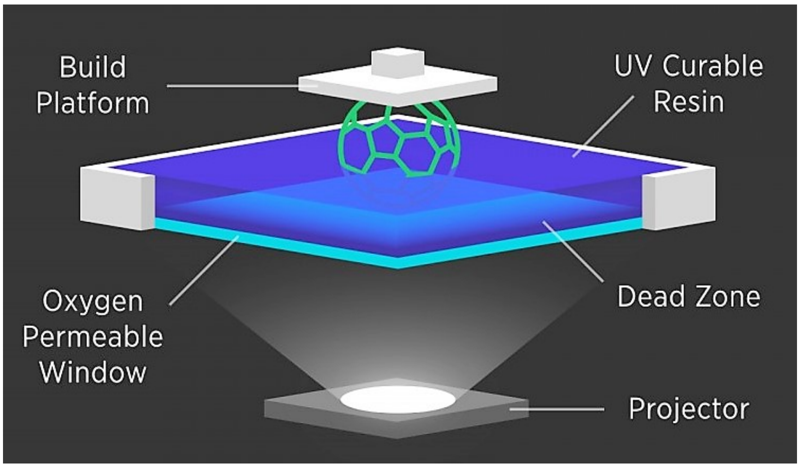


Figure 1.27: The CLIP technology [48]

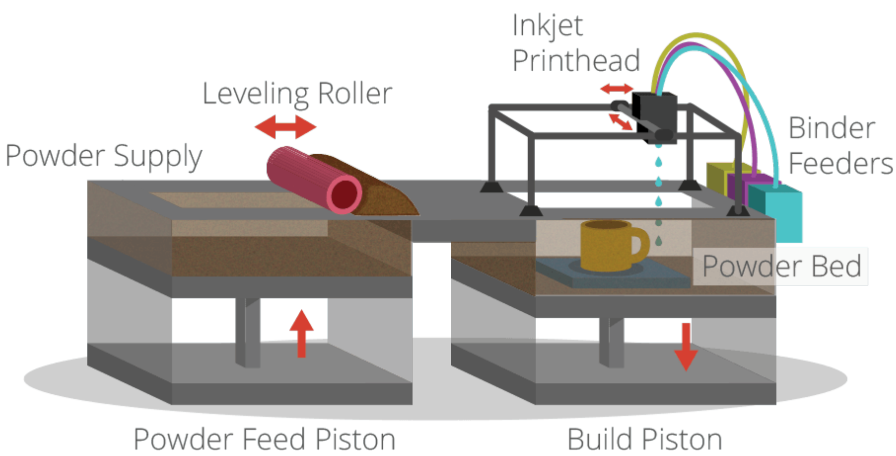


Figure 1.28: The Binder Jetting process [56]

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

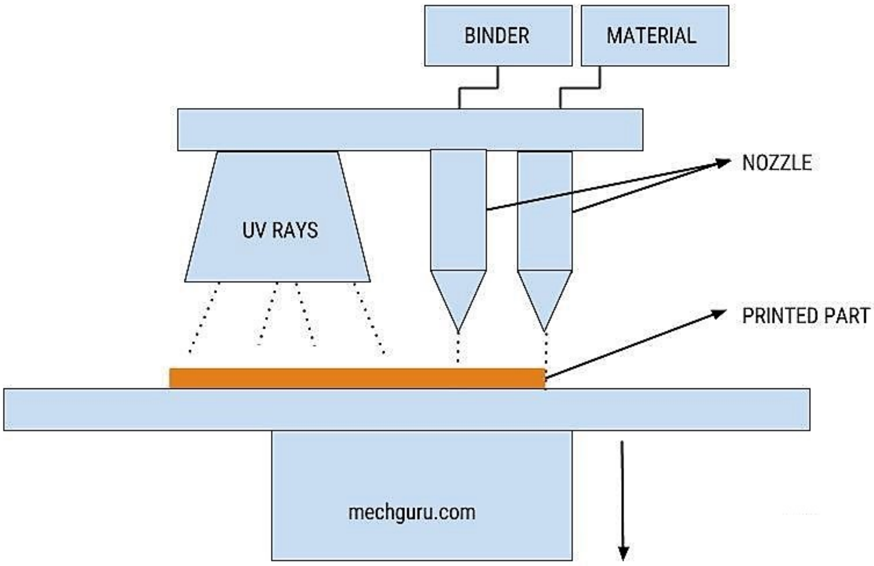


Figure 1.29: The Material Jetting process [35]

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.

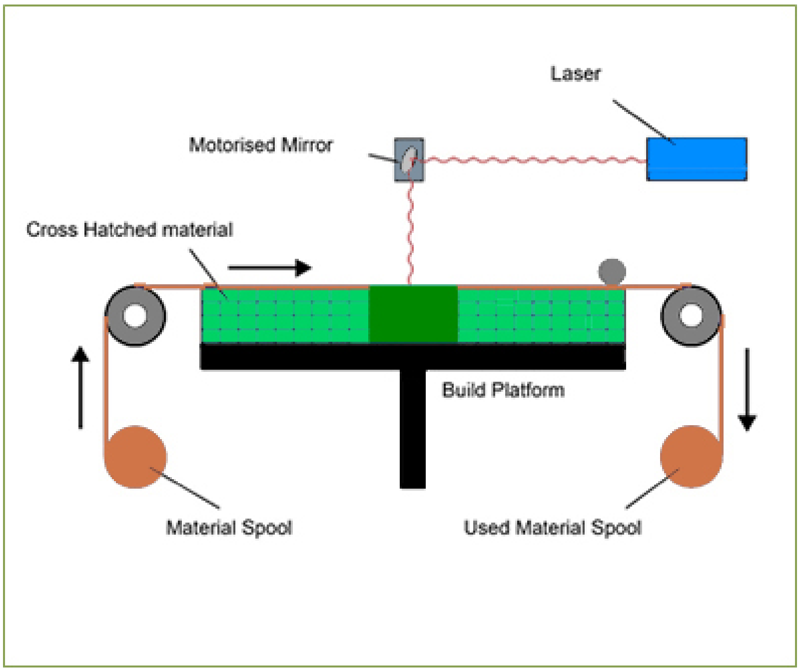


Figure 1.30: The Sheet Lamination process [19]

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.

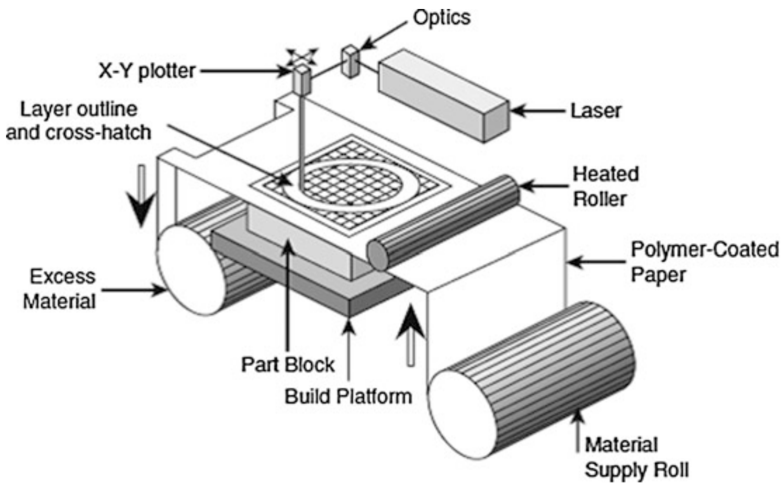


Figure 1.31: Schematic of the LOM process [6]

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.

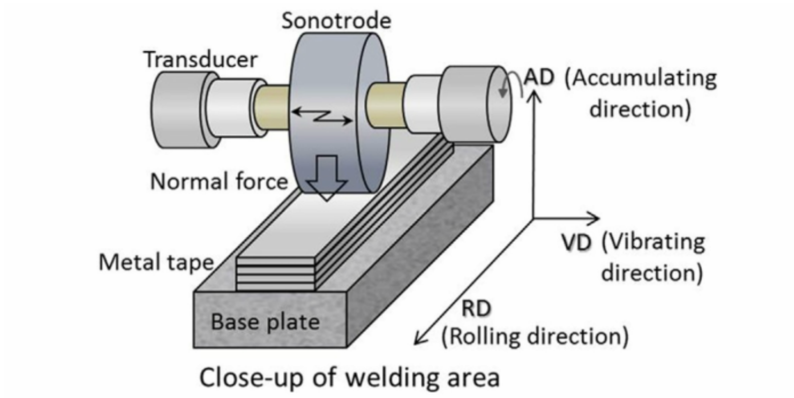


Figure 1.32: Ultrasonic Additive Manufacturing technique [26]

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.

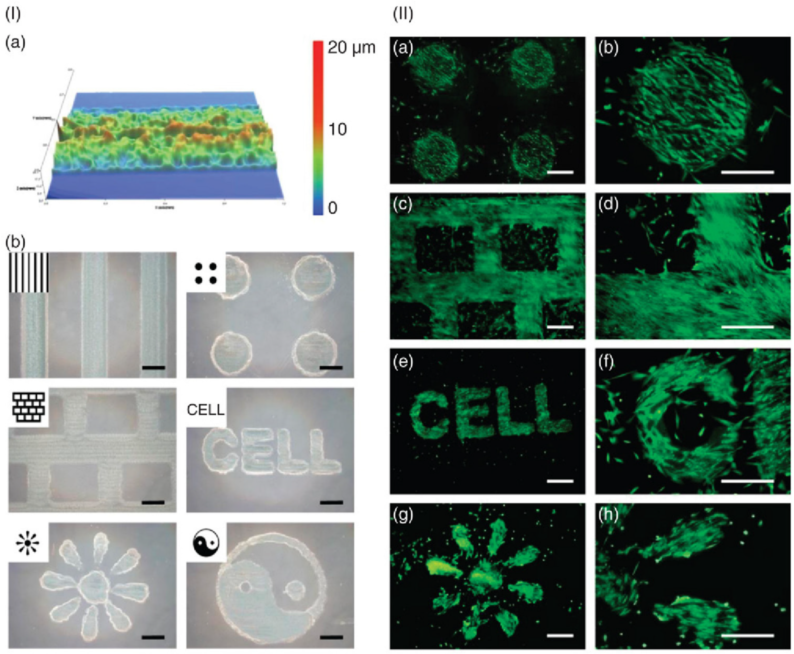


Figure 1.33: The two-dimensional patterning of PLGA onto the culture substrates [27]

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.

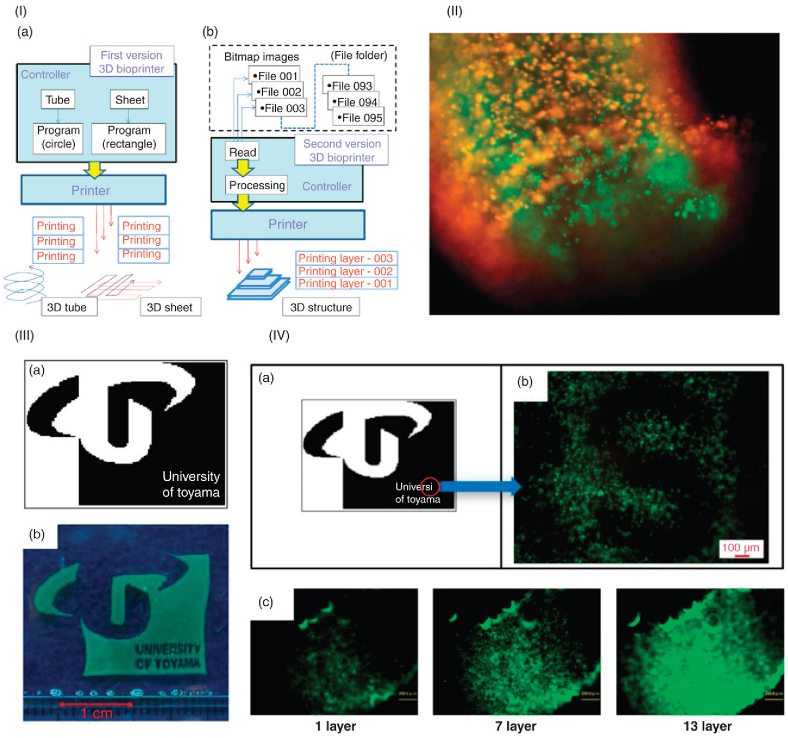


Figure 1.34: The tissue-like structures consisting of alginate hydrogel and cells. [27]

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.

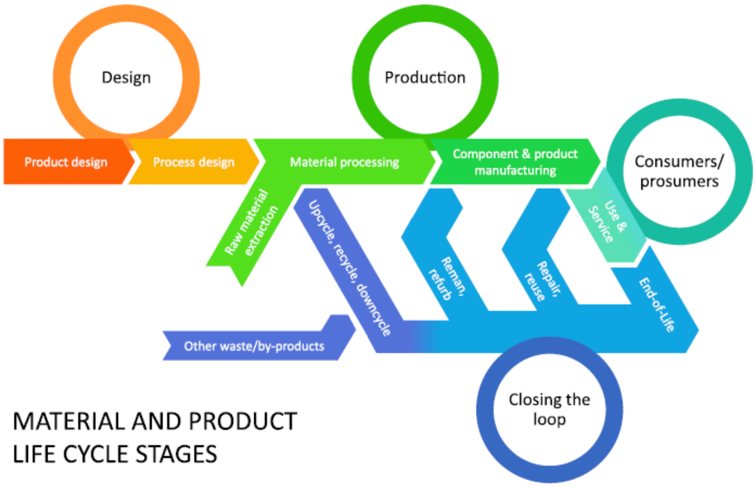


Figure 2.1: Product life cycle stages [21]

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.

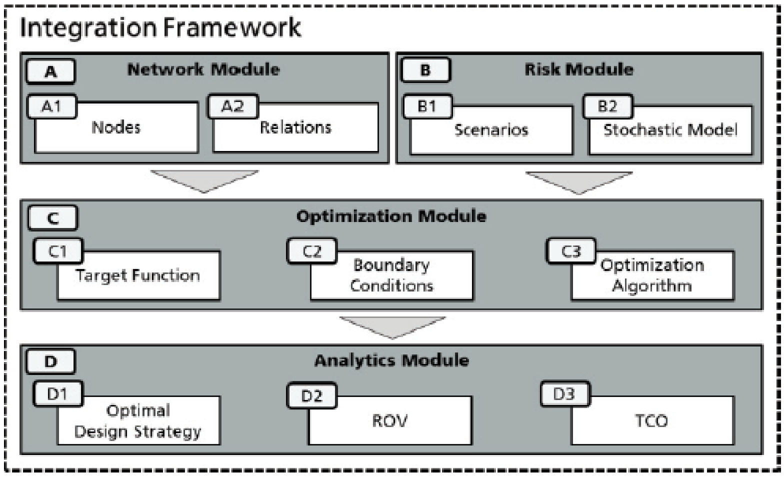


Figure 2.2: AM integration framework [52]

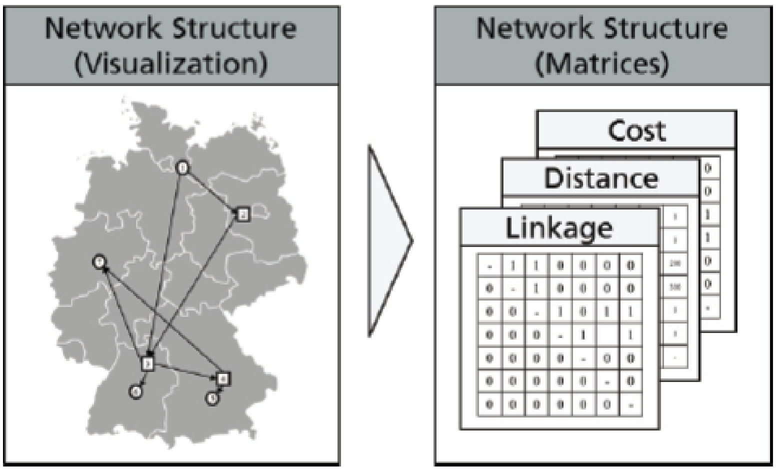


Figure 2.3: Network structure example [52]

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

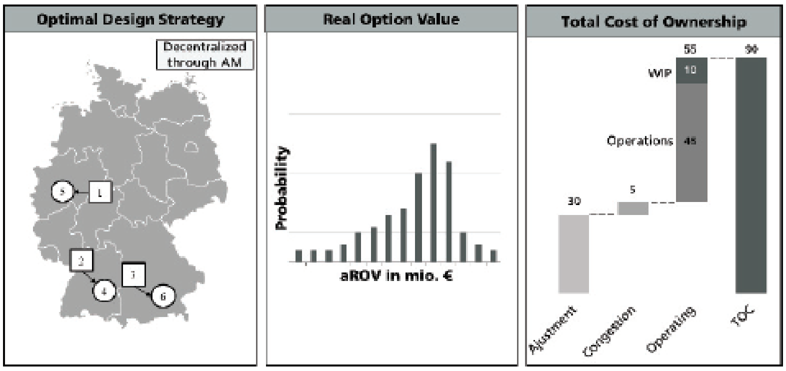


Figure 2.4: Module D output visualization [52]

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;

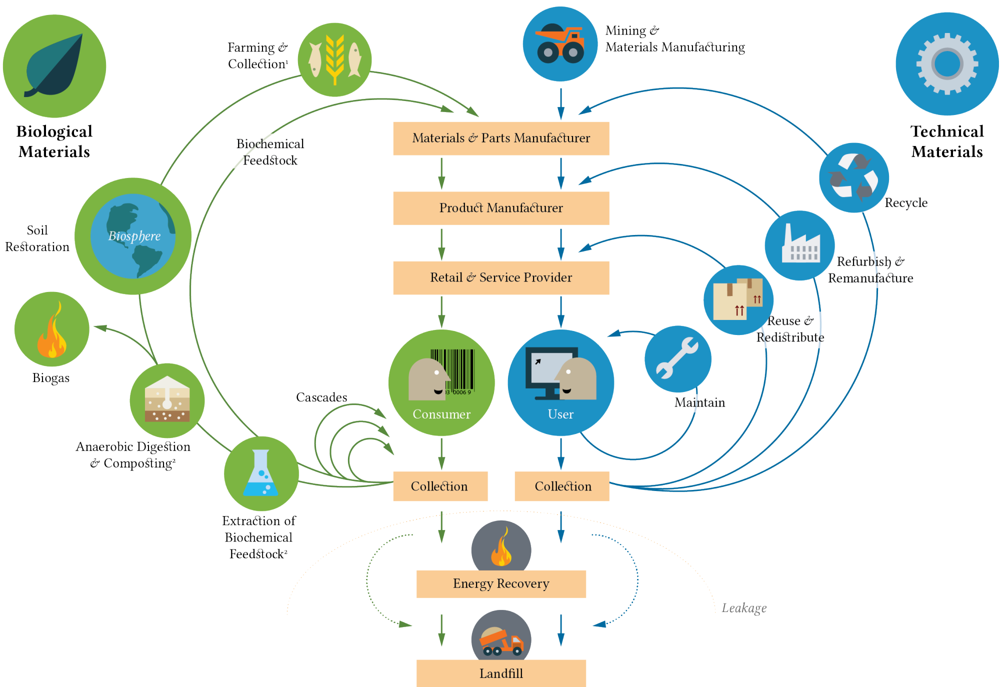


Figure 2.5: Concept of circular economy by Ellen Macarthur Foundation [16]

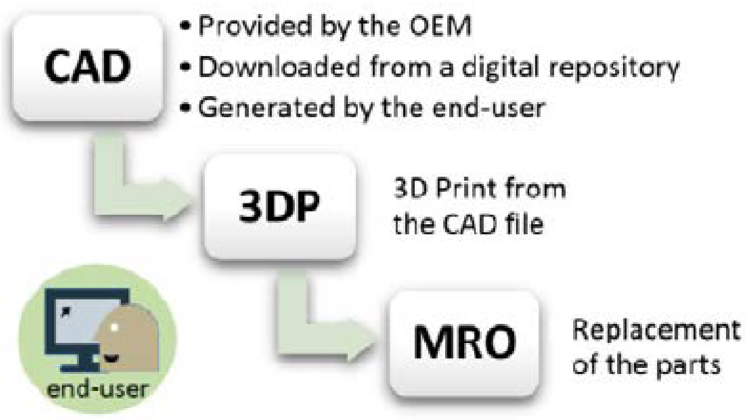


Figure 2.6: Standard MRO process flow for additive manufacturing Foundation [16]

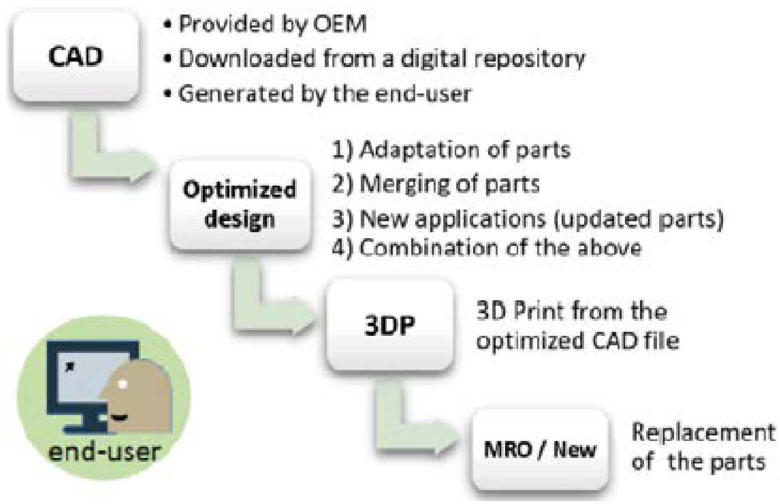


Figure 2.7: Optimized MRO process flow for additive manufacturing Foundation [16]

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) .

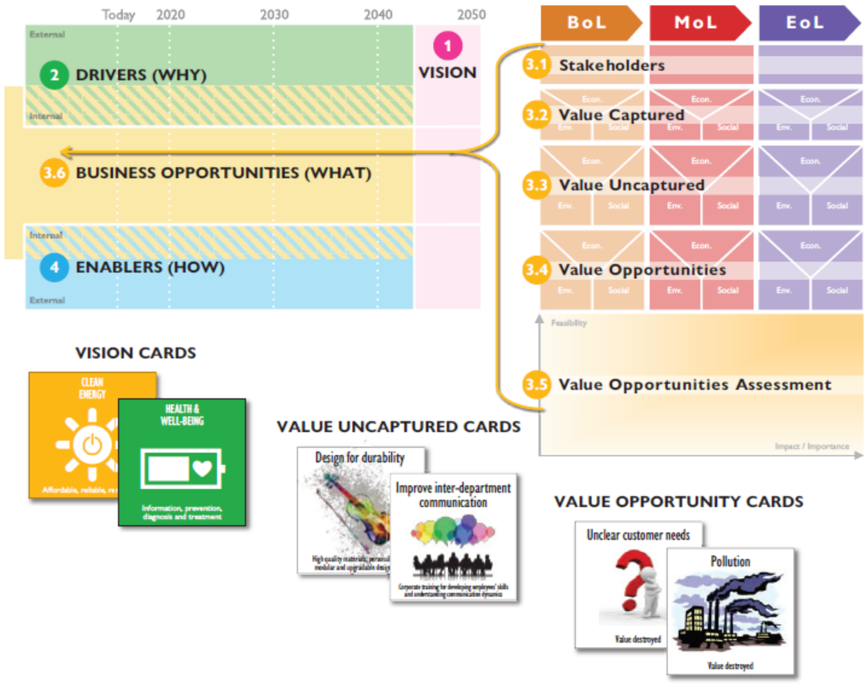


Figure 2.8: Sustainable Value Roadmapping Tool [16]

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.

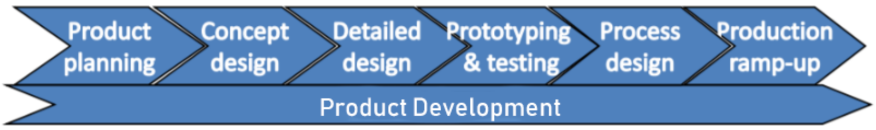


Figure 2.9: Product development process [10]

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.

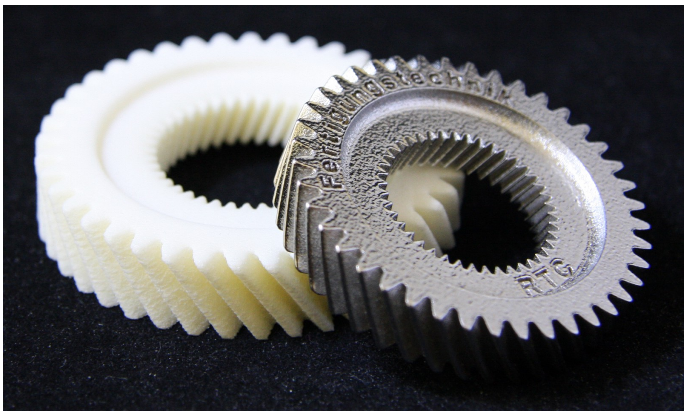


Figure 2.10: A gear made with the Rapid Prototyping technology [28]

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:

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

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:

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

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):

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

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

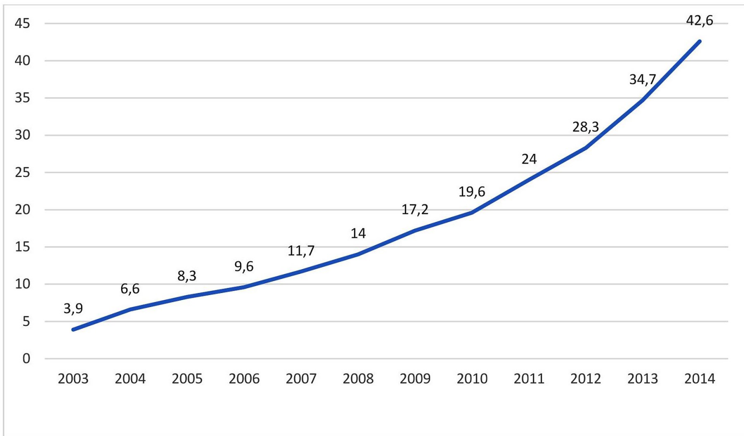


Figure 2.11: The use of AM for part production [63]

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.

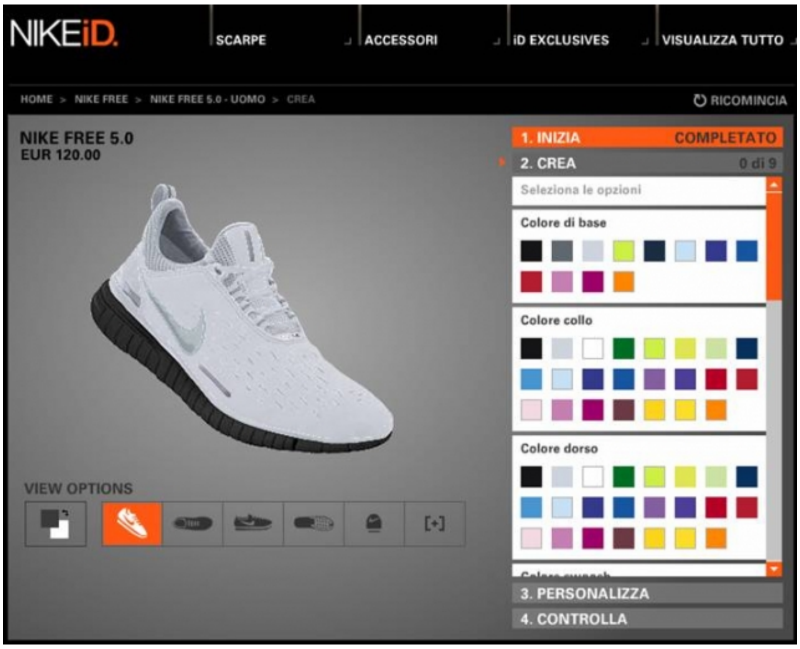


Figure 2.12: Nike ID allows customers to edit the sneakers according to their wishes [40]

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.

	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

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 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,

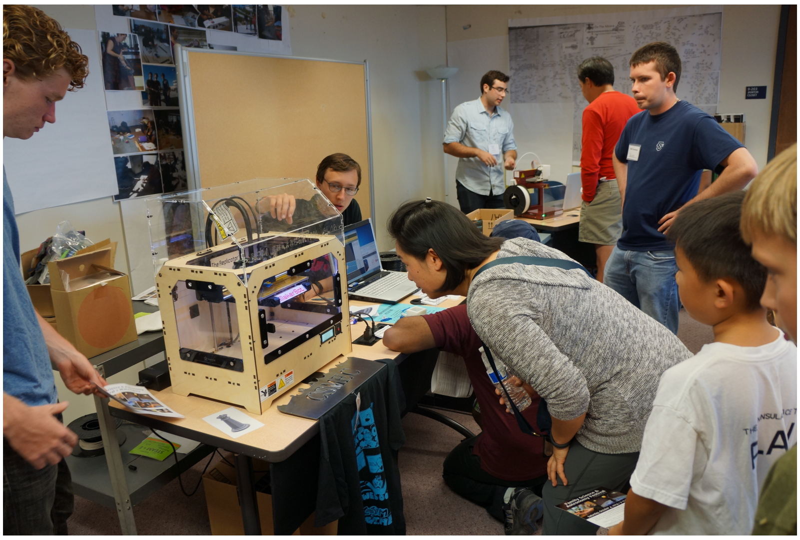


Figure 2.13: A Makerspace in the college of San Mateo, California [31]

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

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

Figure 2.14: A UPS store in U.S. with a 3D printing service [24]

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;

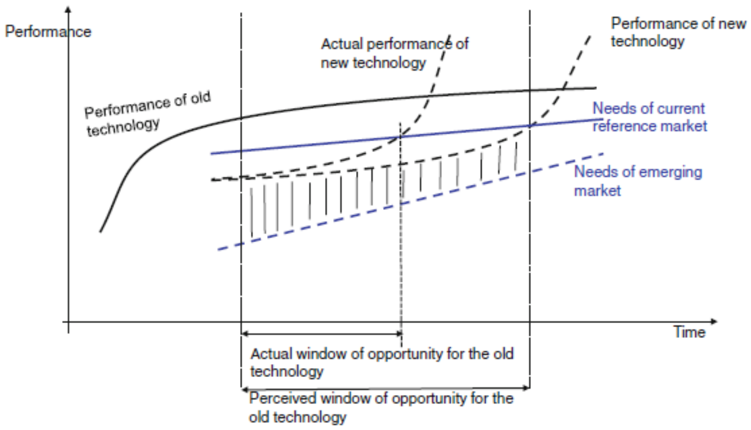


Figure 3.1: The Christensen Effect [10]

- 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).

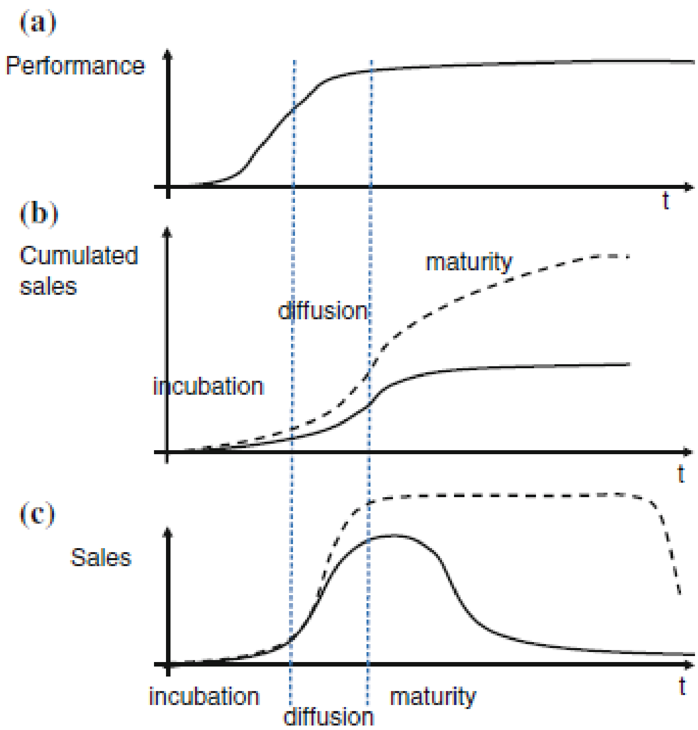


Figure 3.2: Performance and diffusion s-curves [10]

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.

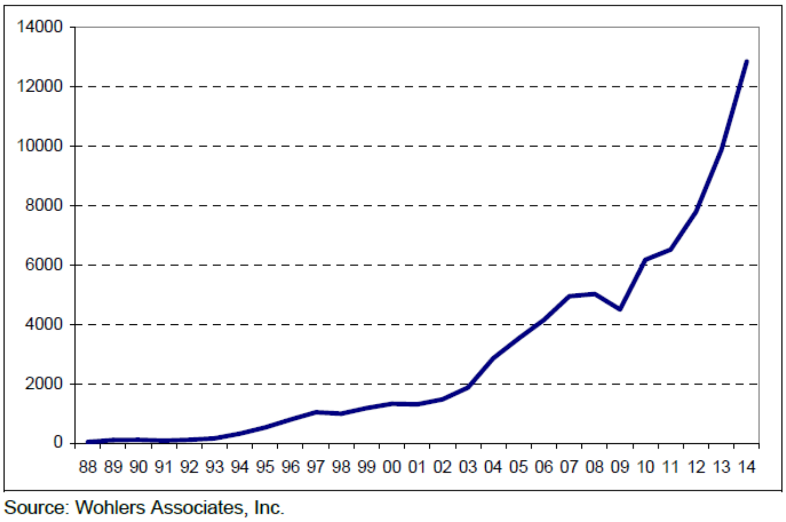


Figure 3.3: Industrial systems unit sales [63]

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

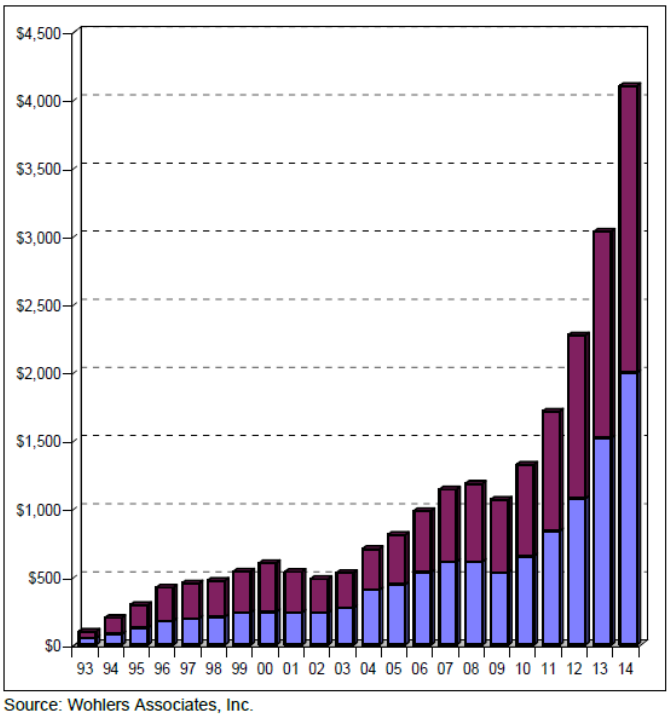


Figure 3.4: Worldwide revenues from AM products and services [63]

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.

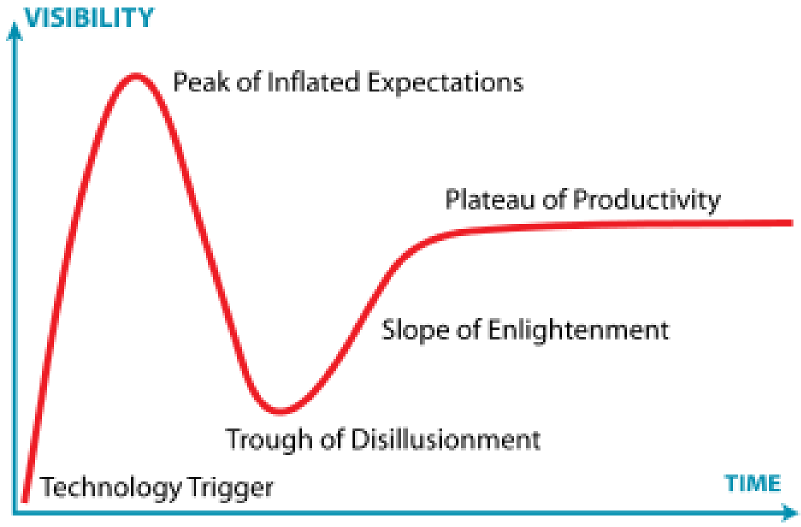


Figure 3.5: Hype cycle phases [25]

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.

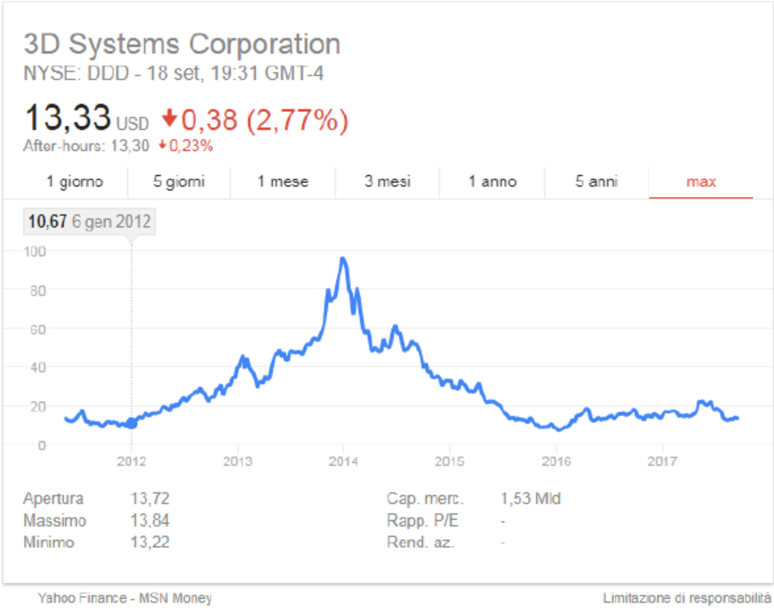


Figure 3.6: 3D Systems stock price evolution [4]

Figure 3.7: Stratasys stock price evolution [4]

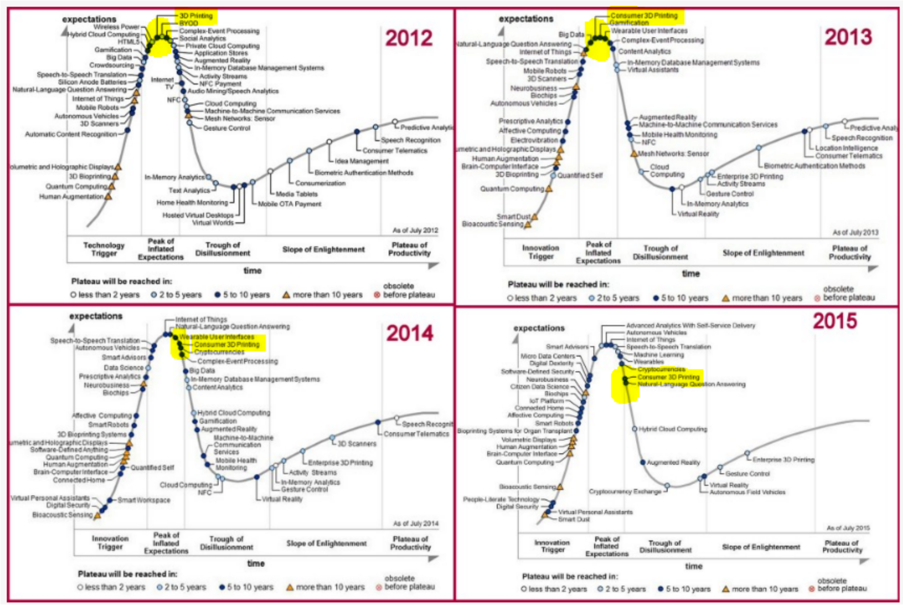


Figure 3.8: Gartner consumer 3D printing hype cycles [2]

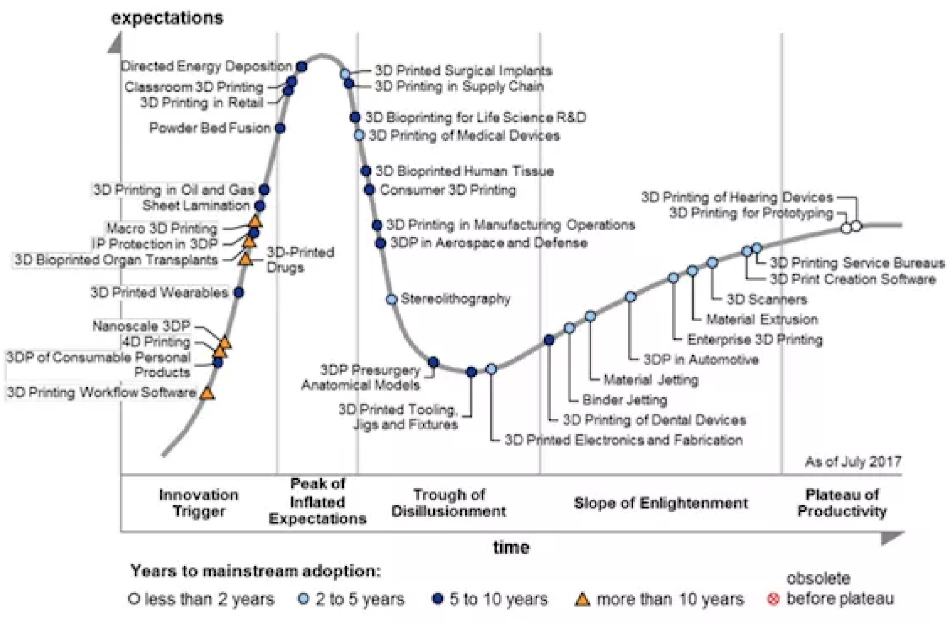


Figure 3.9: Gartner consumer 3D printing hype cycles for 2017 [61]

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 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.

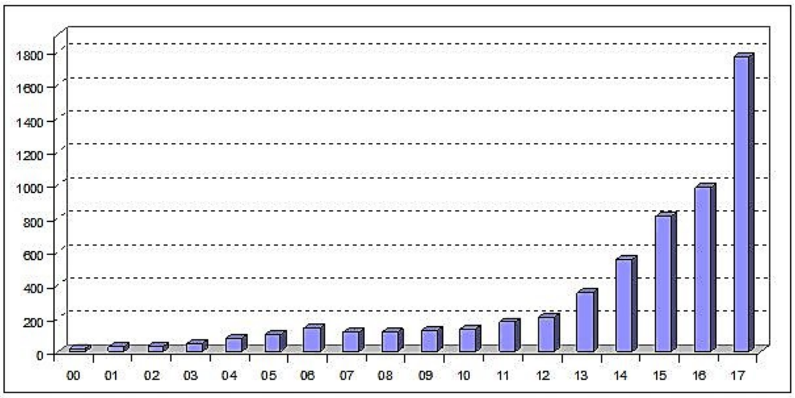


Figure 3.10: Rise of metal AM systems sold from 2000 to 2017 [64]

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

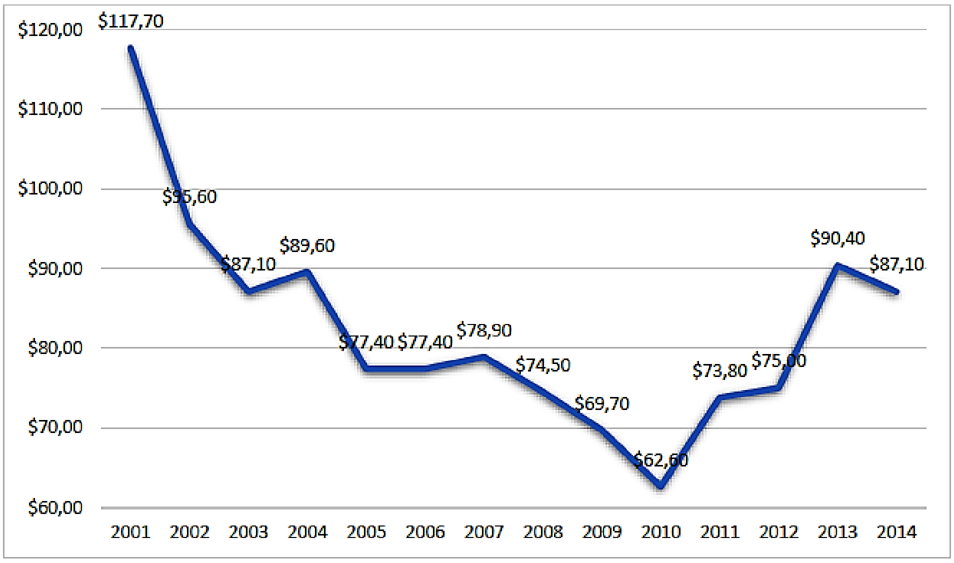


Figure 3.11: ASP trend in Additive Manufacturing from 2001 to 2014 [64]

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 materials and more.

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).

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

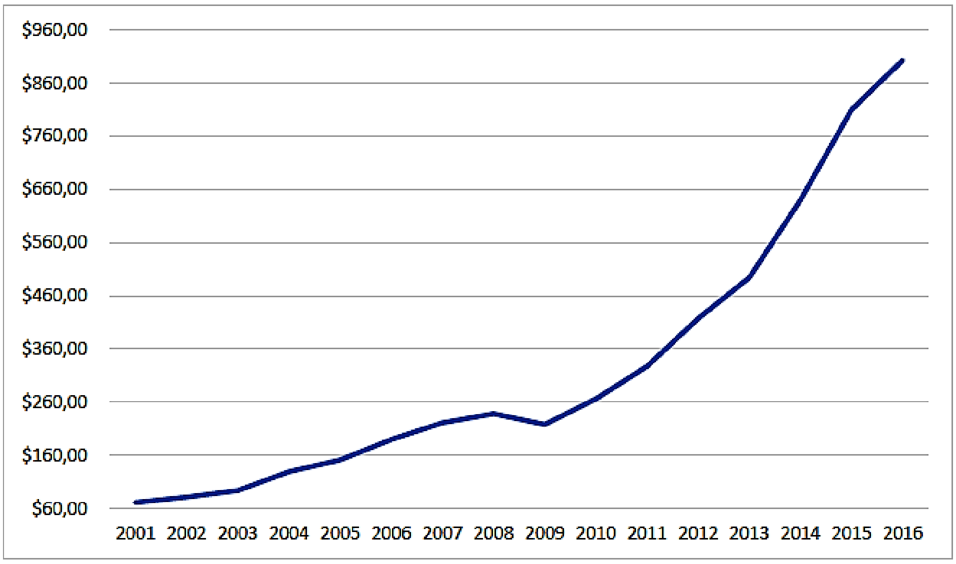


Figure 3.12: Growth of material sales from 2001 to 2016 [64]

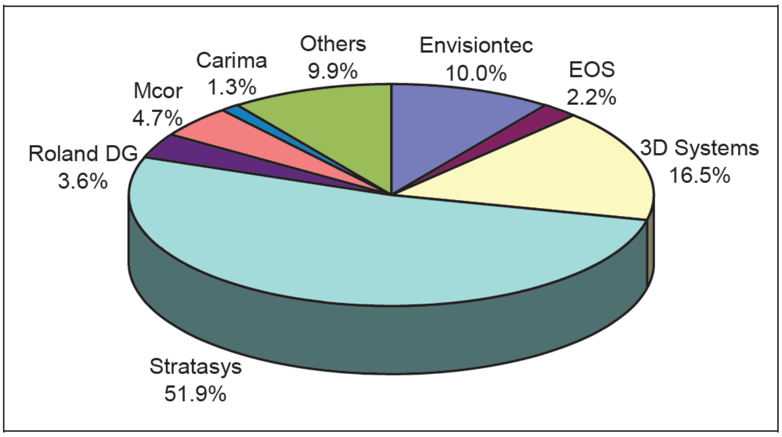


Figure 3.13: Unit sales market share estimates [64]

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,

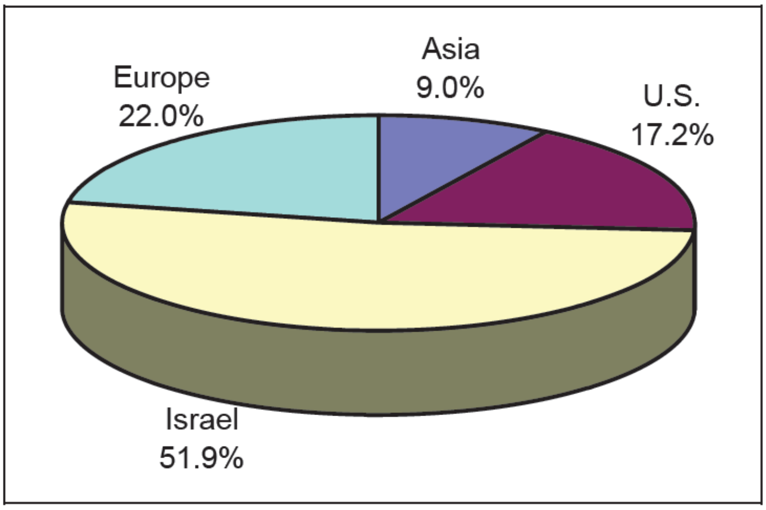


Figure 3.14: Region market share estimates [64]

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%.

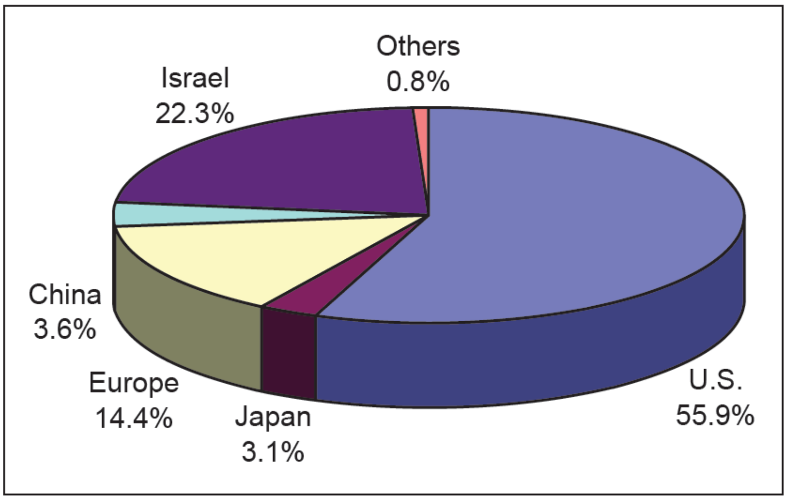


Figure 3.15: Cumulative total number of AM systems sold from each geographic region in 1988 through 2014 [64]

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.

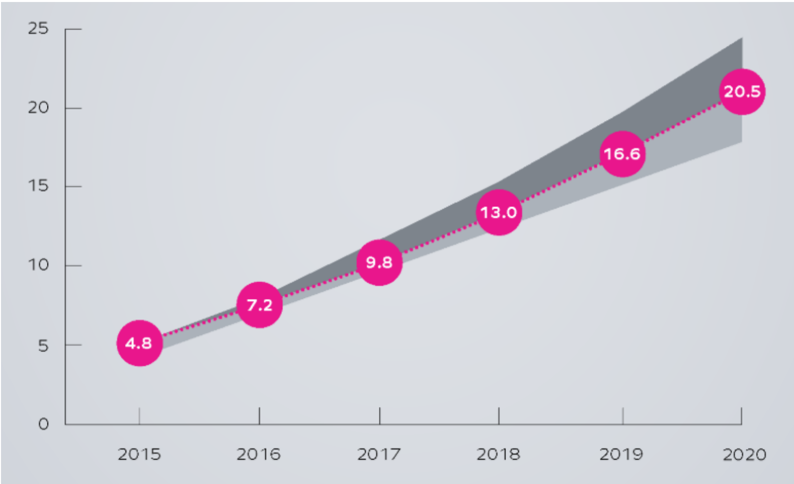


Figure 3.16: Estimated growth of the market by 2020 [44]

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

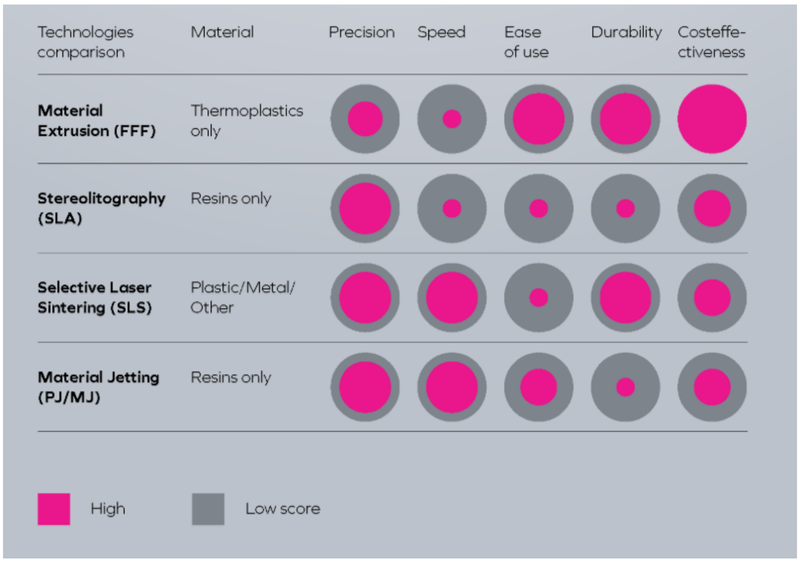


Figure 3.17: Technology overview [44]

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.

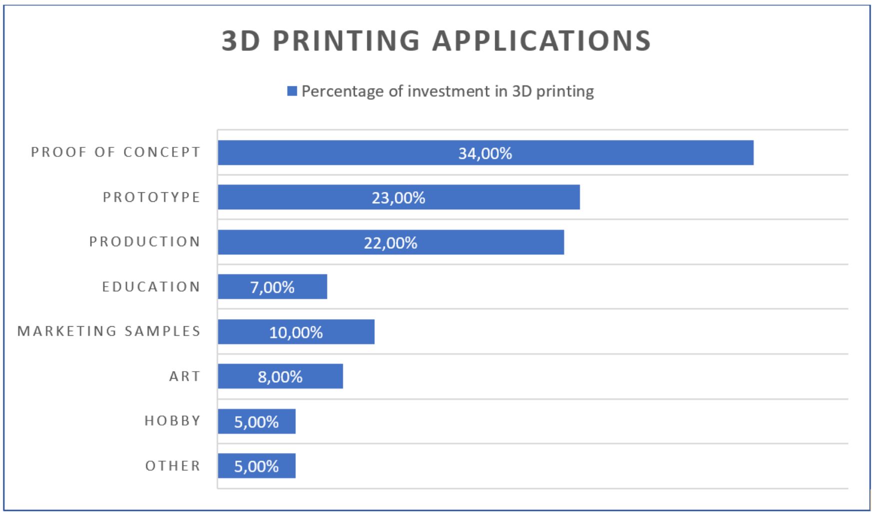


Figure 3.18: Analysis of main 3D printing applications in 2017 [44]

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.

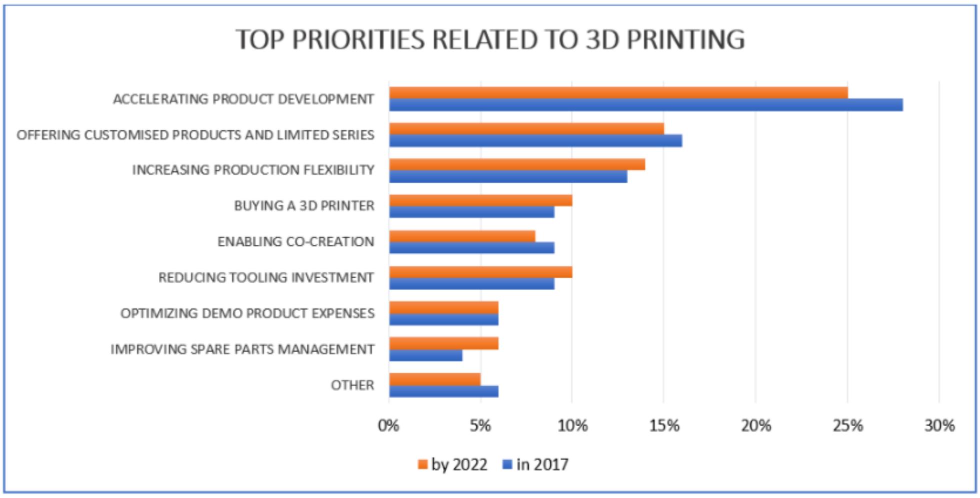


Figure 3.19: The main reasons related to investment in 3D printing from 2017 to 2022 [44]

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.

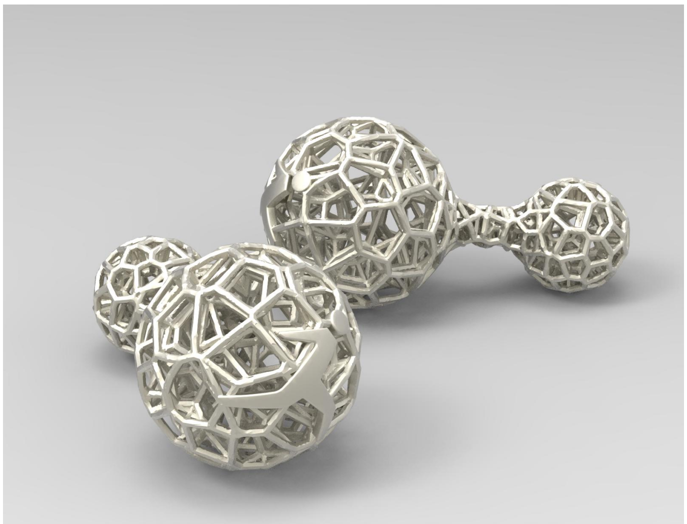


Figure 3.20: The use of additive technologies allows you to experiment with designs that are otherwise impossible to obtain [44]

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.

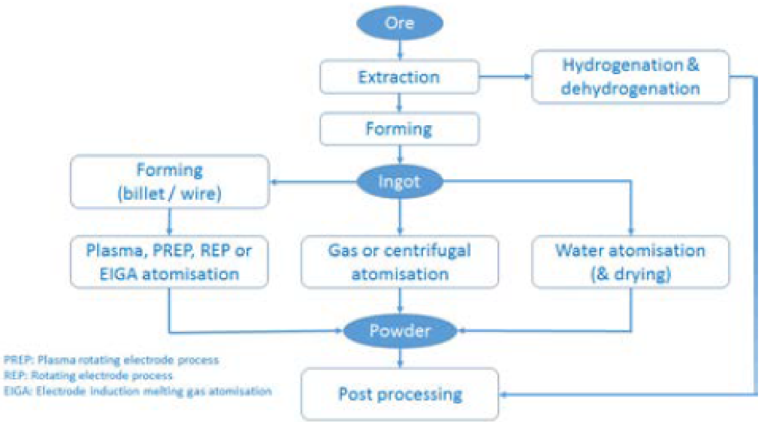


Figure 3.21: Metal atomization routes [29]

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 [29]

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;

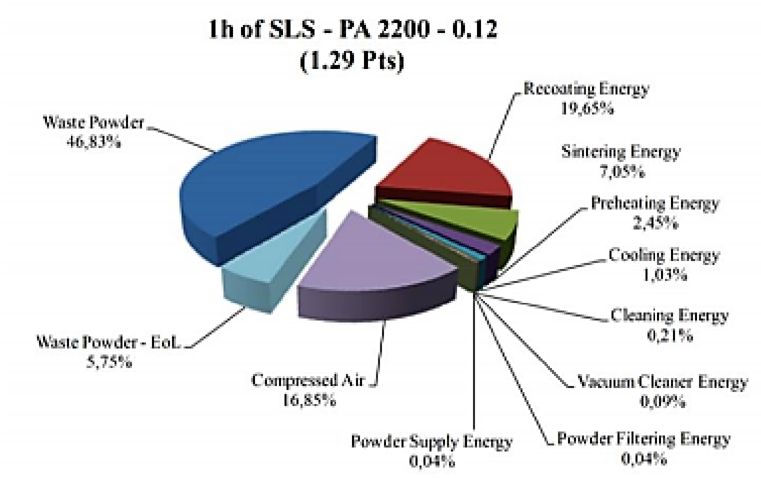


Figure 3.23: Environmental impact (ReCiPe Europe H/A method) distribution of 1 hour of SLS of PA2200 with a layer thickness of 120 µm. [29]

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

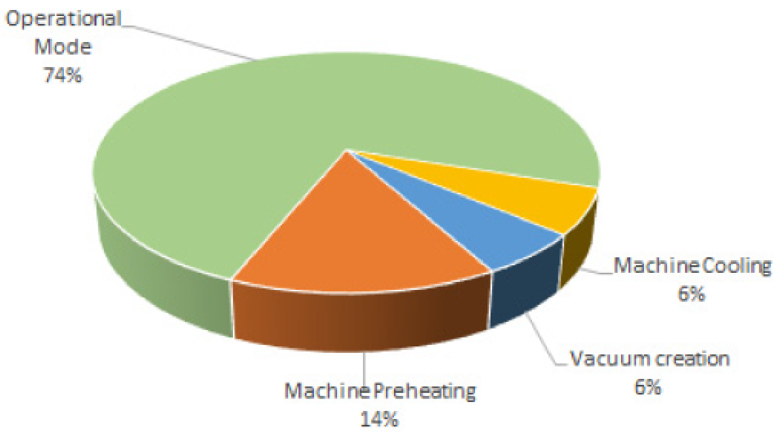


Figure 3.24: Distribution of energy consumption for the EBM production of an aeronautical turbine with a volume of 53.56cm^3. [29]

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. [29]

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]

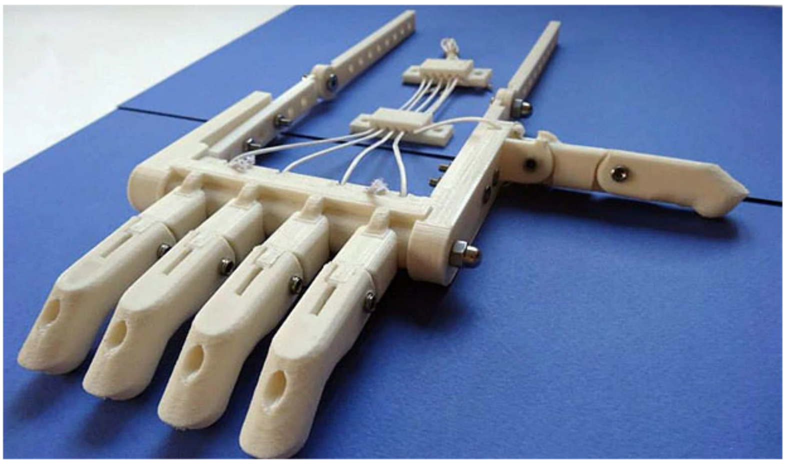


Figure 3.27: Robohand from MakerBot. [61]

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

Dental prostheses manufacturing: a study sector

4.1 Introduction and sector definition

After having discussed about how Additive Manufacturing is spreading in the current market, how it is growing and which are the forecasts for the future, we now move the focus on a specific industrial Italian sector, namely *Dental prostheses manufacturing (reparation included)*, which is defined by the ATECO CODE 2007 32.50.20, trying to analyse the main economical aspects related to it.

Dental prostheses are individual medical devices designed to rehabilitate the oral functions of patients who do not have one or more teeth. The task of a dental prosthesis is therefore to replace the original dentition of the patient with a new one that is able to last possibly for a very long time. Each prosthesis is a particularly complex and varied tool that needs to satisfy both the aesthetic and functional requirements as much as the natural ones for correct chewing.

There are different types of prostheses, but generally they are divided into two main types, namely fixed and mobile. The fixed prosthesis replaces the teeth that have fallen or been lost and corrects the smile in a functional and aesthetic way. This prosthesis is screwed or permanently cemented on the teeth or implants. The components of the prosthesis can be dental veneers, dental crowns or dental bridges cemented to natural supports (dental roots), which the patient can not remove. Crowns are usually the most common restorations when it comes to fixed prostheses. On the opposite side, the mobile dental prosthesis is a more traditional alternative, and is usually used for older patients or as temporary prosthetics in some treatment plans where bone regeneration is needed. These are mobile devices designed to replace natural teeth. The patient should remove the mobile prosthesis at least once a day for oral hygiene. The prostheses can be totally mobile or partially mobile. If partial the prosthesis is anchored to the natural teeth through hooks, and is formed by a metal structure known as a skeleton. Both of them are shown in the Figure 4.1 below.

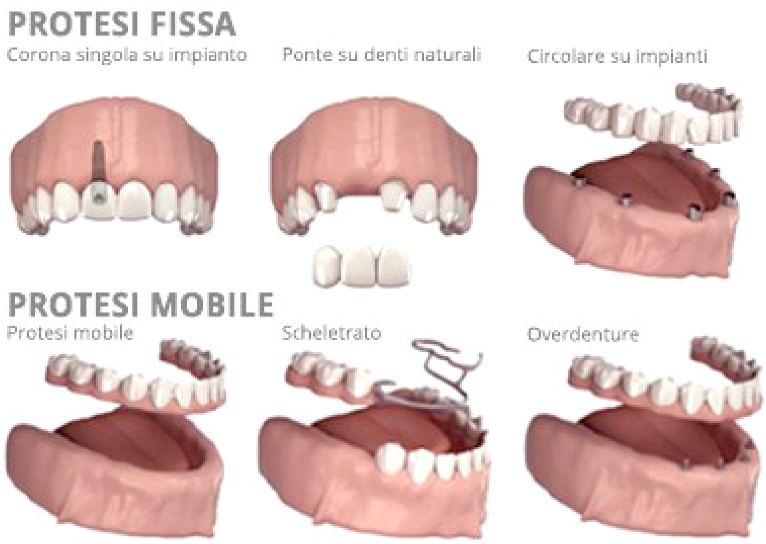


Figure 4.1: Fixed and mobile dental prostheses [43]

4.2 A focus on the market

UNIDI (Unione Nazionale Industrie Dentarie Italiane), together with Key-stone, a marketing research and consulting society and ADDE (Association of Dental Dealers in Europe) has recently presented a sector analysis dedicated to the dental industry and some interesting facts have emerged.

First of all, while dentists show signs of recovery, the Italian market from the point of view of industry and deposits is stagnant. In fact, all the traditional sectors are going down or are static, differently from the divisions strictly related to digital technologies (in particular the one of Cad-Cam and the ones for prosthetic and orthodontic products) as well as the development of the business of custom-made devices (prosthetic structures and aligners) that are more and more becoming a true business area of international industry.

However, while the internal demand stagnates, the data from the Italian industry towards exports is excellent, defining the Italian dental sector as the flagship of the Italian manufacturing sector made up of small and medium-sized enterprises, with growth rates that most of the times were double digits.

4.2.1 Production in Italy

As shown in the Figure 4.2 below, the sector, which was worth more than 600 million in 2009, increased by more than 50% in nine years, approaching around 933 million and with the expectation of reaching one billion euros already this year. Take into account that production is evaluated at the actual selling prices to clients or dealers, hence the values are not corresponding to the final market, but to the *ex-factory* instead, which corresponds to the retail market value only for what regards direct sales to the end user.

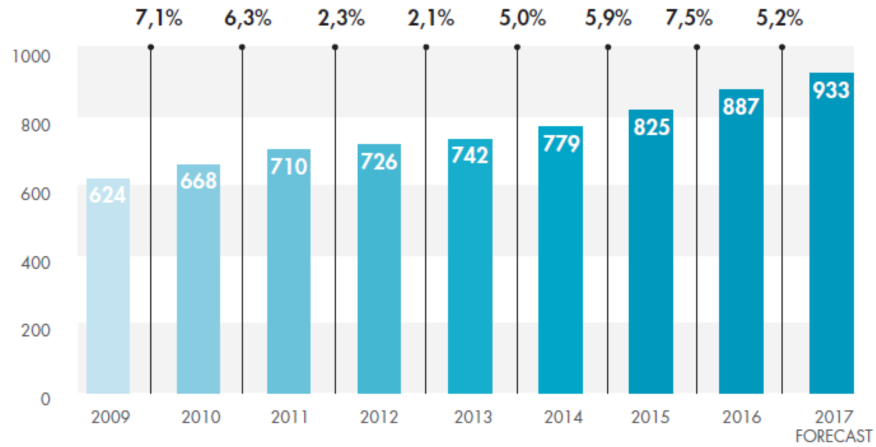


Figure 4.2: CAGR (Compound Annual Growth Rate) 2009/2017: +5,2% [58]

The Compound Average Growth Rate (CAGR) is 5.2% against an average Gross Domestic Product (GDP) of 0.15%, a sign of a more than virtuous trend. In fact, it is evident to see that Italian production shows a steady increase; however, after the shocking 2009 and the extraordinarily positive 2010/2011 period, the sector experienced a slowdown followed by an improvement from 2014 on.

In more detail, in the Figure 4.3 below are presented the ex-factory values (in million of euros) and trends for 2017 by macro-areas in which it is shown that the market is growing overall but in the specialized consumption sector which is slightly down; on the other side, the most evident growth from 2016 to 2017 emerges in the *Equipment* sector, with around 30 million euros (+ 0.7 %) with respect to the clinical equipment and 16 million euros (+ 1.5%) with respect to the laboratory and prosthetic equipment.

Another fact worth mentioning are the ex-factory values in million of euros according related to the segmentation by product category, as depicted in Figure 4.4 below. More precisely, the item "*CAD-CAM technologies and software*" represents the most relevant growth from 2016 to 2017, with an increase from 28.3 to 44.9 million of euros (+ 58.7%). This information to indicate how the Additive Manufacturing is becoming a more and more concrete reality in this sector.

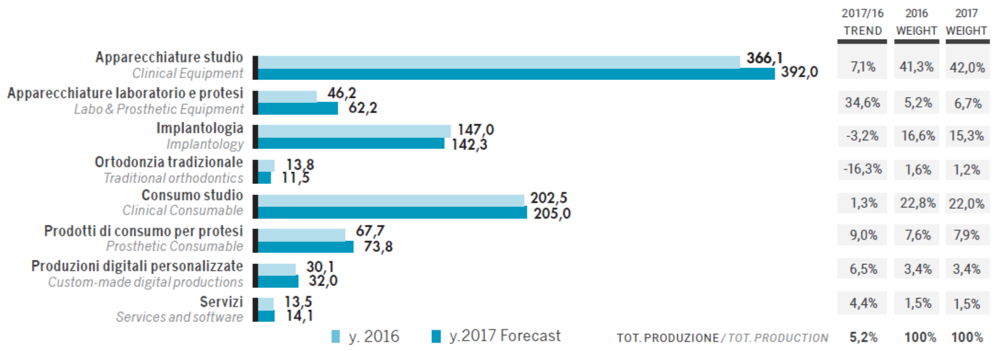


Figure 4.3: Values and trends by macro-areas [58]

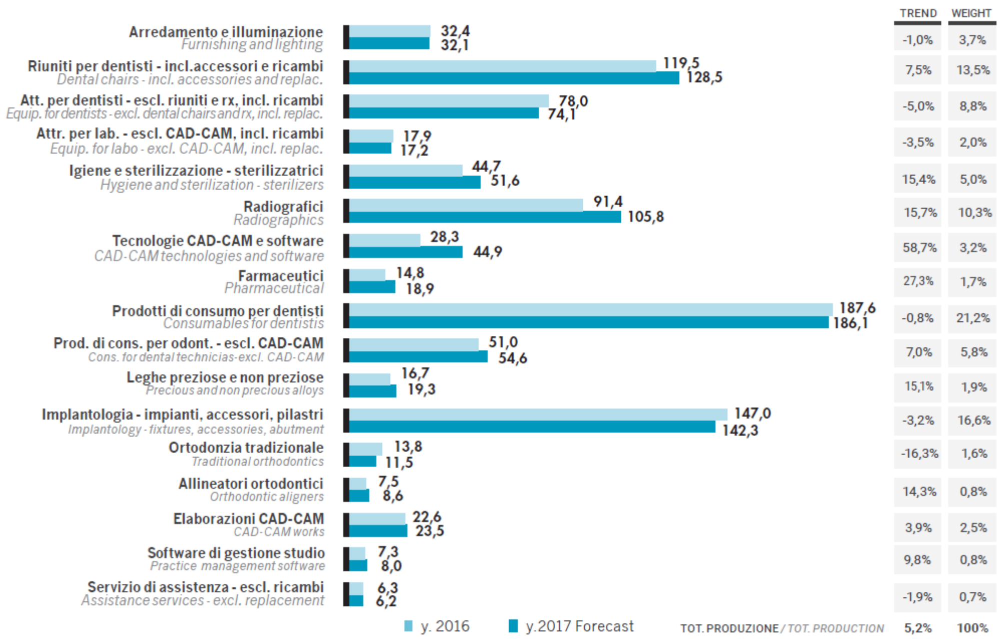
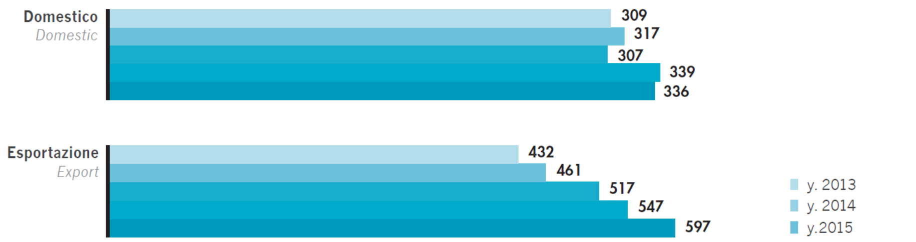


Figure 4.4: Segmentation by product category [58]

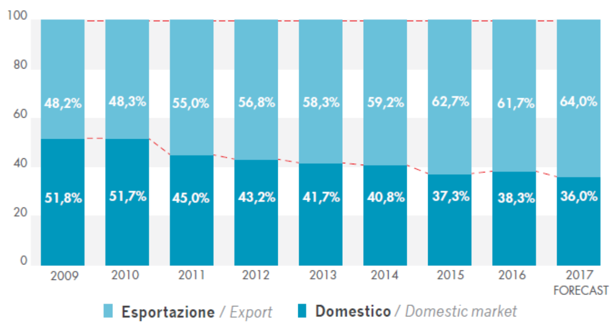
What about the destination of goods? According to Roberto Rosso, president of Key-Stone, the weight of the domestic market is collapsing, meaning that the real problem is that domestic demand does not work, consumption does not increase, hence the market does not evolve. And, as final argument of his speech, no demand implies no patients, differently from other countries, where instead the dental market is growing. In Italy this is not happening.

Furthermore, in the analysis conducted by UNIDI and Key-Stone, it is stated that the period 2009-2017 reveals an internal demand which is stationary, without a real development. In fact, the jolt occurred in the years 2015 and 2016 just represents the return of the population to dental care after the crisis of the previous two years. Nevertheless, the only relevant data is that the market value of 2017 is lower than the one obtained in the period 2008-2009. In addition, the only signs of liveliness in a declining or stationary situation derive from the sectors connected to digital technologies and tailor-made devices. This is represented by the fact that several large producers in the field of implantology, precious alloys and orthodontics, are turning their business from manufacturers of products to manufacturers of tailor-made medical devices.



Produzione/Trend Production/Trend	Verso mercato domestico Domestic market	Vendita export Export
2014/2013	2,6%	6,7%
2015/2014	-3,2%	12,2%
2016/2015	10,5%	5,8%
2017/2016	-1,1%	9,1%
CAGR 2017/2013	2,1%	8,4%

Figure 4.5: Destination of goods [58]



Milioni di euro Million of Euro	2009	2010	2011	2012	2013	2014	2015	2016	FORECAST 2017
Domestico Domestic market	323	346	320	314	309	317	307	339	336
Esportazione Export	301	322	390	412	432	461	517	547	597
TOTALE / Total	624	668	710	726	742	779	825	887	933

Figure 4.6: Weight of destination of goods [58]

As depicted in the Figures 4.5 and 4.6 above, the sharp increase in domestic demand, which started at the end of 2015 and then fully manifested in 2016, took place in 2017. Moreover, the 2017 forecast confirms the trend of constant growth of Export, going from 432 million of Euros in 2013 to 597 million in 2017; this trend is also represented by the difference between the CAGR 2017/2013 related to the domestic market which is 2.1% and the one related to the Export, which is 8.4%.

In addition, consistently with the trends mentioned above, the incidence of exported goods shows a constant increase over time. This confirms the appreciation of **Made in Italy**, reached on all markets thanks to innovation, quality standards, creativity and interpersonal skills, giving the country a leading role in the world dental market. The fact that the sector does not find continuity of growth on the national market is due to a problem of internal demand that does not seem to come out of a systemic an structural crisis. In fact, we can notice the 2017 forecast shows that 64% of the goods will be dispatched to the Export market while the 36% will be represented by the domestic one.

A last consideration to do, with the help of Figure 4.8 below, regards how much exportation of goods affect the Italian production.

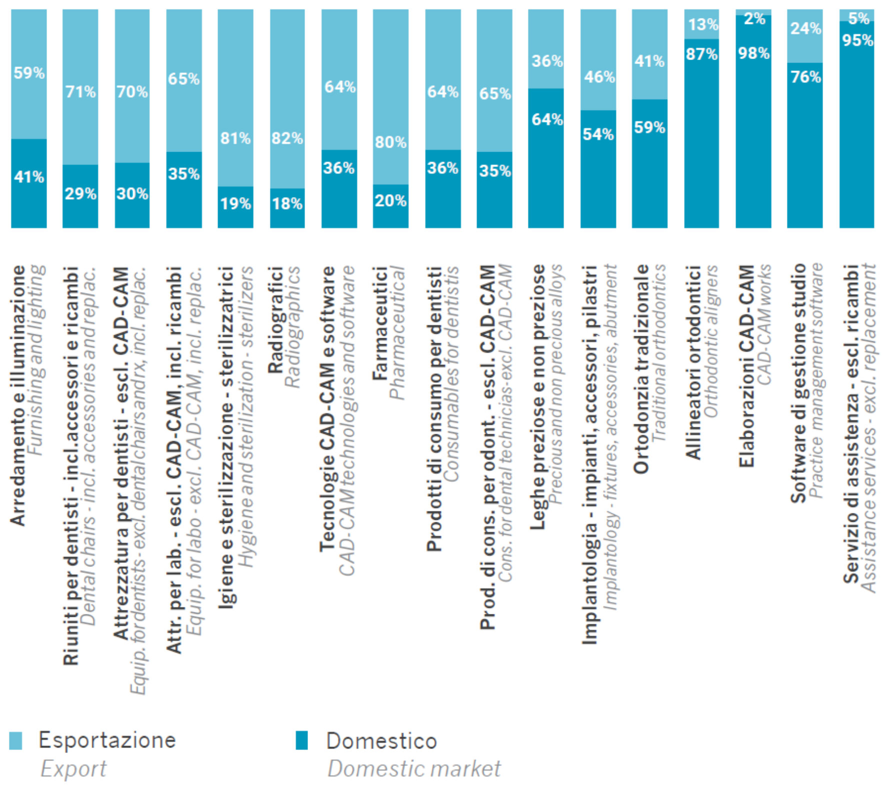


Figure 4.7: Destination of goods: incidence of exports on the Italian production [58]

From the figure, we can find out that *Micromechanics*, and *Digitals* are the families with a higher domestic inclination, obviously besides the world of services, belonging to the country of the company to which they are performed. In fact, considering the Domestic market index, the field of *Implantology* is characterised by an index of 54%, *Orthodontics* by 59%, *CAD-CAM works* by 98% and *Assistance services* by 95%.

4.2.2 The export market

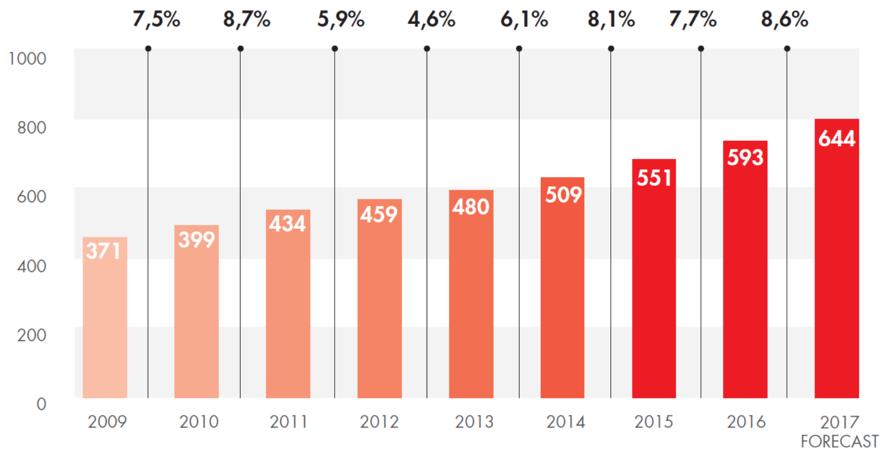


Figure 4.8: CAGR (Compound Annual Growth Rate) 2009/2017: +7,1% [58]

Now we move our focus on the export market, which, according to analysis, is almost entirely controlled by Italian manufacturers (92%). In the Figure 4.8, it is shown a 7,1% CAGR value, while, in terms of million of Euros, 2017 is forecasted at about 644 million with a 55% growth from 2008 until today.

Moreover, the export activity mainly regards the following countries: France (10.4%), Germany (9.0%), Spain (8.9%), Poland (4.1%), rest of Europe (19%), Asia Pacific (8%), Russia (6.8%), the Middle East (5.7%), China (5.6%), USA (4.1%) and Latin America (4%).

A brief but interesting consideration to do concerns the decrease in the number of dentists throughout Europe of the limited growth in the number of members; however, among Germany, Spain, France and England, Italy is the country which registers the least number of new registrations. In addition, if we also consider the lack of propensity for young people to open their own studio, it is easy to understand how the sales data are limited or decreasing. From the point of view of the global turnover of the European sector, namely the sales volume made by the distribution to the dental office and the dental laboratory, it has been declared that a considerable amount has been on a positive trend for over five years, and that amount consists of 6,857,000 Euros, where Italy is indisputably the second largest European market, even though maintaining the position has heavily contributed to the equipment sector, still slightly distorted by the positive effect of tax bonuses activated by the precedent Italian government and which will end, most likely, in this year. In other countries, instead, as France, it was the consumables that sustained the impact on global turnover, which indicates that Italian market, despite it went well, grew more slowly than the neighbouring markets because it is still suffering from unfavourable macro and microeconomic factors of the country.

Dealing with the growth in 2017 with respect to 2016, it is worth considering the two figures below, namely 4.9 and 4.10.

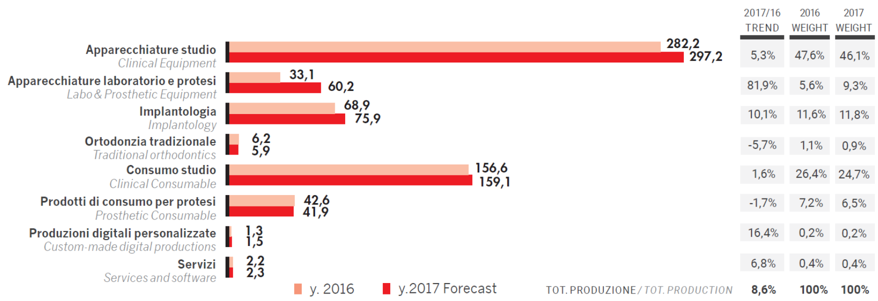


Figure 4.9: Export: values and trends by macro-areas [58]

What it has to be noticed is that with respect to 2016, the following trends have emerged: strengthening of *clinical equipment*, which is characterised by an increase of 5,3% and of laboratory and prosthetic equipment, with an increase of 81,9%. Consumption, instead, features a settlement, with a little increase of 1,6%. Finally, even digital production sees an increase in exports (+16,4%), although this category has a lower weight compared to other sectors.

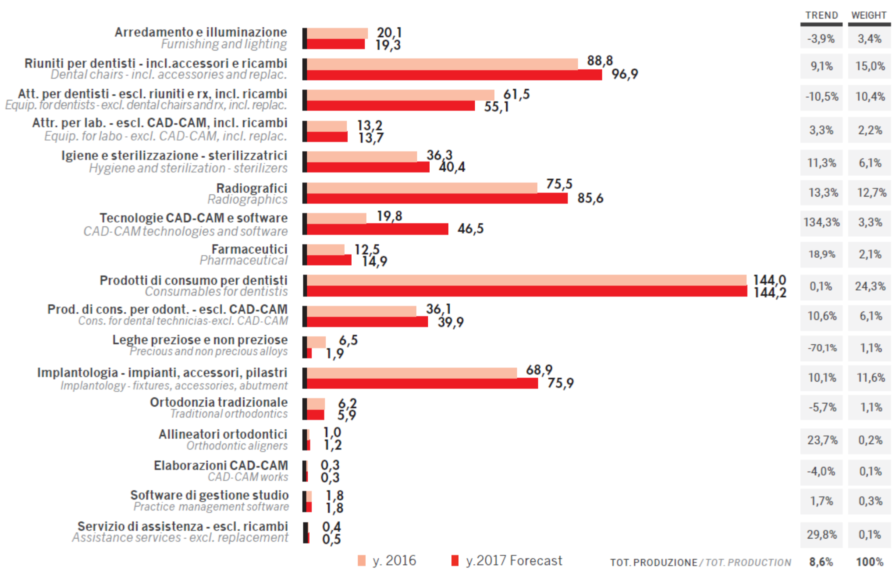


Figure 4.10: Export: segmentation by product category [58]

Surely worth mentioning, considering the segmentation by product category, is that the most relevant growth regards *CAD-CAM technologies and software* with an increase of 134,3% with respect to 2016. Other product categories that have been characterised by a significant increase are *Orthodontic aligners* (+23,7%), *Assistance services - replacement excluded* (+29,8%) and *Pharmaceutical* (+18,9%).

4.2.3 Wholesale distribution

Wholesale distribution is evaluated taking into consideration actual selling prices, meaning that when sales are made through the distribution system (dealers and catalogues), the sell-in value is the one considered. Dental dealers, in fact, enter this category exclusively with private labels and exclusive lines that are not allocated through wholesalers.

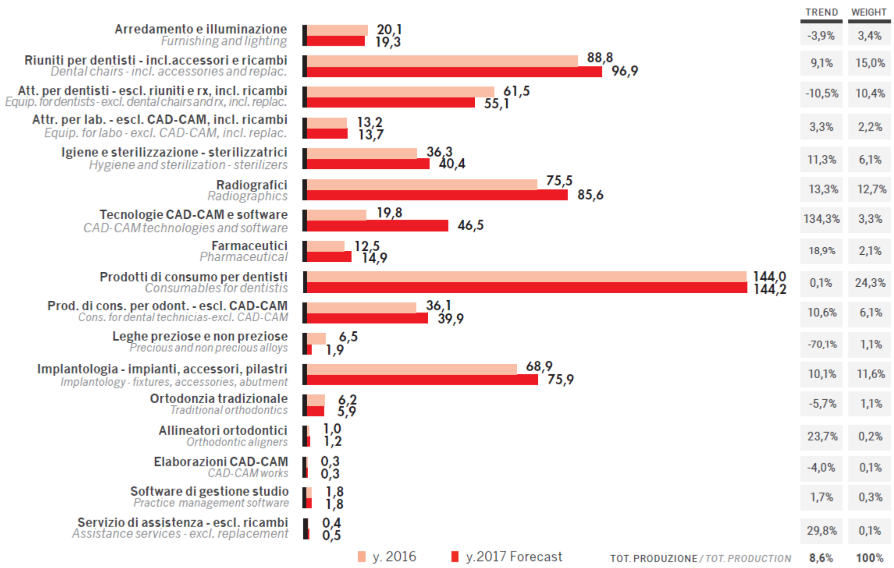


Figure 4.11: CAGR (Compound Annual Growth Rate) 2009/2017: +0,4% [58]

The Figure 4.11 above shows the CAGR for the period 2009/2017. It is evident to see that the wholesale distribution business, after the sharp decline in the two-year period 2012/2013 with a percentage decrease of 3,3%, shows a sight recovery starting in 2014 (sell-in value of 581 million of Euros) due in particular to the distribution of the new technologies from abroad. The forecast for 2017 confirms the recovery and the achievement of values very close to the period before the decline (629 million of Euros compared to the 630 and 634 of years 2011 and 2012).

Taking into consideration the growth in 2017 with respect to 2016, let us pay attention to the Figure 4.12 above. In comparison to 2016 research, there is an adjustment of the equipment (-4,1% for the clinical one and +13,2% for the laboratory and prosthetic equipment), attributable to a drop in the study area and a strengthening of the other categories,

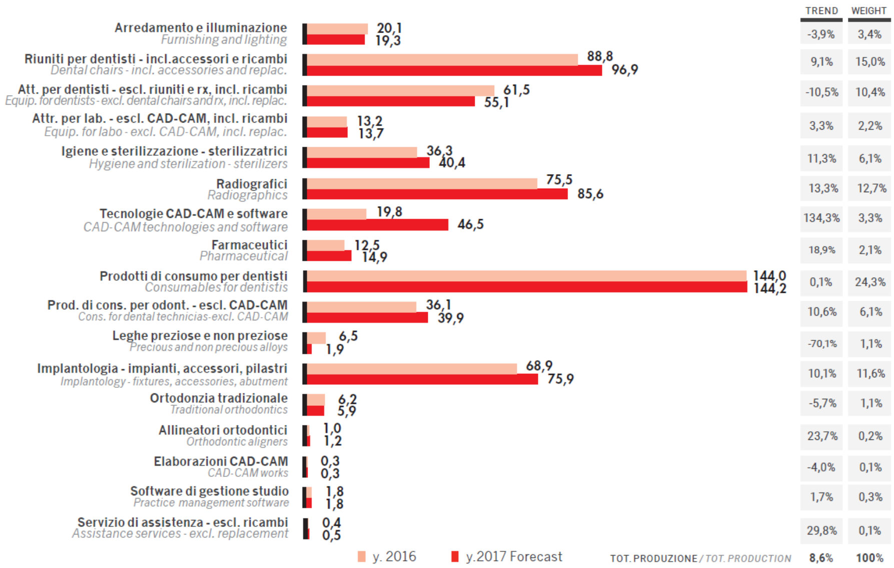


Figure 4.12: Wholesale distribution: values and trends by macro-areas [58]

consumption in particular (+6,5%), especially thanks to the growth of consumables for dentists. Finally, concerning prosthetic consumable, we notice a slight decrease of 2%.

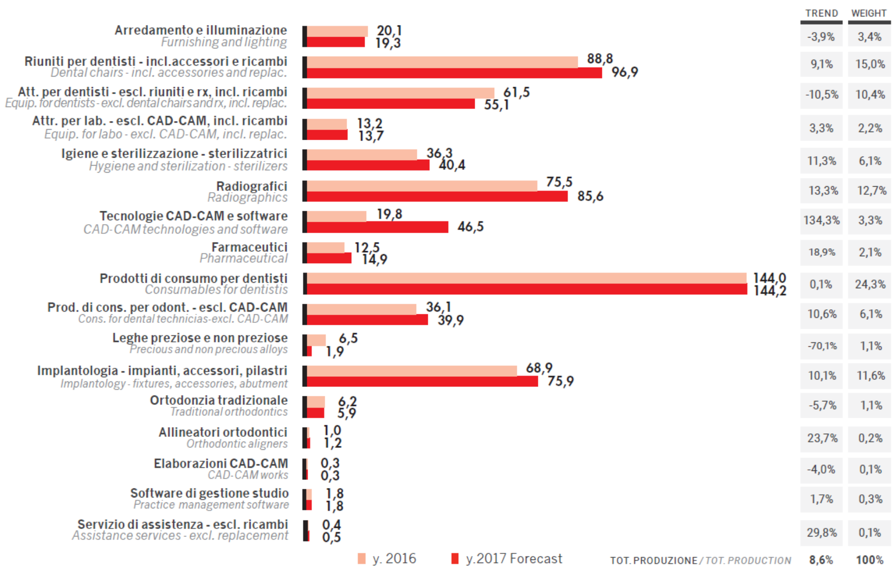


Figure 4.13: Wholesale distribution: segmentation by product category [58]

Last but not least is the focus on the segmentation by product category also for wholesale distribution, as shown in the Figure 4.13 above.

As it is evident, we do not notice substantial difference between 2016 and 2017, except for some categories as *CAD-CAM technologies and software* (+25,1%), *Consumables for dentists* (+6,8%) or even drops as *Radiographics* (-18,8%) and *Equipment for laboratories* (-13,4%).

4.2.4 The sell-out final market

The last considerations have to be made about the sell-out final market, whose values (in million of Euros), have been estimated by applying a standard mark-up to the sell-in values.

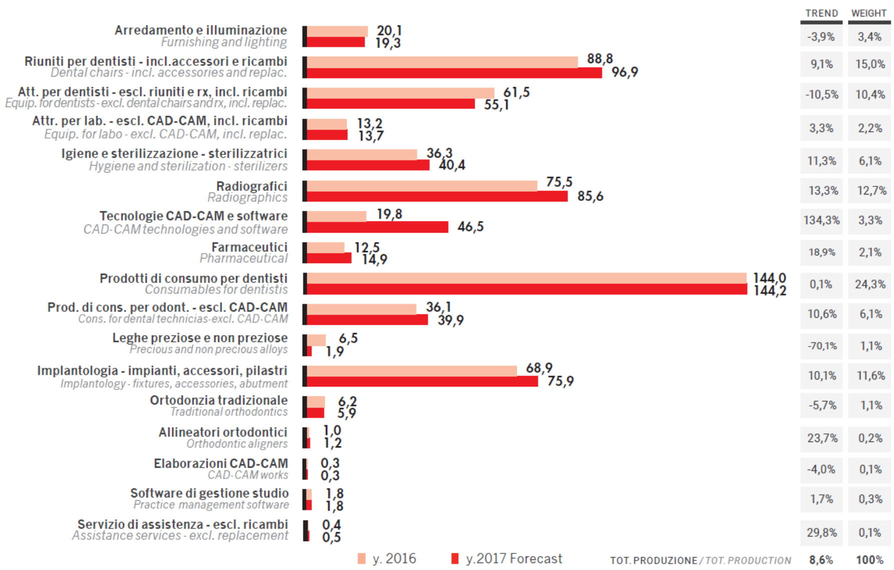


Figure 4.14: CAGR (Compound Annual Growth Rate) 2009/2017: +1,4% [58]

Considering the Figure 4.14 above, the final market, calculated at sell-out prices (that is, selling prices to dentists and dental technicians), shows a new decrease in 2012/2013 (-5,4%), following the recovery in 2010. Forecasts for 2017 confirm the recovery started from 2014 on, as it can be noticed in the figure.

Considering macro-categories (see Figure 4.15), the equipment shows a general negative trend (-4,0% for clinical one and -2,7% for laboratory and prosthetic equipment), probably due to tax incentives that favoured investments in technologies in the previous year, difficult to reproduce again in 2017. Specialist consumption also drops down, maybe due to the decline in implantology (-1,0%).

On the other hand, consumption is growing, especially thanks to the consumption of dentists' consumables (+4,3%), together with digital production, both for sale of new materials and for the transformation of the business from product to service.

Dealing with product categories, instead, the most important ones characterised by relevant growth from 2016 to 2017 are *Consumables for dentists* (+4,4%), *Orthodontic*

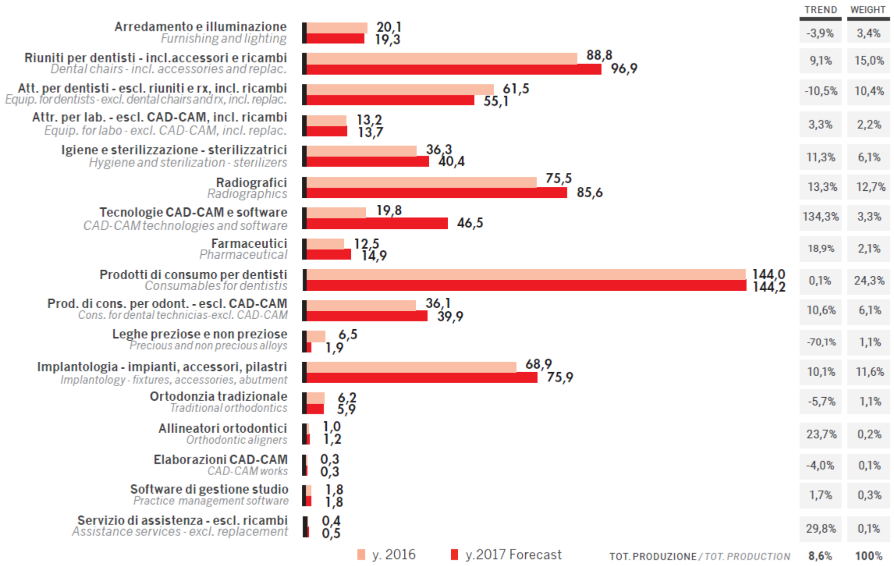


Figure 4.15: Sell-out final market: values and trends by macro-areas [58]

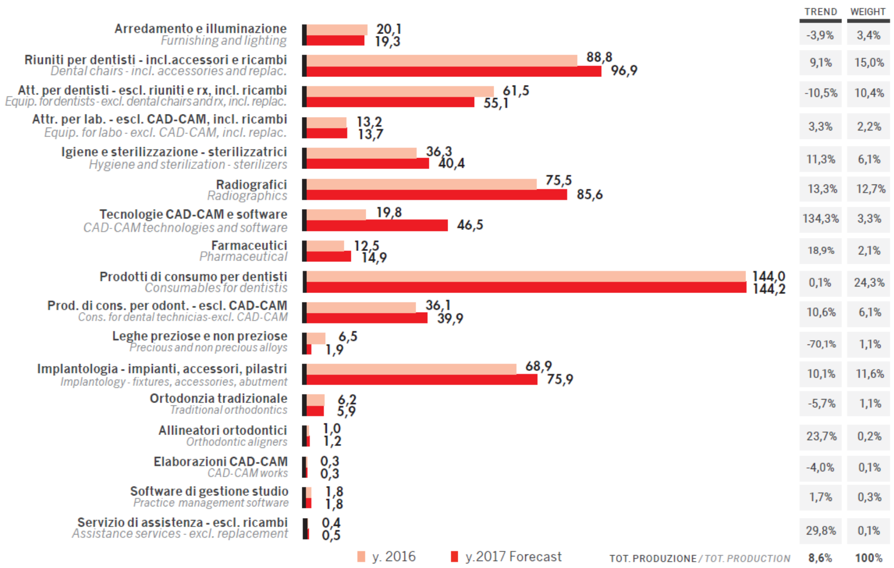


Figure 4.16: Sell-out final market: segmentation by product category [58]

aligners (+13,9%), while we notice drops in *Equipment for laboratories* (-19,8%) and *Radiographics* (-10,6%).

An interesting fact concerns in the weight of the distribution channel, whose numbers are shown in the Figure 4.17 above, considering direct and indirect sales.

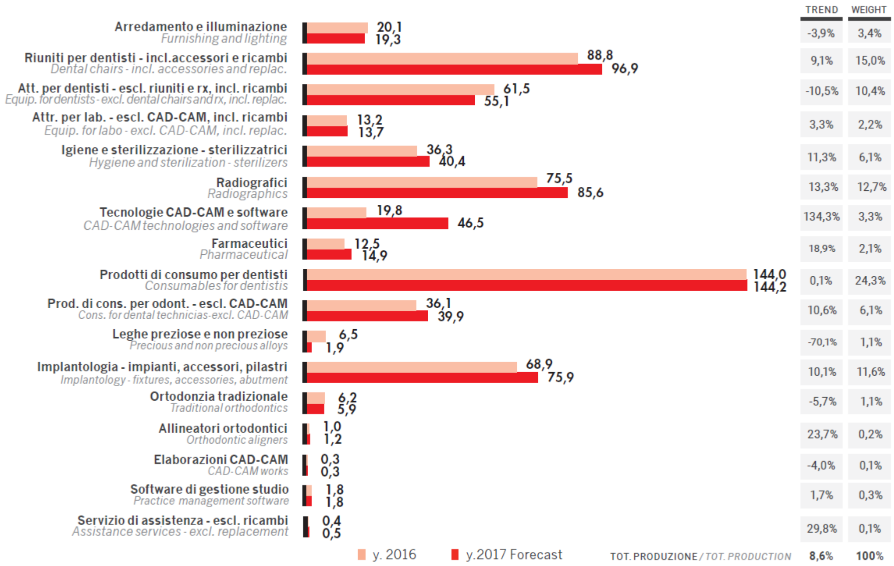


Figure 4.17: Sell-out final market: weight of the distribution channel [58]

Despite the slowdown in the indirect channel business, the weight of full-service distribution remains strategic, going from 58,6% of incidence in 2011 to around 62,1% in the 2017 forecast. Before 2011, the weight of direct sales was lower, so we can sat that the full service channel has resumed its role after the 2008-2010 crisis.

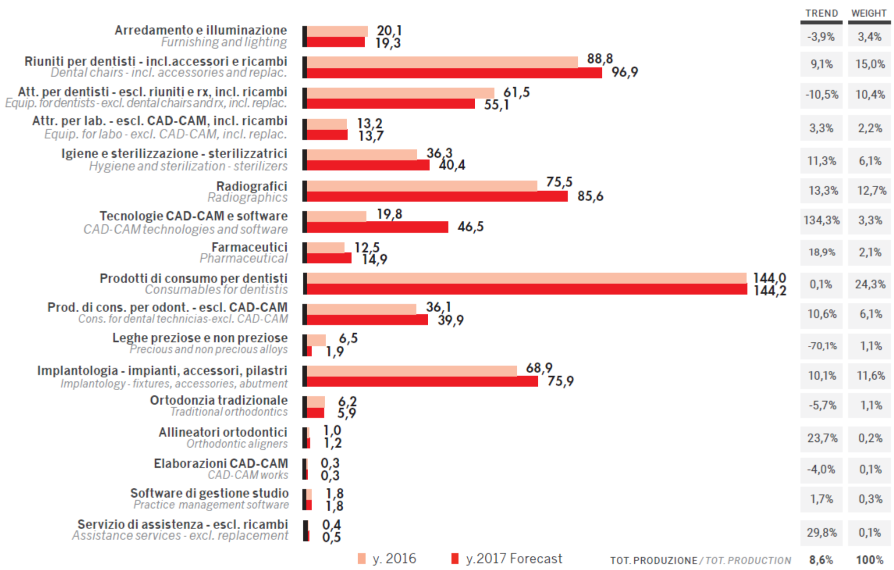


Figure 4.18: Sell-out final market: incidence of domestic origin [58]

Finally, the last picture (see Figure 4.18 above) represents the weight of domestic production and of the import products of the Italian final market. It is evident to see that the main trend favours the imported product, with percentages that oscillate from around 61% to about 63% while, obviously, the domestic product is characterised by percentages which go from around 37% to almost 39%.

Concluding the first part of this analysis, we could say, citing Maurizio Quaranta from ADDE, that summing all it up the dental industry is in good shape, even if we can do more, for instance by investing at all levels, even if returns are kind of slow and low, since we need to know how to go beyond what appears and that is immediately visible to us.

Furthermore, we have to be able to make system as other sectors have already done, starting to understand that the collaboration between industry, distribution, dentists, hygienists and dental technicians passes only through the crucial role of associations.

4.3 AIDA and the dental prostheses sector

Going into further detail with our analysis, we have made use of AIDA (Analisi Informatizzata Delle Aziende Italiane), a database which contains extensive information on Italian companies obliged to deposit the balance sheet, with a retrospective analysis. In fact, you can search for individual companies or companies with a specific profile, combining up to 100 criteria. The data contain information on financial statements, details of receivables and payables, employee numbers and much more. In addition to companies, it is possible to analyse specific sectors of industry, particular regions, etc. All data are indexed and can be used as search keys and processed, evaluated and exported in multiple formats. Searching by ATECO code (namely 32502, "Fabbricazione di protesi dentarie (riparazione inclusa)"), we have found that in Italy there are 949 companies belonging to this sector.

Where are these companies located? The picture 4.19 below shows this information. As depicted, it is evident that most of companies are located in Lombardy (224) and Lazio (157), while the others are mainly in Veneto (92), Emilia (75), Tuscany (64) and Piedmont (52).

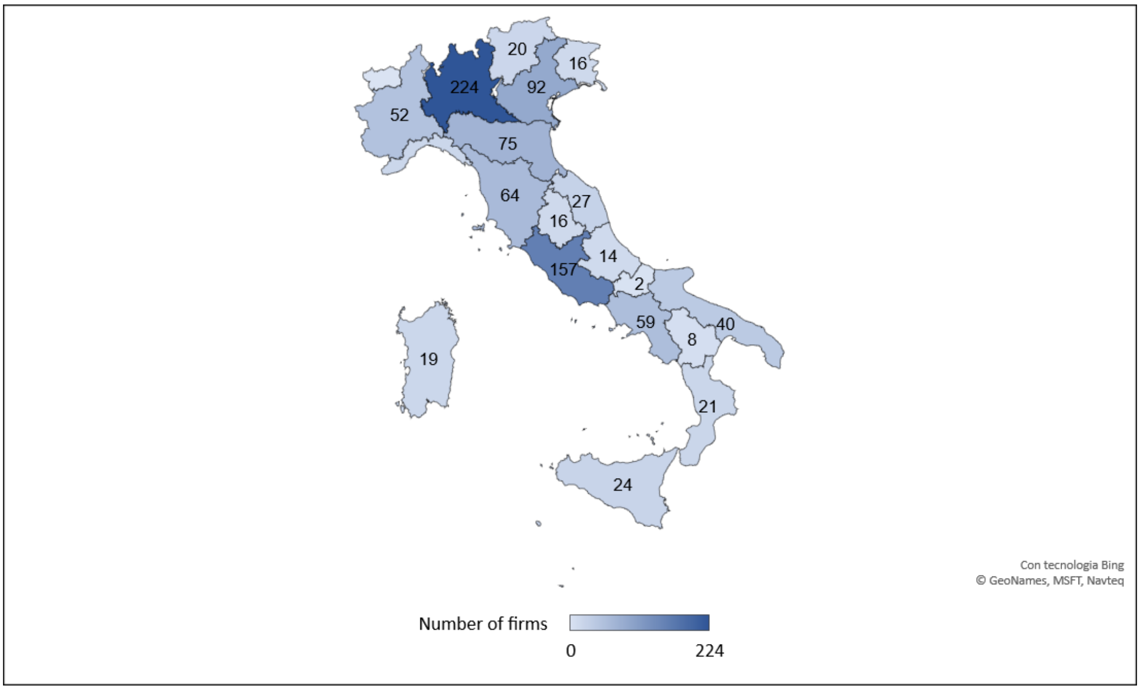


Figure 4.19: Localisation per region of companies belonging to the dental prostheses manufacturing sector [5]

In parallel to this geographic information, it is also important to see which is the amount of sales revenues per region (in 2016), as shown in the Figure 4.20 below. As indicated in the legend, the more intense is the colour, the higher the sales revenues are.

Hence, the region with the highest revenues is Emilia-Romagna (312.556.000 Euros), followed by Piedmont, Liguria, and Lombardy with around 300 million. Consistent numbers also in Lazio, Friuli-Venezia Giulia, Calabria and Campania.

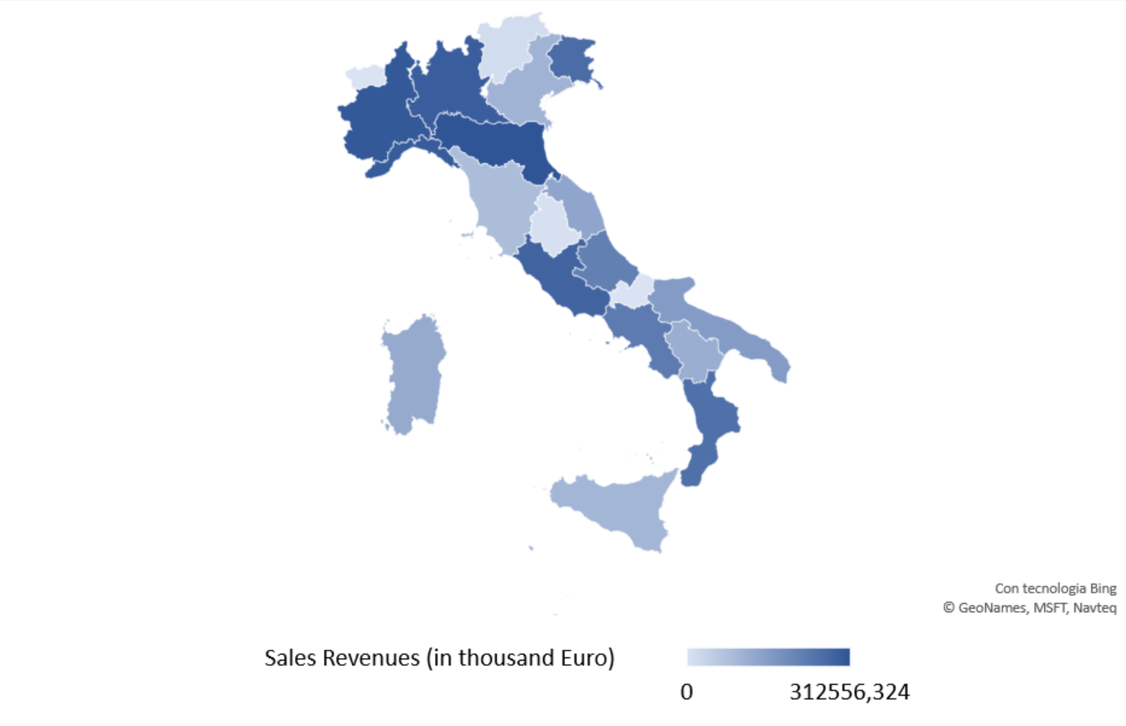


Figure 4.20: Sales revenues per region of companies belonging to the dental prostheses manufacturing sector in 2016 [5]

The same information are shown in detail in the Figure 4.21 below.

Now let us focus to the computation of some concentration indexes such as the Herfindahl–Hirschman Index (HHI), or just Herfindahl index, CR4 and CR10.

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:

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

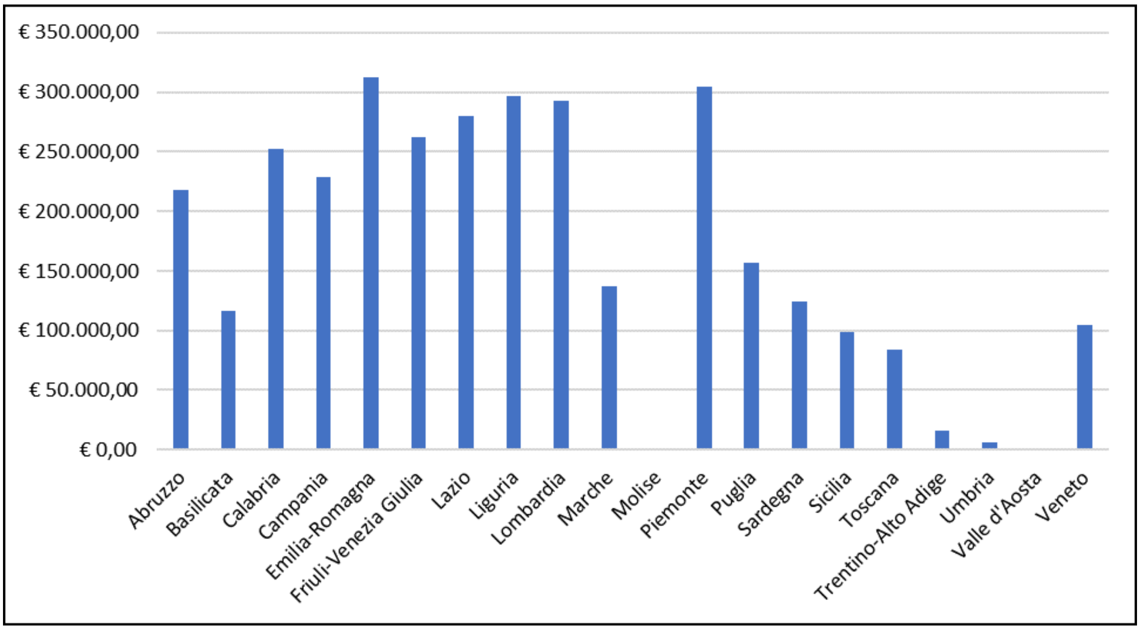


Figure 4.21: Sales revenues per region of companies belonging to the dental prostheses manufacturing sector in 2016 [5]

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 $<$ 1500
- *Moderately concentrated:* if 1500 $<$ HHI $<$ 2500
- *Concentrated:* if HHI $>$ 2500

Inserting into the formula the numbers, we found that the HHI for the dental prostheses manufacturing sector is 519,05, meaning that the sector is competitive, since it is less than 1500.

The Concentration Ratio (CR), instead, is a ratio that indicates the size of the firms with respect to their industry as a whole. Low concentration ratio in an industry would indicate greater competition among the firms in that industry, compared to one with a ratio nearing 100%, which would be evident in an industry characterized by a true monopoly. The most used CRs are CR_4 and CR_8; the first consists of the sum of the market share of the four largest firms in an industry, expressed as a percentage (see Figure 4.22); the latter is calculated for the market share of the eight largest firms in an industry (see Figure 4.23). The three-firm and five-firm are two more concentration ratios that can be used.

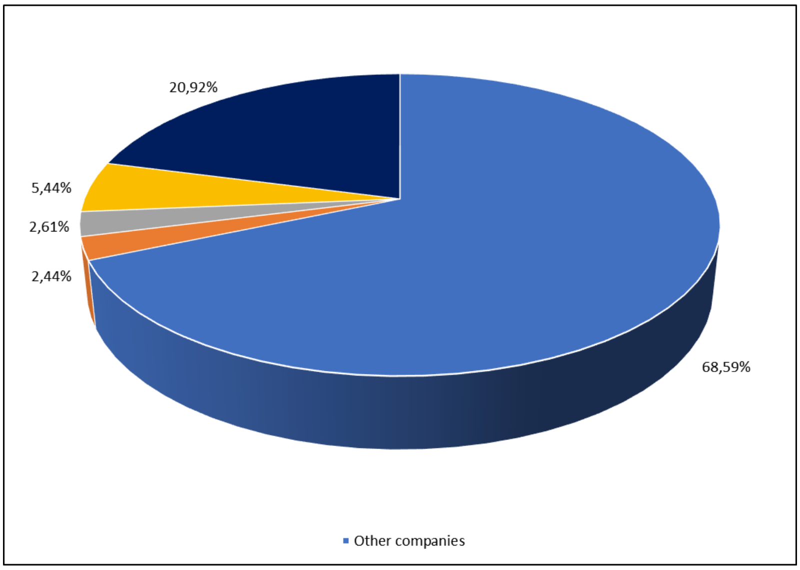


Figure 4.22: Concentration Ratio CR_4 in 2016 [5]

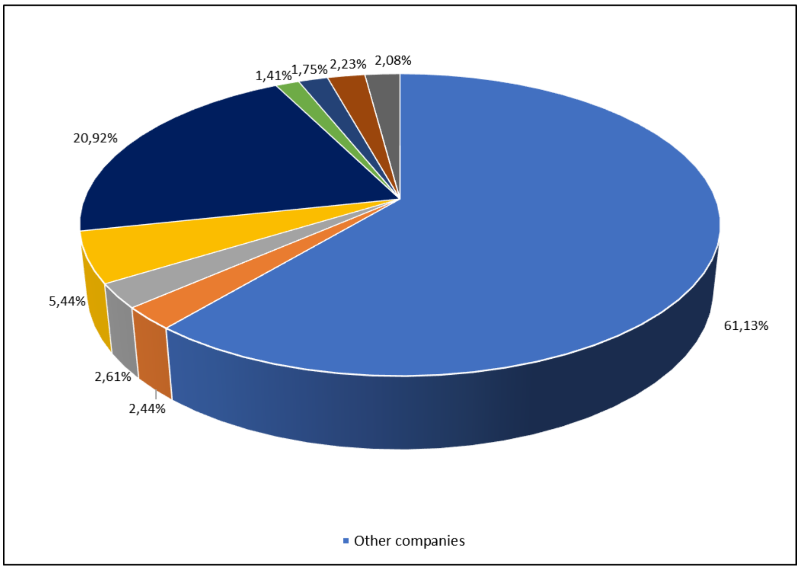


Figure 4.23: Concentration Ratio CR_8 in 2016 [5]

From the figures and applying the formula described above, it resulted that

$$CR_4 = 31{,}41\%$$

meaning that, being less that 50%, there is perfect competition, while

$$CR_8 = 38{,}88\%$$

meaning again the same explanation as before.

Now we continue our analysis taking into consideration other important indexes and variables. For what concerns employees, the Figure 4.24 show data about the number of workers in the dental prostheses manufacturing sector from 2008 to 2016.

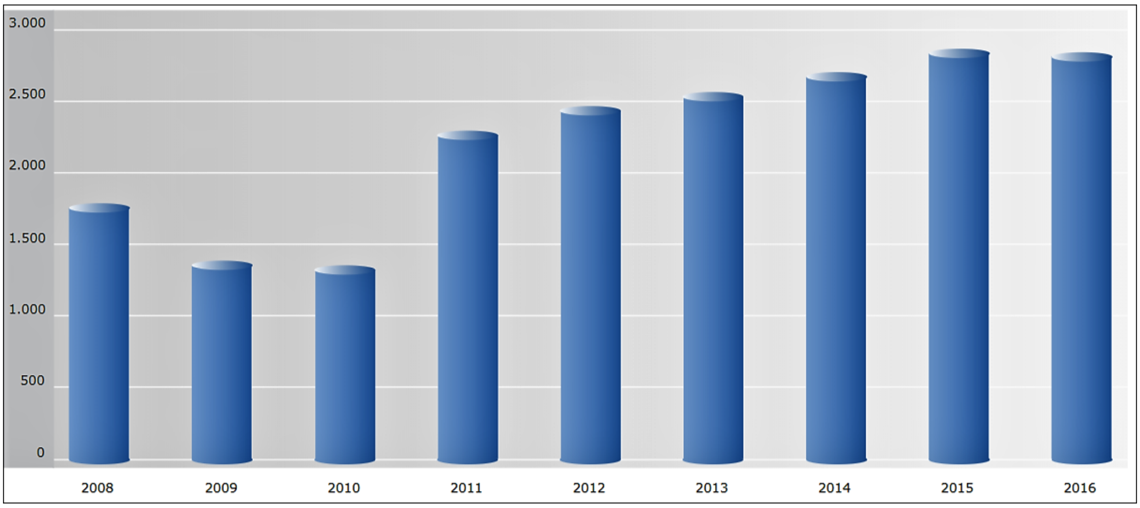


Figure 4.24: Number of employees in the dental prostheses manufacturing sector from 2008 to 2016 [5]

Apart from years 2009 and 2010 in which employees are around 1300, the trend is clearly positive, given that the number constantly grows, stabilizing in the last two years, with more than 2500 employees.

Another information worth mentioning are the sales revenues for this sector, which reveal to be relevant. Looking at the histogram 4.25 below, 2012 is the year with the greatest sales revenues, with a turnover of almost 350 million of Euro; the other most productive years have been 2016 (around 320 million Euro) and 2011 (around 300 million Euro).

Another important index to consider in this analysis is ROS (Return On Sales), as shown in the Figure 4.26 below. This is a ratio used to evaluate a company's operational efficiency and provides insight into how much profit is being produced per Euro of sales. An increasing ROS indicates that a company is growing more efficiently, while a decreasing ROS could signal impending financial troubles.

Numbers are not that bad, considering that the average ROS for the market leader, which is **Sweden & Martina S.p.A.** is 17,6% in the period 2007-2016 and that the ROS of the whole sector is always over the 8%, apart from 2009, with a ROS of around 5%.

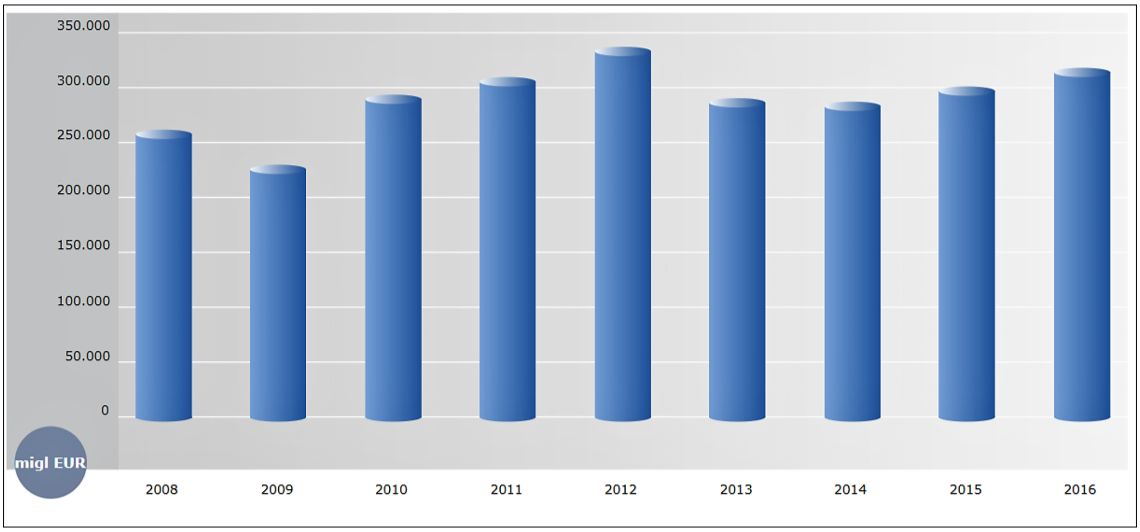


Figure 4.25: Sales revenues in the dental prostheses manufacturing sector from 2008 to 2016 [5]

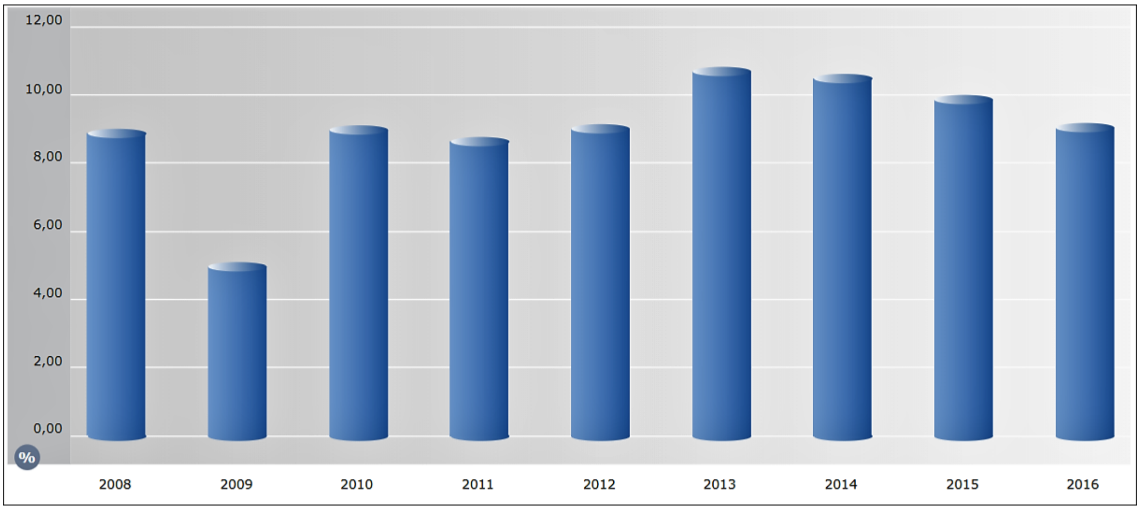


Figure 4.26: ROS percentages in the dental prostheses manufacturing sector from 2008 to 2016 [5]

Chapter 5

The use of AM in the dental prostheses manufacturing sector

5.1 Introduction

After going into further detail with the analysis of the companies belonging to the dental prostheses manufacturing sector (see page 104 and 105 of Chapter 4), let us now move the focus to the last part of our work, the questionnaire.

In fact, our work consisted in submitting a questionnaire on the adoption of Additive Manufacturing in the producing process of the selected 50 companies we already mentioned above. In the next sections, we will analyse the answers of the companies to the survey, trying to extrapolate some considerations about the adoption of AM.

5.2 The questionnaire and analysis of the answers

In the Appendix A of this thesis, the questionnaire submitted to the companies is shown.

First of all, we selected the first 50 companies (sorted by sales revenues) from the AIDA database; then, after having created a database with the contacts of all the companies, we have prepared a marked letter signed by the supervisor to present our project to the companies.

The third and, I would say, main important step was the calling activity, through which we have tried to convince companies to answer to our survey.

After terminating this activity, and understanding that there were 4 companies over 50 which do not manufacture dental prostheses or that have been acquired by foreign societies in the middle time, we realized that the conversion rate was 36,95%, meaning that 17 companies over 46 answered the questionnaire. And that is a quite good result.

The first question has been made to understand if the company belongs to a group of companies or not. As shown in Figure 5.1, the results state that 70,6% of respondents said no, while the remaining 29,4% answered yes. It is curious that in this last percentage belong those company which cover the highest positions in the ranking, starting from the market leader.

In fact, its group includes companies from Spain, Portugal, Great Britain and United States, and this sets forth its power and leadership, considering also that its market share in 2016 was 4 times the other main competitors, as already discussed above.

Same as the market leader, another big company owns distribution channels all over the world, from Russia to Canada, Asia and Africa.

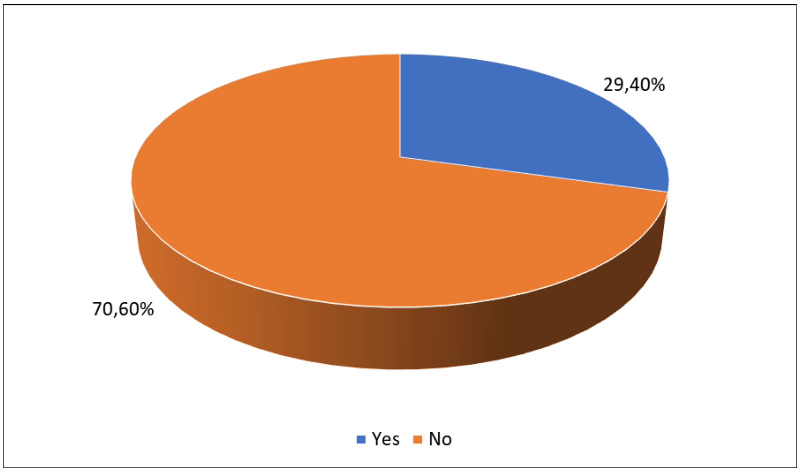


Figure 5.1: Question 1: Does the company belong to a group of companies? [47]

The second question regarded the legal institution of the company, if family business or not. The results in Figure 5.2 show that in this sector companies tend to be partnerships, with a percentage of 64,7, against the 35,3% which settled a family business. Yes, it is a lower percentage but we should remember that conducting a family business has its advantages, like restrained costs to set up the company and total freedom in taking important decisions.

The third and pretty important question concerned the allocation of the production, with a quite evident result, actually two, as shown in Figure 5.3: the first is that almost all companies interviewed allocate the production in Northern Italy, with a percentage of 88,2, none in the South and 5,9% in the Center. This last percentage characterises also those companies which allocate their production abroad, maybe because of cheaper manpower, lower production costs and less taxes. However, most companies prefer the "home-made" product.

The fourth question concerned the production strategy, whether centralized (hence, one production site) or decentralized (more production sites). The results in Figure 5.4 show almost equal percentages, with the 58,8% of companies operating on one production site and the remaining 41,2% which opted for offshoring. We could imagine that these last companies decide to move some of their production functions abroad because of different reasons: first, economic ones, deriving from the research of countries in which there is a concrete advantage compared to others, that is a set of rules, situations, uses and customs which make that kind of work better achievable there than elsewhere.

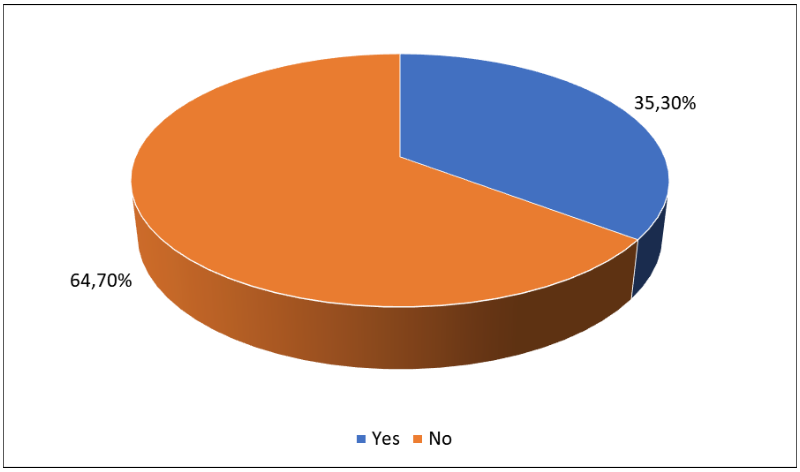


Figure 5.2: Question 2: Is the company a family business? [47]

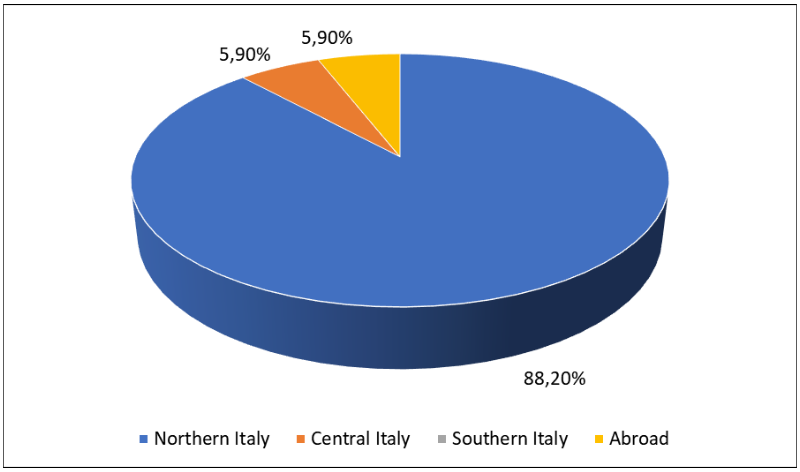


Figure 5.3: Question 3: Where is the production mainly allocated? [47]

To make an example, a production in which the focal part is constituted by the workforce with respect to the intrinsic value of the goods in transformation, is realized in a place where the labor cost is minimal, for example China. Differently, a production in which a considerable supply of cheap know-how and software is needed, is carried out in India where high professionalism is present at a limited hourly price. A call-center whose main cost is derived from the staff can be technically realized where it is possible to find professional, low-cost personnel able to speak good Italian, for example in Romania.

Secondly, apart from the natural comparative advantage, there are incentives for delocalisation due to economic development policies. Hence, we have a regional delocalisation, for example when there are incentives for production in one Italian region rather than another, or an international delocalization, when a country adopts systemic policies able to attract foreign direct investments and production settlements.

Currently, the European country in which it is cheaper to relocate industrial production is Bulgaria, thanks to regulations that cancel the income tax of companies that invest and the presence of numerous free zones for the application of VAT.

A third reason to relocate is the organizational possibility of delocalizing, that is, having an organization of work for which it is possible to "detach" a part or the whole of a certain production and realize it elsewhere. We therefore have the chance, to simplify, of an automotive industry that produces certain models in Italy and certain others in a different European state: it happens for example with Fiat, which has some models in production in Poland.

On the contrary, those companies which have adopted one production site, have probably embraced a set of political philosophies that prioritize local realities, supporting, for example, local production and local consumption of goods, as well as local government control. Moreover, outsourcing the production may imply some critical risks as reduction of employment, increase of logistic costs, loss of quality control, as well as risks related to the transfer of know-how.

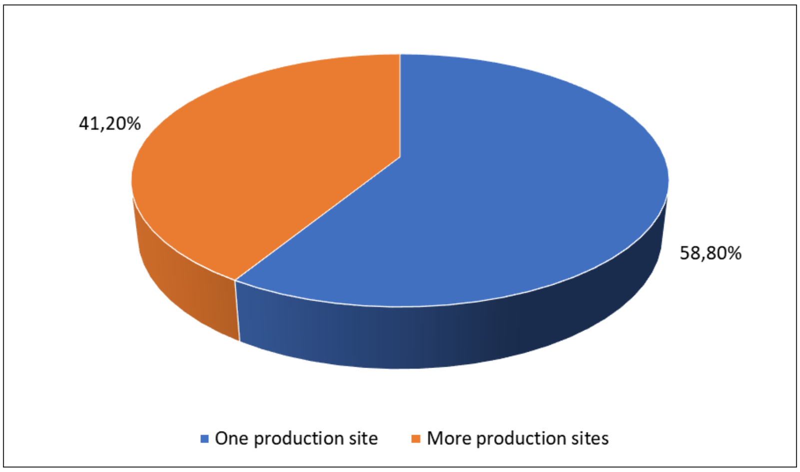


Figure 5.4: Question 4: Which is the production strategy currently adopted? [47]

The next question regarded the localization of suppliers. As depicted in the Figure 5.5, most of the suppliers are located in Italy, more precisely 76,5% in the North and 5,9% between North and Center. Moreover, a little percentage (5,9%) characterises those companies which have suppliers uniformly distributed between Italy and European Union while 11,8% of companies supply from abroad (EU). Hence, we could state that almost all companies interviewed trust Italian suppliers while a little percentage prefer to buy out of boundaries, maybe because of cheaper materials to produce the prostheses or machines, or, on the other side, for their better quality.

Thereafter, we have asked if the ownership of the company was Italian or not. Well, it is quite evident from the pie chart below that most respondent companies are Italian (80%), while the remaining 20% is owned by foreign people.

Actually, not all companies answered this question. We just say that only one company answered "Yes", since it was recently acquired by a foreign investment group. Why?

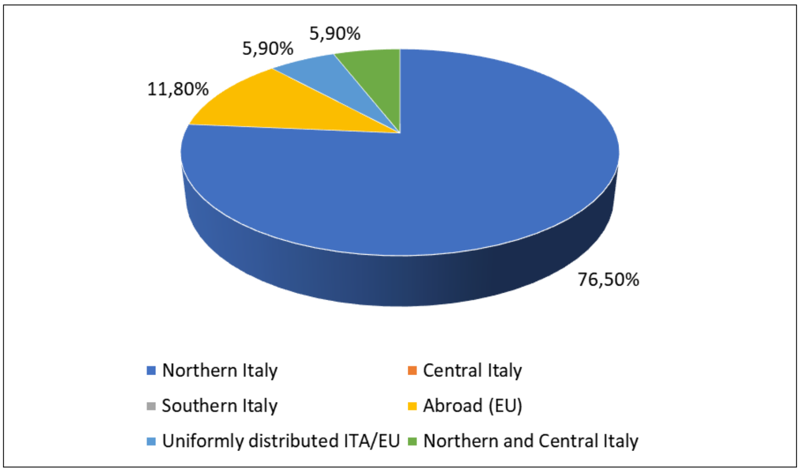


Figure 5.5: Question 5: Where is most of the company's suppliers located? [47]

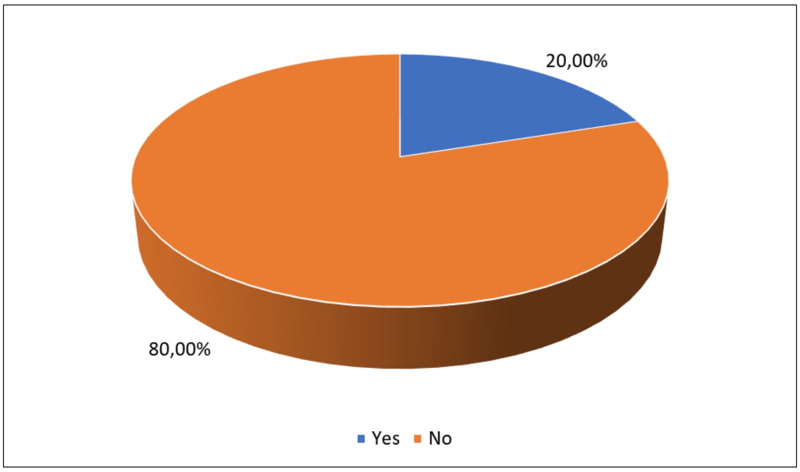


Figure 5.6: Question 6: Is the company part of a group whose property is not Italian? [47]

Because Italy is a country full of leading companies in market niches, according to the foreign investor. Besides, they declared to be ready to invest in other sectors, from the moment that they are discovering excellent realities with excellent performances.

Related to this, there is an interesting Istat research of 2015, according to which in Italy there are 14.007 foreign holdings, with 530 billion Euro of revenues, an added value of 104 billion Euro, 12 billion Euro invested and 3 of which in R&D. The graph 5.7 below shows the 10 countries where the societies that control most of Italian companies are located, where, needless to say, United States leads the rank with 2.347 active companies.

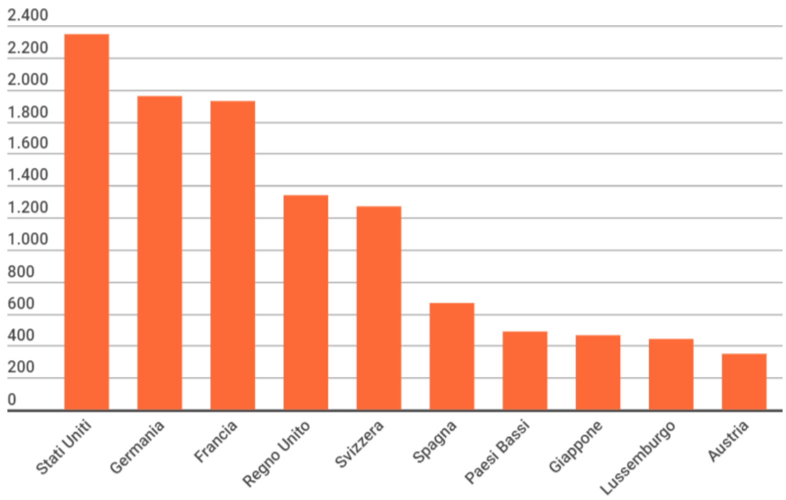


Figure 5.7: Number of foreign companies located in Italy [45]

Here we come to the core question: whether the companies interviewed have ever invested in additive manufacturing technologies or not. Data are clear (see Figure 5.8): 64,7% have invested while the remaining 35,3% have not, meaning that 11 companies over 17 interviewed have invested. And this is a result that places some hope for the future of additive manufacturing.

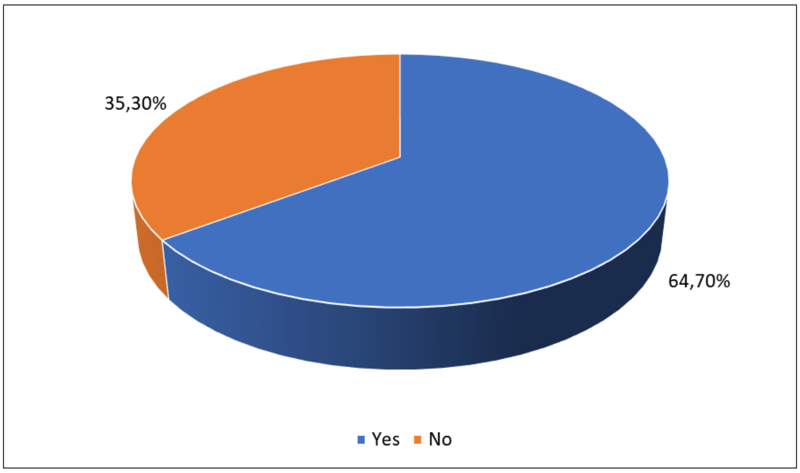


Figure 5.8: Question 7: Has the company made investments in additive technologies? [47]

Let us know focus on only those companies who have adopted AM for their manufacturing process, while later on we will make some considerations on the companies which adopt, instead, conventional manufacturing processes.

The subordinate question to the previous one, , whose results are shown in the Figure below, regarded the kind of materials worked in adopting AM. Most companies use only polymers to make dental prostheses, namely 54,5%, 27,3% instead use both metals and polymers while the remaining 18,2% use only metals.

In such a way, this was an expected result. In fact, there are different reasons to adopt polymers for this kind of product:

- Good chemical stability both in the state of the supply and in the finished prosthesis;
- Good dimensional stability;
- Adequate appearance (color and translucency);
- Color stability;
- Insolubility in the oral cavity;
- Minimum absorption of oral fluids;
- Absence of taste, odor and irritative and allergic phenomena. Speaking of which, using polymers instead of metals has also the advantage of having no metallic taste;
- Adequate adhesion to other resins and alloys;
- Ease of processing
- Ease of repair
- Radiopacity
- Sufficiently high deformation temperature (110/150 °C)

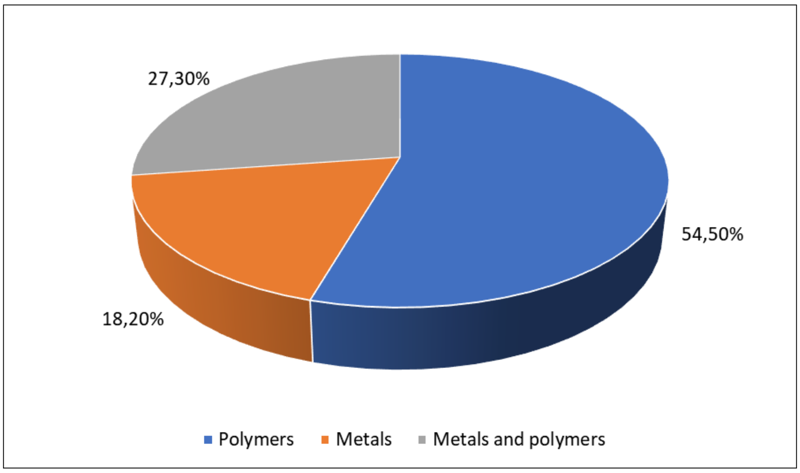


Figure 5.9: Question 8: Which materials do you use additive technologies for? [47]

The next question has been very crucial for our analysis, since it regarded the year in which companies have made their first investment in additive technologies so the answers have been relevant to understand how revenues and other indicators have changed after this investment.

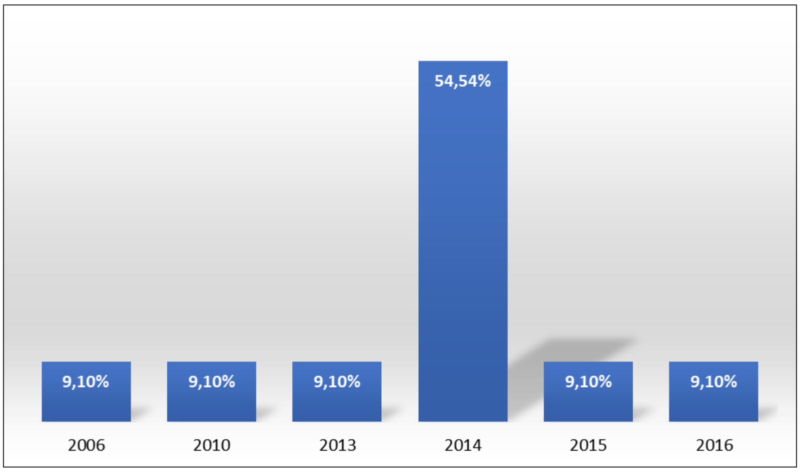


Figure 5.10: Question 9: When did you make the first investment in additive technologies? [47]

As emerges from the graph 5.10, it is evident that most companies, namely 54,54% (that is 6 over 11 respondents) have decided to invest in AM in 2014. All the others, have invested respectively in 2006, 2010, 2013, 2015 and 2016. However, the graph you see is not the original one; in fact, we have made a little adjustment because there was an anomaly: we realised that two companies have wrongly answered, indicating 2017 as year of first investment but later declaring an amount of investment in AM technologies in 2014 (to better understand, see next question).

Strongly related to the previous question is the next one, in which we asked the range of amount invested in AM technologies from 2014 to 2017, as depicted in Figure 5.11.

From the graph, it is evident that most companies have opted for the lowest range of investment, that is till 15.000 Euro per year, even if in a continuous way, thus investing every year. Apart from this information, there is only one company which has made a huge investment in 2015 (over 200.000 €.), while the market leader has made a little investment in 2014 and a notable one in 2015 (from 100.000 to 200.000 Euro).

However, the information mentioned above are relative to the total fixed assets owned by the company the previous year to the investment, and see how much they have allocated for AM. To let it be clear, let us make two significant considerations.

First, we found that the market leader has invested a very little portion of its fixed assets for AM technologies, considering that they amounted from 21 to 30 million in those years.

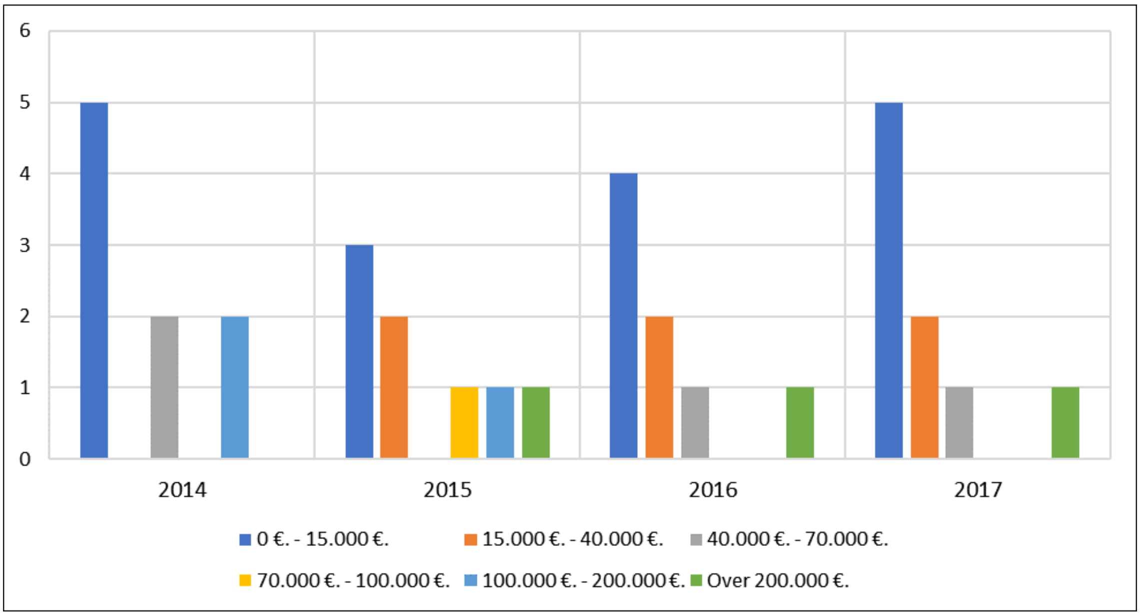


Figure 5.11: Question 10: Which is the amount of investment in additive technologies in each year from 2014 to 2017? [47]

On the contrary, the other company which made an investment from 100.000 to 200.000 Euro was allocating around 1/3 of its fixed assets, and this is an information worth mentioning.

After asking for the amount invested in AM technologies, the next question regarded the main objectives that companies have proposed to achieve with the aforesaid investments. More precisely, we asked them to give a score from 1 (most important) to 5 (least important) according to the relevance attributed to the following goals:

- Production costs reduction
- Increase in the variety of product range
- Greater correspondence with customer needs
- Reduction of transition times from design to mass production

Analysing the graph 5.12 below, we can make some considerations. First of all, considering the first objective, we have that 2 companies believe it to be very important, 3 do not take it into account too much while the remaining ones are in the middle. In the previous chapters we stressed about the main advantages achievable trough AM and reduction of production costs was one of those, especially in sectors like medical applications, dentistry and prosthetics.

In fact, labour costs are reduced thanks to process automation, there are less machining steps so cycle time and factory footprint are reduced. Moreover, the absence of moulds and patterns help to reduce costs too; however, for further details see 2.

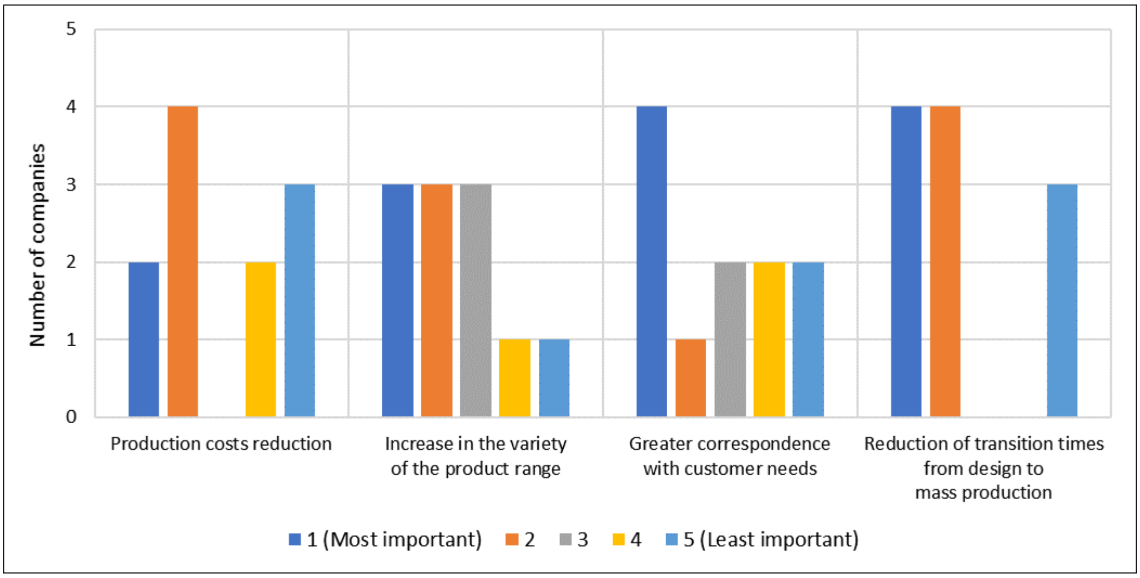


Figure 5.12: Question 11: Which have been the main objectives that the company has proposed to achieve with the investments in additive technologies carried out in 2014-2017? [47]

The second and third objectives are quite related if we consider one of the main feature of AM: customization; however, responses have been various. 3 companies believe the increase in the variety of product range to be very important, since AM allows to make omnifarious products thanks to the fact that their design is made using especially CAD software (see 1), hence it is very versatile and, eventually, easy to modify.

At the same time, this versatility allows companies to better meet customer needs without incurring in design issues, thanks to the reasons mentioned above. In fact, 4 companies retain that having greater correspondence with customer needs is one of the most important achievement, even if there are companies which think it the opposite, not considering these objective too much important.

Reduction of production costs can be achievable also reducing lead times (as mentioned above), and, in particular, reducing the time that goes from design to mass production. According to the histogram, in fact, it seems that almost all the companies interviewed care much for this achievement with 8 companies over 11 that believe it to be crucial for their business.

The following question was made to understand if AM technologies are used from these companies for production or also in a such experimental way as Rapid Prototyping, hence for Research & Development goals.

Well, results are clear: looking at the graph 5.13 below, all the companies interviewed use AM for production, even if a part of them (namely 4), use additive technologies also for RP. We could insinuate that those last companies have in mind to make products in large batches or characterised by very expensive material and specialised work, given that prototypes are much relevant in this case.

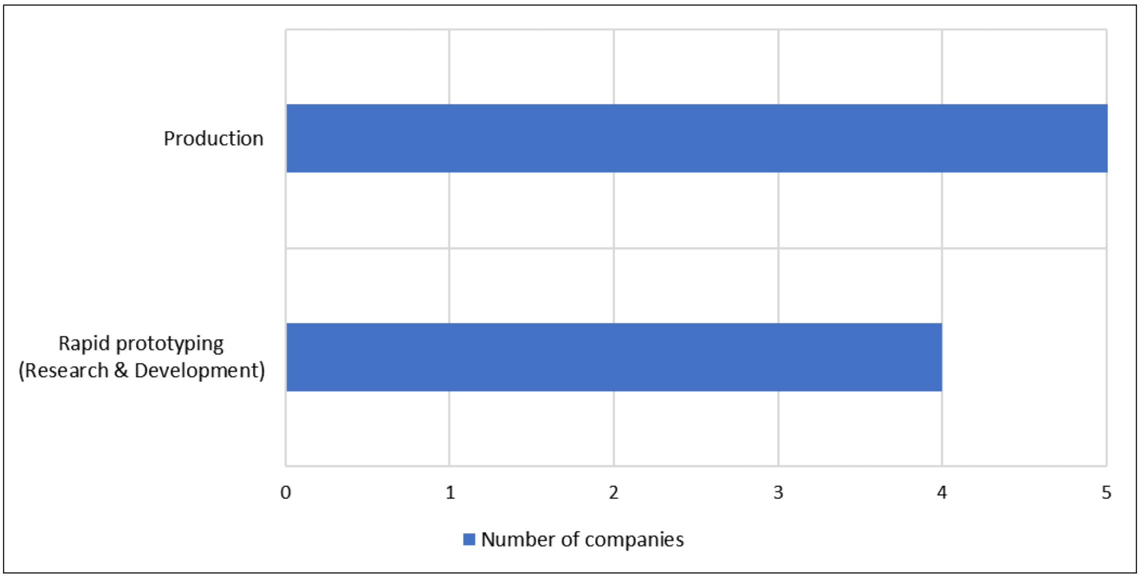


Figure 5.13: Question 12: Which process do you use AM technologies for? [47]

The next question is quite crucial to understand the usefulness of AM technologies; in fact, we asked if actually the use of AM has implied the resolution of any kind of issue concerning supply chain, or, if not, at least in part.

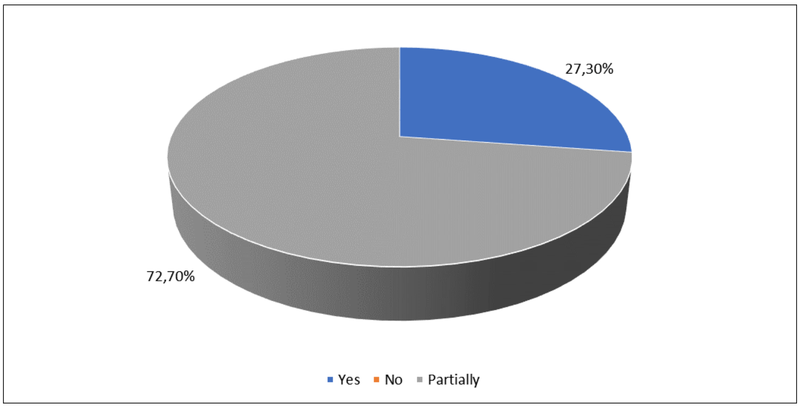


Figure 5.14: Question 13: Do you think that a production supported by additive technology could solve or at least mitigate the criticalities of its Supply Chain? [47]

As it could be expected, no one answered negatively, the 72,70% of companies believe that AM partially solve those problems while the remaining 27,3% of them seem to totally trust the use of additive technologies in their production processes. In fact, the benefits of this optimized supply chain are increasingly evident, as shown in the infographic 5.15 below. Transitioning to on-demand manufacturing leads to cost savings by eliminating or significantly reducing inventory requirements. The benefits of digital files also provide the ability to quickly produce new iterations at little to no additional cost.

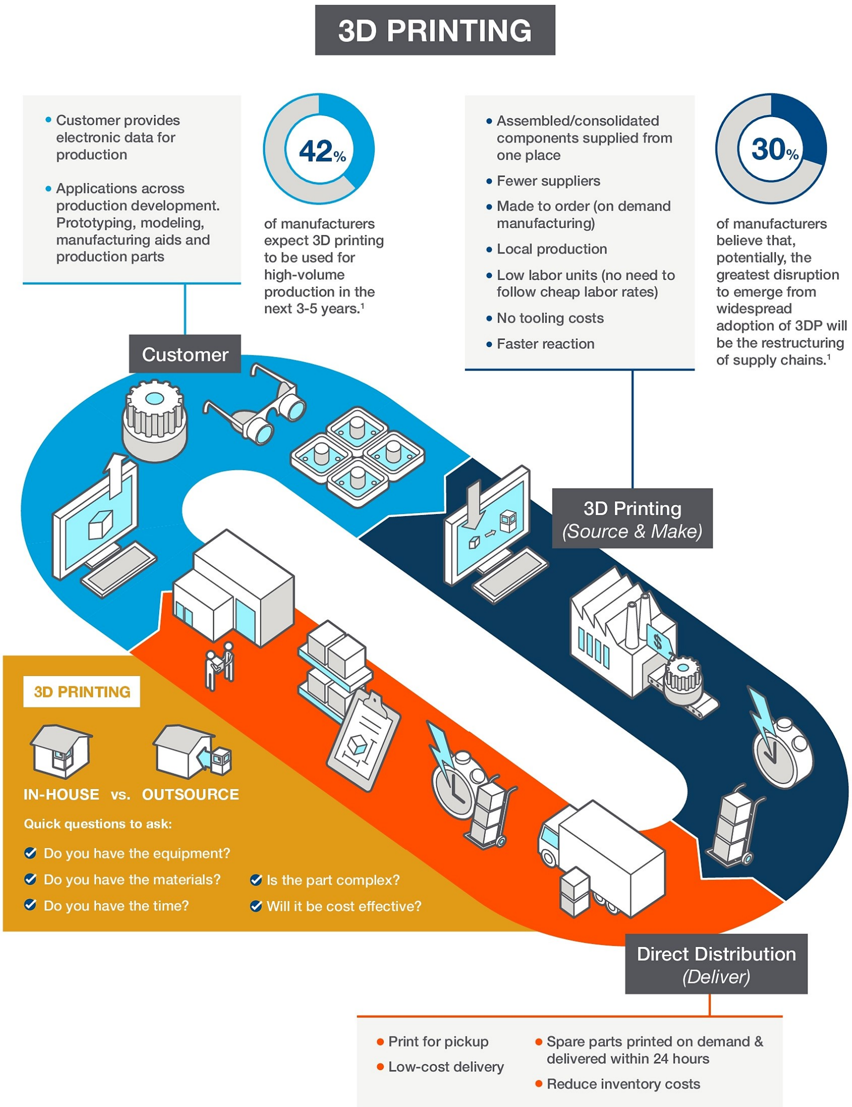


Figure 5.15: A supply chain using AM technology [47]

Furthermore, with a single source for a variety of parts, businesses that use 3D printing contract manufacturers deal with less risk, more control and added agility in relation to their product lifecycle. Local facilities can 3D print designs on-demand from files sent across the globe, or they can print securely from a nearby supplier.

The next and last question concerning those companies which have invested in AM technologies regard the impacts that the adoption of additive technologies may have on their supply chain.

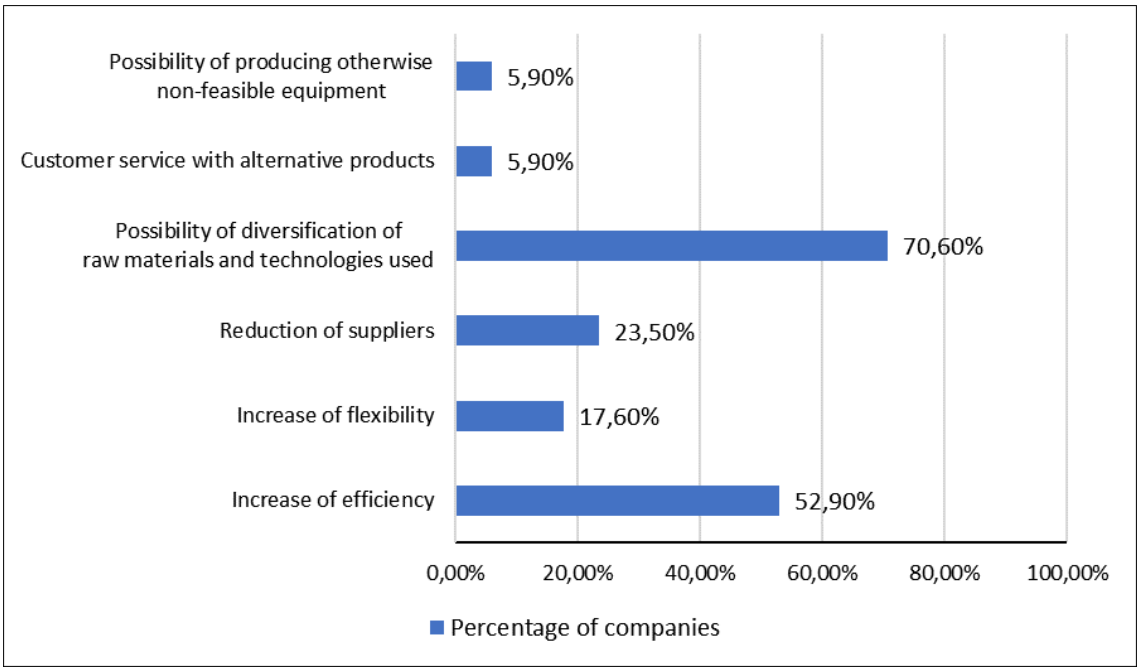


Figure 5.16: Question 14: Which are or could be the impacts of additive technological solutions on your Supply Chain? [47]

As it emerges from Figure 5.16, most companies, namely 70,6% are of the idea that adopting AM technologies can help diversifying raw materials and technologies; in fact, as stressed much in the previous chapters, AM offers different kinds of material (from metal to thermoplastic, thermosets, powder composites and sealant tapes) and technologies (for further details, see 1).

Going forward in the analysis, we find that 52,90% of respondents believe that AM can increase efficiency. And that is true, for the reasons explained in Question 11. The other answers are also consistent with the benefits and advantages entailed by AM: customer service with alternative products thanks to customization (5,9%), increase of flexibility (17,60%), reduction of suppliers (23,50%). A curious fact is that one company answered stating that *"By now our dental sector uses these technologies. In fact, since our laboratory has been supplying semi-finished products to dental technicians for 65 years, the company has had to acquire these technologies, in order to stay in the market"*.

Well, lingering on this answer we could imagine that it was not in the company plans to invest in additive technologies but since the market is day by day converting to this way of manufacturing, the company decided (maybe reluctantly) to invest in AM technologies, with the aim of still being competitive.

Time now to move on and focus on the other part of respondents, those who have not invested in AM technologies yet, namely 35,3%. Trivially, the first question asked was for the reasons of not having invested, and the following are the answers received:

- *"We are not interested in at the moment"*
- *"We have invested on subtractive technologies"*
- *"We are waiting for the range of materials to be used for the additive process to increase"*

Predictable responses, even if the last one is curious, considering that there are various materials which can be used.

In the next question, we have tried to understand if these companies are allocating part of their budget for investments in additive technologies.

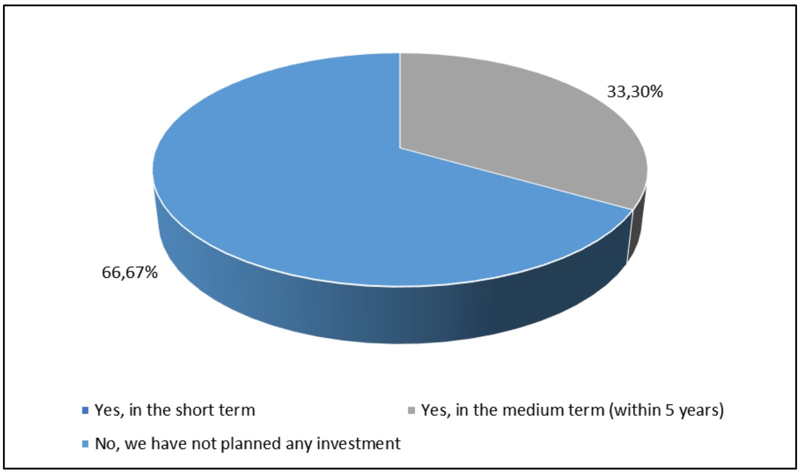


Figure 5.17: Question 15: Have you already planned future investments in additive technologies? [47]

As depicted in the Figure 5.17 above, none of the companies is planning investments in the short term, 33,3% will instead in the medium term (that is within next 5 years) while the remaining 66,67% is not planning investments at all. In this last percentage, there is one company which is simply not interested and another which is waiting for a larger material range to be used. However, we could imagine that there is still resistance to change, that maybe those companies still do not trust this kind of innovative process and prefer to wait a few years.

Finally, we are the end of our analysis, with the last question (already submitted to the companies adopting AM) in which we asked if additive technologies may represent a solution for the criticalities of the supply chain.

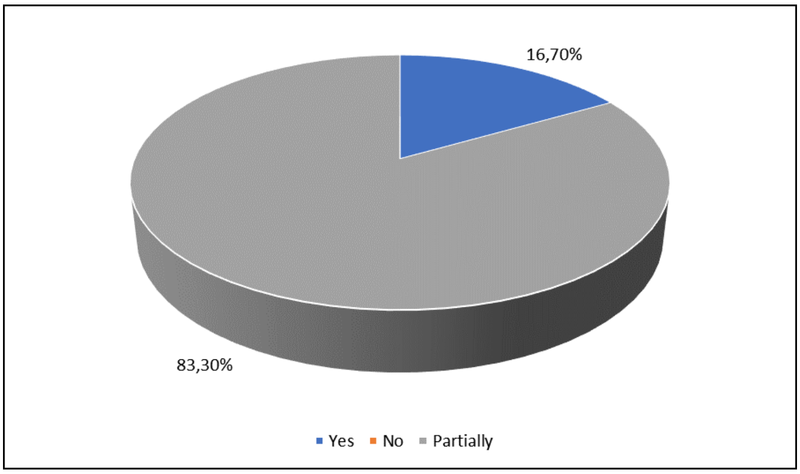


Figure 5.18: Question 16: Do you think that a production supported by additive technology could solve or at least mitigate the criticalities of its Supply Chain? [47]

As shown in the graph 5.18 below, most of the respondents, 83,3% think that AM technologies could partially solve all the issues related to supply chain while the remaining 16,70% is firmly sure that they are able to. Positive results: in fact, considering that those companies have not invested in AM yet, believe that this way of manufacturing might potentially be the solution to their problems can certainly be a point of start to plan some future investments.

5.3 Conclusion

After having analysed the answers to the questionnaire, it is time now to make final considerations both generally and about the adoption of AM in this sector. In order to do this, we first take advantage of some statistic tables, taking into consideration some important variables, as performance and profitability indexes.

By using statistic data, we have 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.

In addition, it is good to say that each variable has been analysed in relation to the moment in which the companies interviewed have adopted additive technologies, with the aim of understanding the differences before and after that moment.

The first variable to be analysed is the total tangible fixed asset per employee, which has positive effect, even if little (see Table 5.1 below).

The next index considered is the labour productivity, which is defined as the real economic output per labour hour, whose growth is measured by the change in economic output per labour hour over a defined period. However, it has not be confused with employee productivity, which measures the individual worker's output. The calculation is obtained by dividing the total output by the total number of labour hours.

Even in this case, the effect is positive and slight, with a difference of 8058.9 Euro after the adoption of AM (see Table 5.2).

The next variable considered is a profitability index, namely ROS, which stands for Return On Sales. This index, in fact, also known as a firm's operating margin profit, is a financial ratio whose aim is to evaluate a company's operational efficiency and it is calculated dividing the operating profit by net sales. In this case we have a negative effect, even if not so relevant, after the adoption of AM adoption, with a percentage difference of 3.81 % (see Table 5.3).

Another imperceptible but positive effect (difference of 106.1 Euro after the adoption of AM) is given by considering the added value per employee, which is an outstanding measure of the extent to which you are utilizing your employee's strengths. The calculation is obtained summing operating profit, salaries, wages and payroll expenses and then

	(1) Total tangible fixed asset per employee
Post AM adoption	3963.1
	(0.93)
Year 2007	1403.9
	(0.33)
Year 2008	6493.1
	(1.53)
Year 2009	−8669.4
	(−2.04)
Year 2010	−11494.8*
	(−2.71)
Year 2011	−4433.9
	(−1.13)
Year 2012	−7434.3
	(−1.89)
Year 2013	−8387.2
	(−2.08)
Year 2014	−8735.2
	(−1.53)
Year 2015	−9742.5
	(−1.71)
Year 2016	−7907.2
	(−1.39)
Constant	22075.8***
	(6.28)
Observations	33

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5.1: Total tangible fixed asset per employee

	(1) Labour productivity
Post AM adoption	8058.9
	(0.50)
Year 2007	−28436.6
	(−1.76)
Year 2008	−43793.7*
	(−2.72)
Year 2009	−65734.9***
	(−4.08)
Year 2010	−70491.1***
	(−4.38)
Year 2011	−44279.4**
	(−2.97)
Year 2012	−53145.6**
	(−3.56)
Year 2013	−55642.4**
	(−3.63)
Year 2014	−62291.7**
	(−2.88)
Year 2015	−62906.4**
	(−2.91)
Year 2016	−55661.4*
	(−2.58)
Constant	211030.3***
	(15.83)
Observations	33

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5.2: Labour productivity

	(1) ROS (%)
Post AM adoption	−3.818
	(−0.84)
Year 2006	−4.928
	(−0.80)
Year 2007	1.682
	(0.31)
Year 2008	1.584
	(0.30)
Year 2009	1.592
	(0.30)
Year 2010	2.617
	(0.50)
Year 2011	2.807
	(0.53)
Year 2012	0.819
	(0.16)
Year 2013	0.521
	(0.12)
Year 2015	3.573
	(1.35)
Year 2016	5.018
	(1.90)
Constant	7.157
	(1.46)
Observations	40

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5.3: ROS %

dividing it by the average numbers of employees (see Table 5.4).

	(1) Added value per employee
Post AM adoption	106.1 (0.01)
Year 2007	8952.9 (0.85)
Year 2008	13945.6 (1.33)
Year 2009	8786.8 (0.84)
Year 2010	14667.7 (1.40)
Year 2011	25395.4* (2.61)
Year 2012	23776.5* (2.45)
Year 2013	21405.0* (2.14)
Year 2014	20471.3 (1.45)
Year 2015	20724.2 (1.47)
Year 2016	22627.6 (1.61)
Constant	39595.4*** (4.56)
Observations	33

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5.4: Added value per employee

EBITDA/Sales is the next variable considered and it is a financial metric used to evaluate a company's profitability by comparing its revenues with earnings. More precisely, it reports the total amount a company can expect to receive after operating costs have been paid. In addition, as the name of the index already suggests, the calculation is given by dividing EBITDA (Earnings Before Interests, Taxes, Depreciation and Amortization) by the amount of sales. In this case we have a negative effect (negative difference of 1.56% after the adoption of AM adoption). Once again, the aforesaid effect is very slight.

	(1) EBITDA/SALES (%)
Post AM adoption	-1.559 (-0.37)
Year 2006	-3.494 (-0.61)
Year 2007	3.555 (0.70)
Year 2008	2.833 (0.58)
Year 2009	2.297 (0.47)
Year 2010	3.353 (0.68)
Year 2011	3.643 (0.74)
Year 2012	2.066 (0.42)
Year 2013	1.376 (0.34)
Year 2015	2.840 (1.15)
Year 2016	3.738 (1.52)
Constant	10.86^{*} (2.37)
Observations	40

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5.5: EBITDA over Sales (%)

Now we focus on the two last indexes which are related one each other, namely market share and market share growth rate. Considering the first one, we say that it represents the percentage of an industry or market's total sales that is earned by a particular company over a specified time period. The Table 5.6 below shows a positive effect after the adoption of AM, with a percentage difference of 2.58%.

	(1) Market share
Post AM adoption	2.581**
	(2.96)
Constant	6.733***
	(13.42)
Observations	39

t statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5.6: Market share

The latter index, instead, considers the increase of a company in the size of a market and it is typically expressed as an annual percentage rate. Hence, the calculation is obtained by subtracting the market size of the past year from the market size of the current year; then, you have to divide the result by the market size of the past year and multiply by 100 to obtain a percentage. Once again, we have a little but positive effect, with a percentage difference of 16.58% after the adoption of AM.

	(1) Market share growth rate
Post AM adoption	16.58 (1.06)
Year 2008	103.7*** (6.86)
Year 2009	115.1*** (7.83)
Year 2010	98.70*** (6.71)
Year 2011	107.1*** (7.28)
Year 2012	104.1*** (7.08)
Year 2013	132.1*** (8.74)
Year 2014	73.98** (3.50)
Year 2015	91.53*** (4.33)
Year 2016	92.98*** (4.40)
Constant	-104.3^{***} (-7.89)
Observations	36

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5.7: Market share growth rate

In conclusion, summing it all up, and considering that we had not too much observations to make robust considerations, we could affirm that the adoption of AM, at least in this specific sector, does not seem to bring solid and significant effects. There are not the premises to state that the performance, the profitability or the economic position have considerably improved after the adoption of additive manufacturing technologies but effects have all been almost imperceptible, maybe even for the fact that there is still resistance to change. However, if we want to wave the flag for the cause, we would like to think that times are still premature, and that we are just at the beginning (results are not that bad so far, anyway) of a revolution and awareness that will not come in a long time.

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Appendix A

Questionnaire

The following pages show the questionnaire submitted to a sample of 50 Italian companies operating in the dental 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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