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Additive Manufacturing: analysis of the economic context and evaluation of the indoor air quality, with a Total Quality Management approach

SETTORE SCIENTIFICO DISCIPLINARE: SECS-P/13-SCIENZE MERCEOLOGICHE

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A Daniela e Luciano, a cui devo tutta la mia vita,

A Federica, insegnante, amica e guida di questo percorso

Ad Alessio, amore mio grande

INTRODUCTION

The world has started to speak about a possible new revolution that would change radically the way in which the entire economic system will be managed: Additive Manufacturing, together with the other enabling technologies of the industry 4.0, has the potential ability to change the traditional concepts of manufacturing and the way in which the production is managed throughout its supply chain.

Even Jeremy Rifkin, one of the sharpest and recognized analyzers of socio-economic scenarios, believes that the phase of digitization, the Third, has just begun and has yet to fully show all its implications and its potential.

On the contrary Klaus Schwab, a German engineer and economist, best known as the founder and executive chairman of the World Economic Forum, in his book "The Fourth Industrial Revolution", argues that the first three revolutions are the transport and mechanical production revolution of the late 18th century; the mass production revolution of the late 19th century, and the computer revolution of the 1960s. He accepts that some people might consider the fourth revolution just an extension of the third but argues that the scale, speed and impact of the latest technologies mean they deserve a revolution of their own.

Whether the revolution in act today is in the Third or the Fourth, while the old way of making things involved taking lots of parts and screwing or welding them together, now a product can be designed on a computer and "printed" on a 3D printer, which creates a solid object by building up successive layers of material. This new way of producing objects, that is called Additive Manufacturing (AM), is considered to be revolutionary.

This study, divided in four chapters will analyze the changes that the Industry 4.0 is making to the whole economic system focusing on the manufacturing technology of Additive Manufacturing (AM) and analyzing the Italian economic context of reference, in the wood-furniture manufacturing sector. It will consider the supply side, that is the propensity of businesses to use 3D printers in the prototyping and subsequent production phase and the role of Fab Labs as mediators for the use of the technology between private consumers and businesses; the demand side and therefore Italian consumers knowledge of AM, 3D printing technologies and Fabrication Laboratories (Fab Labs), their perceptions about products made using 3D printers, their propensity to buy products made with these technologies and to use these ones to create their one products. Finally it will consider also environmental aspects related to the "indoor air quality” and 3D printers melting techniques when printing for example plastic filaments of materials.

In detail chapter 1 investigates, through a literature review, what is Additive Manufacturing, starting from its origins, trying to outline its developments over time and understanding its future lines of development. After the description of the Additive Manufacturing technique and of its application fields, the chapter deals with the analysis of the international significance of the phenomenon and then focuses on the Italian situation, investigating the presence of a potential gap between the International and Italian economic system.

Chapter 2 deals with the places where digital manufacturing technologies and 3D printing take shape, that is, Fabrication Laboratories (Fab Labs). They are defined as a platform for learning and innovation: a place to play, to create, to learn, to mentor, to invent. After describing the born of the International Maker Movement, the chapter describes the typical layout of these digital manufacturing spaces, where makers operate; the tools and machines used in it and the people that appeal to it. Subsequently the main Fab Labs realities are taken into account, through an empirical research, describing the diffusion and typology of laboratories present in the Italian territory and making a comparison between this reality and the other main European and American ones, highlighting their potential strength and weaknesses and identifying their role both towards consumers and businesses in the Industry 4.0 era. The aim of this second chapter is therefore to analyze where Do Ii Yourself (DIY) comes to life; these laboratories work with the typical mechanisms of the sharing economy: they provide a space with tools and equipment for digital manufacturing, making them available to individual users, small businesses and schools.

As for chapter 3, this takes into consideration the analysis of the perception and development of Additive Manufacturing techniques in the Italian market. To do this, the results of three research works are presented. The first tries to investigate the knowledge and perception that Italian consumers have of 3D printers, and their propensity to use these manufacturing technologies in order to evaluate how much Italian consumers are near to the definition of the new consumer called “Prosumer” given by Alvin Toffler (1980).

Subsequently it has been investigated the role of businesses in investing in this new manufacturing technology. The research focus was the Italian wood-furniture industry, solid pillar of the Made in Italy, where design is the first element of importance. The aim was to understand if companies in this sector were investing in digital technologies and in particular in AM techniques, to remain competitive in their reference markets. The research also attempted to investigate the potential sustainable benefits and barriers to the implementation of AM in this specific sector, trying to identify the gaps in perception between "traditional companies", which have never implemented AM techniques and those "innovative", which have implemented these technologies yet.

Finally chapter 4 deals with Additive Manufacturing and the possible problem of Indoor Air Pollution due to the melting process of 3D printers, during which materials such as plastics emit gaseous substances, commonly called Volatile Organic Compounds (VOCs). Assessing that the quantity of substances emitted does not exceed threshold levels is important for the health and safety of those using such digital tools.

The chapter starts defining the concept of Air Pollution, and distinguishing between Indoor and Outdoor Air Pollution. It continues describing what VOCs are and the guidelines for Indoor Air Quality defined at an European and Italian level. The chapter ends with the description of the results of the research, which performed air sampling of indoor air environments, while a 3D printer was under function, with different types of plastic materials (PLA, ABS, PET) in order to understand and assess the potential dangerousness to human health of this technological tool. Non-manufacturing environments such as offices, homes, classrooms, and libraries are usually designed for occupant comfort, not exposure mitigation. Hence, use of 3D printers in non-manufacturing or private settings potentially represents another contribution to VOC exposure for indoor workers and the general public to particles with potential dangers for human health. Since most desktop 3D printers are not equipped with exhaust ventilation or filtration accessories and users in home and public settings typically do not utilize appropriate personal protective equipment, it is important to characterize the physicochemical properties of 3D printer emissions to understand exposure potential and risk as early on as possible in the adoption of this technology to non-industrial settings. To this end, in collaboration with laboratory Cosmob Spa, this research performed air sampling of indoor air environments, while a 3D printer was under function, with different types of plastic materials in order to understand and assess the potential dangerousness to human health of this technological tool.

1. ADDITIVE MANUFACTURING: IS IT THE FUTURE?

ABSTRACT

The world has started to speak about a possible new revolution that would change radically the way in which the entire economic system will be managed: Additive Manufacturing has the potential ability to change the traditional concepts of manufacturing and the way in which the production is managed throughout its supply chain. The aim of this chapter is to investigates what Additive Manufacturing is, starting from its origins, trying to outline its developments over time and understanding its future lines of development. After the description of the Additive Manufacturing technique and of its application fields, the chapter will deal with the analysis of the international significance of the phenomenon and then will focus on the Italian situation, investigating the presence of a potential gap between the International and Italian economic system.

1.1 Additive and Subtractive Manufacturing

Currently the world economy is going through a period of transition and change that the journal *The Economist* has defined as "The Third Industrial Revolution":

> *"The first industrial revolution began in* Britain *in the late 18th century, with the mechanisation of the textile industry. Tasks previously done laboriously by hand in hundreds of weavers' cottages were brought together in a single cotton mill, and the factory was born. The second industrial revolution came in the early 20th century, when Henry Ford mastered the moving assembly line and ushered in the age of mass production. The first two industrial revolutions made people richer and more urban. Now a third revolution is under way.*

> *Manufacturing is going digital."(The Economist,*
> *April 21st, 2012)*

Even Jeremy Rifkin, one of the sharpest and recognized analyzers of socio-economic, technology and production scenarios, believes that the phase of digitization, the Third, has just begun and has yet to fully show all its implications and its potential (Rifkin, 2011; Carlucci, 2015; Ruffilli, 2015).

On the contrary Klaus Schwab, German engineer and economist, best known as the founder and executive chairman of the World Economic Forum, in his book "The Fourth Industrial Revolution", argues that the first three revolutions are the transport and mechanical production revolution of the late 18th century; the mass production revolution of the late 19th century, and the computer revolution of the 1960s. He accepts that some people might consider the fourth revolution just an extension of the third but argues that the scale, speed and impact of the latest technologies mean they deserve a revolution of their own. *"The changes are so profound that, from the perspective of human history, there has never been a time of greater promise or potential peril*" (Schwab, 2016; Thornhill, 2016).

Whether the revolution in act today is in the Third or the Fourth Industrial Revolution, while the old way of making things involved taking lots of parts and screwing or welding them together; now a product can be designed on a computer and "printed" on a 3D printer, which creates a solid object by building up successive layers of material. This new way of producing objects, that is called Additive Manufacturing (AM), is considered to be revolutionary.

The AM technique is a production mode that, even using very different technologies, allows the creation of objects (components parts, semi-finished or finished products) generating and adding successive layers of material (Additive Manufacturing) rather than by subtraction from the full (Subtractive Manufacturing), just as it is in many of the traditional technical production (turning, milling, etc.) (Centro Studi Confindustria, 2014). It is an important evolution in the context of the broader trend of the digitalization of manufacturing that takes place through dialogue between computers and machines thanks to the sharing of information (among machines, people and between people and machines) made possible by the spread of the Internet.

AM is a radical innovation, capable of producing profound changes in the economy and society from many points of view. There is the possibility of creating objects with new geometries, reducing the stocks, achieving a "mass customization" of many products, redefining the location processes of production activities with different logistics, a new work organization, new professional figures in the field of manufacturing and crafts and new spaces for creative action of individual citizens. The revolutionary aspect of AM consists in the fact that the objects are not realized by removal of material, as it is in the case of operations with computerized numerical control machines (CNC) such as milling machines, lathes, presses, machining centers, or for welding of separate pieces; on the contrary, the objects are generated for stratification and addition of material directly into a single piece. AM allows to produce items with complex geometries not otherwise achievable in a single piece with the traditional techniques and ensures that the development of variants of costs compared to a basic model are substantially zero. For these reasons this technique is currently used mainly in the following cases (Centro Studi Confindustria, 2014):

a. productions in which it is the technology of choice, that is, when it allows to reduce the costs and made objects with equal or greater technical characteristics to obtain unique qualitative standards, not achievable with traditional techniques;
b. productions where technology is cost competitive only if you change the object's design that has to be realized. Changes in design allow to maximize the potential of AM without compromising (or improving) the technical characteristics of the object;
c. productions where technology is not competitive in absolute terms but may be economically advantageous because:
    - the piece printed in 3D is more expensive, but AM (due to its flexibility, the speed of production without the need for molds or other tooling) allows you to "store" files instead of products, thereby reducing the capital tied up in inventory and stock costs;
    - AM can allow to withstand sudden and unanticipated lack of components for in-line production;
    - AM allows the constructive reengineering of more efficient pieces (and more expensive) that help increase the productivity of existing industrial facilities.

The sectors most involved today are, in addition to prototyping in general, aerospace, automotive, biomedical, packaging and it is widespread in jewelery. While some areas will see rapid and disruptive changes, such as those just mentioned, others will change slowly and steadily. Either way we are going to the so-called *"New Normal"* (Potti, 2015), that is to say, this is already the new world in which physical objects are perfectly integrated into the network of information.

In this new world, manufacturing has an important role due to the fact that it is the main engine of economic growth because it generates productivity gains which then are spread, through the goods it produces among the other sectors; it creates skilled jobs and better paid; it makes the most part of research and innovation, making benefits to the whole system through new innovative content of manufactured goods used from the other sectors (Paolazzi, 2015).

Technological developments, together with those of the production allow products and machines to communicate with each other and exchange commands wirelessly, directly or via the *Internet of Things*. The result is a much more flexible production environment, with less central control and more integrated intelligence locally in equipment, able to optimize the efficiency of processing.

In this production scenario, the strategic challenge of companies that aim to be part of the future of European manufacturing is grafted: understanding how to plan the development paths that promote technological advancement in production systems, based on the diffusion of the key technologies of this new Industrial Revolution in its production structure.

1.2 The road towards Additive Manufacturing

Additive Manufacturing has roots in topography and photosculpture which date back almost 150 years. Both of these early technologies might be categorized as manual “cut and stack” approaches to build a freeformed object in a layerwise fashion. The first successful AM process was effectively a powder deposition method with an energy beam proposed by Ciraud in 1972. Over the last 20 years increasingly sophisticated technologies have been developed to produce complex, freeform solid objects directly from computer models without part-specific tooling; these are often labeled “solid freeform fabrication” (SFF) technologies. Until recently they have been applied principally to prototype models and have encompassed predominantly additive or layered manufacturing techniques. These technologies are evolving steadily and are beginning now to encompass related systems of material addition, subtraction, assembly, and insertion of components made by other processes. Furthermore, these various additive/subtractive processes are starting to evolve into rapid manufacturing techniques for masscustomized products, away from narrowly defined rapid prototyping (Beaman et al., 2004).

1.2.1 Prehistory of AM

An essential element of AM is layerwise creation of a part. From a review of the US patent literature, Bourell et al. (2009) identified two early roots of the modern AM technique that is to say topography and photosculpture.

Topography

Topography is the study of the shape and features of the surface of the Earth and other observable astronomical objects including planets, moons, and asteroids. It involves the recording of relief or terrain, the three-dimensional quality of the surface, and the identification of specific landforms. This is also known as geomorphometry. In modern usage, this involves generation of elevation data in digital form (DEM). It is often considered to include the graphic representation of the landform on a map by a variety of techniques, including contour lines, hypsometric tints, and relief shading. Topography is considered a precursor of AM since Blanther (1892), suggested a layered method for making a mold for topographical relief maps. The method consisted of impressing topographical contour lines on a series of wax plates and cutting these wax plates on these lines. After stacking and smoothing these wax sections, one obtains both a positive and negative three-dimensional surface that corresponds to the terrain indicated by the contour lines. After suitable backing of these surfaces, a paper map is then pressed between the positive and negative forms to create a raised relief map.

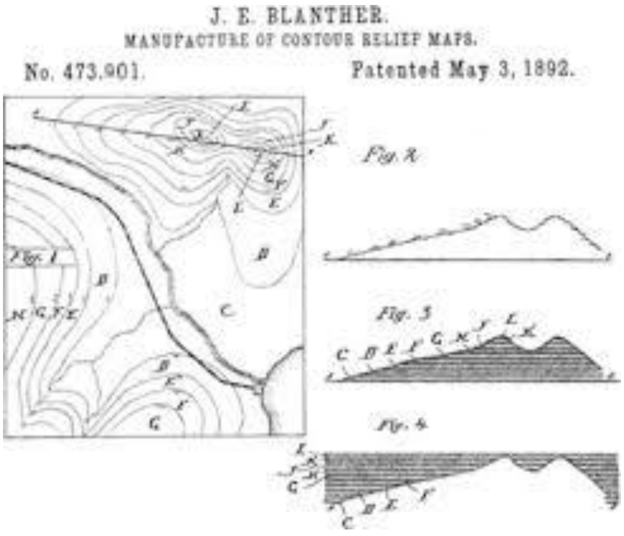

Figure 1.1 Blanther's layering method for producing topographical maps

In a similar way, Perera (1940) proposed a method for making a relief map by cutting contour lines on sheets (cardboard) and then stacking and pasting these sheets to form a three-dimensional map. In 1972, Matsubara (1974) of Mitsubishi Motors proposed a topographical process that uses photo-hardening materials. In this process, a photopolymer resin is coated onto refractory particles (e.g., graphite powder or sand). These coated particles are then spread into a layer and heated to form a coherent sheet. Light (e.g., mercury vapor lamp) is then selectively projected or scanned onto this sheet to harden a defined portion of it. The unscanned, unhardened portion is dissolved away by a solvent. The thin layers formed in this way are subsequently stacked together to form a casting mold. Subsequently DiMatteo (1974) recognized that these same stacking techniques could be used to produce surfaces that are particularly difficult to fabricate by standard machining operations. In one embodiment, a milling cutter contours metallic sheets, these sheets are then joined in layered fashion by adhesion, bolts, or tapered rods. This process has obvious similarity to the earlier 19th century work, and are forerunners techniques of the recent AM technique.

Photosculpture

Photosculpture arose in the 19th century as an attempt to create exact three-dimensional replicas of any object, including human forms (Bogart, 1979). One, somewhat successful realization of this technology was designed by Frenchman François Willème in 1860. A subject or object was placed in a circular room and simultaneously photographed by 24 cameras placed equally about the circumference of the room (Figure 1.2) An artisan then carved a 1/24th cylindrical portion of the figure using a silhouette of each photograph.

In an attempt to alleviate the labor-intensive carving step of Willème's photosculpture, Baese (1904) described a technique using graduated light to expose photosensitive gelatin that expands in proportion to exposure when treated with water.

In some of the earliest work in Japan, Morioka (1935, 1944) developed a hybrid process between photosculpture and topography. This method uses structured light (black and white bands of light) to photographically create contour lines of an object. These lines could then be developed into sheets and then cut and stacked or projected onto stock material for carving.

Figure 1.2 The photosculpture method of François Willème using cameras surrounding the subject.

1.2.2 First attempts to modern AM

The first step towards the modern AM was made in 1956 from the mind of John Munz, who developed a method to "register" solid objects in a resin by ultraviolet light, baptizing "photo-glyph recording". Munz (1956) proposed a system that has features of present day stereolithography techniques. He disclosed a system for selectively exposing a transparent photo emulsion in a layerwise fashion where each layer comes from a cross section of a scanned object. Subsequently in 1968, Swainson (1977) proposed a process to directly fabricate a plastic pattern by selective, three dimensional polymerization of a photosensitive polymer at the intersection of two laser beams, while Ciraud (1972) proposed a powder process that has all the features of modern direct deposition AM techniques. This disclosure describes a process for the manufacture of objects from a variety of materials that are at least partially able to melt. To produce an object, small particles are applied to a matrix by gravity, magnetostatics, electrostatics, or positioned by a nozzle located near the matrix. A laser, electron beam, or plasma beam then heats the particles locally. As a consequence of this heating, the particles adhere to each other to form a continuous layer.

In 1979, Housholder (1981) presented the earliest description of a powder laser sintering process in a patent. He discussed sequentially depositing planar layers and solidifying a portion of each layer selectively. The solidification can be achieved by using heat and a selected mask or by using a controlled heat scanning process. Two years later, Hideo Kodama (1981) of Nagoya Municipal Industrial Research Institute was the first to publish an account of a functional photopolymer rapid prototyping system. In his method, a solid model is fabricated by building up a part in layers where exposed areas correspond to a cross-section in the model.

In August 1982, Alan Herbert of 3M Graphic Technologies Sector Laboratory published a paper titled Solid Object Generation in the Journal of Applied Photographic Engineering. In this paper, Herbert described a system that directs an Argon Ion laser beam onto the surface of photopolymer by means of a mirror system attached to an x-y pen plotter device. With the system, Herbert was able to create several small, basic shapes. The primary purpose of the work, however, was to develop an understanding of the requirements of a real system.

The real AM technique first emerged with *Stereolithography* (SL) from 3D Systems, a process that solidifies thin layers of ultraviolet (UV) light-sensitive liquid polymer using a laser. All begun in 1984 when Charles Hull, co-founder and chief technical officer of 3D Systems (at that time, in Valencia, California), applied for a U.S. patent titled Apparatus for Production of Three-Dimensional Objects by Stereolithography, which was granted in March 1986. At the time of the patent application, Hull was working for UVP, Inc. (San Gabriel, California) as vice president of engineering. In March 1986, Hull and Raymond Freed co-founded 3D Systems Inc. (Wohlers Report, 2014). The company presents itself today as:

> *"The inventors of 3D Printing and global providers of 3D content-to-print solutions. Our expertly integrated hardware and software solutions and services replace, augment and complement traditional development and manufacturing methods reducing the time and cost of designing and delivering new products. ...As the originator of 3D printing and a shaper of future 3D solutions, 3D Systems has spent its 30 year history enabling professionals and companies to optimize their designs, transform their workflows, bring innovative products to market and drive new business models ".(www.3Dsystems.com)*

After that, Hull's 1986 patent described a process of photo-hardening a series of cross sections using a computer-controlled beam of light. In this year, Yehoram Uziel, had invented a basic machine resembling stereolithography. Uziel had read about Hull's work, so he traveled to the U.S. to visit him and Ray Freed. In January 1989, he joined 3D Systems as vice president of engineering. In late 1987, 3D shipped its first beta units to customer sites in the U.S., followed by production systems in April 1988. These were the first commercial AM system installations in the world. In 1986, Hull was not the only one with patent activity on his mind. The same year, Takashi Morihara of Fujitsu Ltd. patented two elements of stereolithography. One of them involved passing a blade over the surface of a new layer of resin to speed the leveling of the layer. This technique is especially important when the resin is viscous. For many years, 3D Systems used this leveling technique in its SLA family of stereolithography products.

Subsequently different AM techniques developed. In 1991 Scott Crump produced the world first *Fused Deposition Modelling machine* (FDM). This technology uses plastic and an extruder to deposit layers on a print bed. 3D printers with FDM technology build parts layer by layer, from bottom to top, by heating an extrusion of thermoplastic filament (www. stratasys.com). In the same year other two important AM technologies were developed, that is *Solid Ground Curing* (SGC) from Cubital, and *Laminated Object Manufactu*ring (LOM) from Helisys.

One year later 3D System, after the SLA patent in 1986, produced the first SLA 3D Printer machine, and in the same year DTM produced the first *Selective Laser Sintering* (SLS) machine. This machine was similar to SLA technology but used a powder (and laser) instead of a liquid.

In 1996, Stratasys introduced the Genisys machine, which used an extrusion process similar to FDM but based on technology developed at IBM’s Watson Research Center. After eight years of selling stereolithography systems, 3D Systems sold its first 3D printer “Actua 2100” in 1996, using a technology that deposits wax material layer by layer using an inkjet printing mechanism.

In 1997 another new 3D technology has been invented; Aeromet developed a process called *Laser Additive Manufacturing* (LAM) that used a high-power laser and powdered titanium alloys. Until it shut down in December 2005, AeroMet manufactured parts for the aerospace industry as a service provider.

In 1999 there is a turning point in AM: scientists manage to grow organs from patient’s cell and use a 3D printed scaffold to support them. The first ever 3D organ, a bladder, is created with the patient's own cells. This means that there is little chance of the organ being rejected by the body (Wohlers Report, 2014).

April 2000 was a month full of new technology introductions. Object Geometries of Israel announced Quadra, a 3D inkjet printer that deposited and hardened photopolymer using 1,536 nozzles and a UV light source; moreover Precision Optical Manufacturing (POM) announced *Direct Metal Deposition* (DMD), a laser-cladding process that produces and repairs parts using metal powder.

1.2.3 The RepRap project

The RepRap Project, the abbreviation of Replicating Rapid Prototyper, is an initiative aimed at developing a 3D printer that produces for itself most of its own components. It is a robot that uses fused-filament fabrication to make engineering components and other products from a variety of thermoplastic polymers. RepRap has been designed to be able automatically to print out a significant fraction of its own parts (Jones et al., 2011). RepRap was founded in 2005 by Dr. Adrian Bowyer, a senior lecturer in mechanical engineering at the University of Bath in the United Kingdom.

Adrian Bowyer has declared[1]:

> *"Our aim was to create and give away a machine that makes useful stuff…It enables its owner to easily and cheaply make another for someone else. This is particularly useful where capital investment is low. It makes manufacture similar to agriculture".*

All works created under this project are published under open source licenses in an open source community. An open source community is where people gather knowledge and information about a product or solution. Community members will use the shared knowledge to further develop the product or solution without any member claiming ownership of the idea.

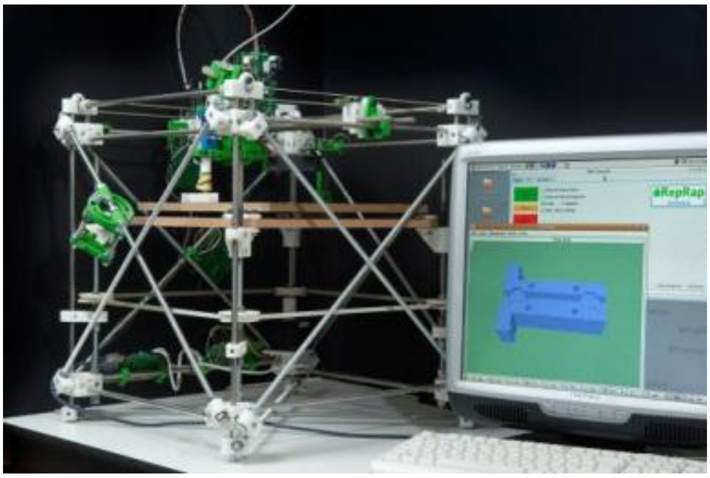

Figure 1.3 First Reprap machine named "Darwin".

The RepRap community envisions that in the not too distant future it

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[1] Adrian Bowyer quotation cited on a paper entitled "shortlisted for two times higher education awards "located on the site of the University of Bath , the 17 September 2012.

will be possible to distribute RepRap units cheaply to people and communities, enabling them to build complex products without the need for an expensive industrial infrastructure (www.reprap.org).

With regard to the RepRap project, in September 2006 an initial prototype of a RepRap printer printed a printer part for the first time. This part was then used to replace an already existing part of the prototype machine. In February 2008 the first RepRap version 1.0 was ready and was named “*Darwin*”, shown in figure 1.3. Its rapid prototyped parts (white, blue, and green) were made in a Stratasys Dimension commercial Rapid Prototiping machine. The cube of the machine has side lengths of about 500 mm.

Within two months it had printed its first end-user item – a clamp to hold an iPod in a Ford Fiesta automobile. By September 2009 at least 100 versions of the Darwin had been assembled across the world (Kentzer et al., 2011).

Figure 1.4 shows the first reproduced RepRap machine. All the rapid prototyped parts for the child machine on the right were made in PLA by the machine on the left, except for one grandchild part (a timing-belt tensioner) that the child machine made for itself. That grandchild part was the first part made by the child. It took about twenty minutes to make, and was finished at 14:00 hours on 29 May 2008 at Bath University in the UK. The child machine was within tolerance of the parent, and worked just as well. RepRap is thus a kinematic assisted self-replicating self-manufacturing machine. The design of the machine includes screw and other adjusters to allow a child machine to be set up to produce parts as accurately as its parent (in just the same way as conventional machine tools are adjusted). RepRap assisted replication is thus not subject to degeneracy (Jones et al., 2011).

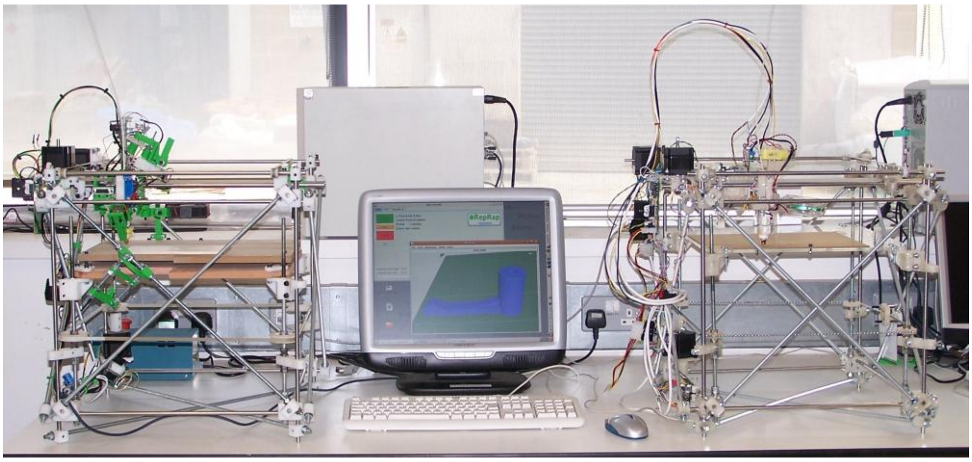

Figure 1.4 The first reproduced RepRap machine – parent (left) and child (right).

In October 2009 RepRap version 2 was released and named “*Mendel*”. Mendel works by melting plastic filament via a heated extruder head, which is then used to build up 3D objects. The plastic is deposited in layer by layer onto the printer bed until the 3D component has been built. Table 1 shows a comparison between *Darwin* and *Mendel*.

Table 1.1 A comparison of Darwin and Mendel RepRap (Jones et al., 2011)

	RepRap Version I “Darwin”	***RepRap Version II “Mendel”***
Cost of materials to build (€)	500	350
Percentage self-manufactured	48%	46%
Size (mm^3)	600(W)x520(D)x650(H)	500(W)x400(D)x360(H)
Weight (Kg)	14	7
Deposition rate (ml per hour)	15	15
Positioning Accuracy (mm)	0.1	0.1
Nozzle diameter (mm)	0.5	0.5
Volume of RP parts to build (ml)	1200	1110
Power supply (W)	12 V x 8 A	12 V x 5 A
Interface	USB/G-Codes	USB/G-Codes
Host computer	Linux, Windows or Mac	Linux, Windows or Mac

The designs of both machines allow their sizes and working volumes to be changed simply by cutting longer or shorter rods to make up the framework, so the values for both of those are nominal. However the percentage of the machine that it makes for itself has dropped slightly from Darwin to Mendel. The deposition rate of 15 ml per hour is the volume extruded by the extruder. In common with commercial fused-filament fabrication machines, RepRap does not usually build parts completely solid – there are some air inclusions. With RepRap the degree to which this happens is completely under the control of the user. It is possible to build parts very fast with a sparse honeycomb interior, or more slowly with a dense interior. Unlike commercial machines, RepRap also allows interiors to be built fullydense. As for the 0.5mm nozzle diameter was chosen as a compromise between ease of manufacture, speed of deposition, and fineness of feature resolution (Jones et al., 2011).

In August 2010 the third RepRap generation, a scaled down version of Mendel, named “*Huxley*” was released (Kentzer et al., 2011). After that, it was born “*Snappy”* an Open

Source RepRap 3D printer designed by RevarBat from July 2014 to December 2015. It is a true RepRap, using very few non-printed parts. This design needs no belts, pulleys, metal rails, and almost no screws outside of the motors or extruder hot-end. Snappy is an original design, created in OpenSCAD, in which so many individual design parameters can be altered to fit the end user's specific needs (www.reprap.org).

The RepRap community calls free open-source rapid prototyping machines that cannot make a significant fraction of their own parts, but that can make parts for RepRap machines, RepStraps (from bootstrap). Many private individuals have made RepStraps in order to allow themselves subsequently to make RepRaps. Two companies have been formed to make and to sell RepStraps using laser-cutting rather than rapid prototyping (Bits from Bytes in the UK, and MakerBot Industries LLC in the USA). Increasingly, people are using their RepRap machines to make sets of RepRap parts for other people, as the project plan intended. According to Jones et al. (2011) owing to the free distribution of the machine it is difficult to make an estimate of the number of RepRaps and RepStraps that there are in the world. However, the sale of electronics kits for the machine (which are also produced commercially) sets a lowerlimit of 2,000 machines in 2009. A RepRap printer can be acquired for approximate 550-710€ depending on the version, plastic printing availability, suppliers and additional factors. However, some people construct their own electronics rather than buying; 2,500 machines would seem to be a conservative estimate of the total population. Figure 1.5 shows a map showing the places where there are people who use or are building a RepRap. There are five companies in Europe that have joined the project (www.reprap.org)

Figure 1.5. Places in the world in which people are building or using a RepRap. (www.reprap.org)

1.2.4 The Fab@Home project

Almost a year after the birth of RepRap, the second open-source project in the field of 3D printing as well as the first printer multi-material has developed: his name is Fab@Home. Hod Lipson and Evan Malone were students of mechanical and aerospace engineering at Cornell University, and started the project in 2006. In less than a year the Fab@Home website received seventeen million visits and the project won awards such as the "*Popular Mechanics Breakthrought Award*" and the "*Rapid Prototyping Best Paper Award*" (www.makerbot.com). Fab@Home systems are, in essence, a 3-axis robotic gantry systems with interchangeable tool heads. The robotic nature of the Fab@Home naturally leverages itself to other forms of manufacturing aside from deposition.

Unlike RepRap, Fab@Home uses a production technique based on syringe pumps depositing material through their tips (the accuracy of the pistons of the syringes is of a microliter). Thanks to the use of syringes as deposition tools it is possible to use all materials which can potentially leak from the nozzle of the syringe. The materials used are: resins, silicone, hydrogel, edible materials such as cheese and chocolate, powdered stainless steel or powdered magnets impregnated in silicone.

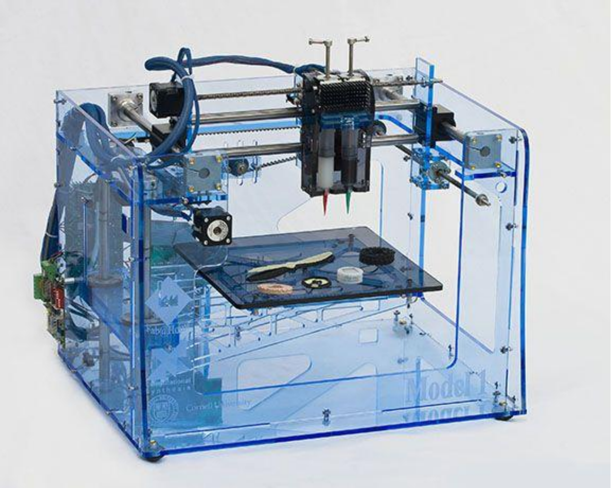

Figure 1.6 Fab@Home project: first 3D printer realized called "Model 1".

In 2006 it was presented at the conference "Solid Freeform Fabrication " the first printer produced, Model 1 (Figure 1.6), with only two syringes.

The next printer, the Model 2, behaved of important improvements as greater ease of assembly and a lower number of parts used. The most advanced Model 3 is available to the public from February 2013.

There are many contributors and experts who day by day make improvements to the existing technology: canisters have been developed with the ability to contain a greater amount of material and an ice deposition tool.

The Fab@Home project is currently working on the Fab@School project. The Fab@School project aims to revolutionize Science, Technology, Engineering and Mathematics (STEM) education by introducing engineering into the classroom to integrate science technology and math education into a tangible activity. The project uses digital fabrication technologies to enable students and teachers to make abstract notions in mathematics tangible. The program will begin in the second grade and build up towards high school (Lipton et al., 2011). Table 1.2 shows similarities and differences between the 3D printing produced by the RepRap project and the one produced by the Fab@Home project.

Table 1.2 A comparison between RepRap and Fab@Home 3D printers

Features	RepRap	Fab@Home
Licence	Open source	Open source
Target	Making an economic printer which produces objects and is able to reproduce its parts from itself	Making an economic multi material printer
Interface	Technical skills required	User friendly
Printing system	Fused Filament Fabrication (FFF)	syringe system
Compatible materials	Acrilonitrile-Butadiene-Stirene (ABS), Polylactic Acid (PLA), High-Density Polyethylene (HDPE)	Liquids, gels, pastes, metals in dust, food etc.
Cost of the 3D printing	$ 600-1000	$ 1900-2000

1.3 AM today: 3D printing in the digitalization of manufacturing

The need for reduced development time together with the growing demand for more customer-oriented product variants have led to the next generation of Information Technology (IT) systems in manufacturing (Chryssolouris et al., 2009). The possibility of controlling through a computer the equipment for the Manufacturing production was a reality as early as the 80s, when the first numerical control equipment for milling, turning, drilling, etc. were introduced, according to the logic of "subtraction from full ", typical of traditional manufacturing (Beltrametti and Gasparre, 2015). Another example of the introduction of IT, in the manufacturing world, is the concept of computer-integrated manufacturing (CIM). This concept was introduced in the late 1980s, favouring the enhancement of performance, efficiency, operational flexibility, product quality, responsive behaviour to market differentiations, and time to market (Cagliano and Spina, 2003). Almost simultaneously the first 3D printers, which were used to realize plastic prototypes, developed. Unlike numerical control machines, for a few decades this technology had important applications in the process of development of new products but its diffusion was relatively limited and it started to be used into the final production only about ten years later. As in the case of numeric control machines and robot, 3D printers manufacturing can be called "digital" since the designer must be able to use a software - the computer Aided Design (CAD)- which gives a virtual representation of the object that has to be produced starting from its geometric parameters that are transmitted from a computer to a machine that realizes it (Beltrametti and Gasparre, 2015). The CAD systems have become indispensable to today's manufacturing firms, because of their strong integration with advanced manufacturing techniques such as 3D printing. CAD models are often considered sufficient for the production of the parts, since they can be used for generating the code required to drive the machines for the production of the part. Rapid prototyping is just an example of such a technology (Chryssolouris et al., 2009).

Over the past few decades, the extensive use of IT in manufacturing has allowed these technologies to reach the stage of maturity.

In this context, Digital Manufacturing represents the natural evolution of the manufacture: 3D Printing, Generative Manufacturing, e-Manufacturing, Constructive Manufacturing, Additive Layer Manufacturing, Direct Digital Manufacture, Freeform Fabrication, Rapid Manufacturing are just some of the terms that are used to describe "features" or "impacts" of digital technologies and the technologies of 3D printing on the production systems. Thus it was born the need to arrive at a clear definition of business models that exploit this set of new technologies. In this sense, the definition of *Digital Manufacturing* is justified by the need to describe an already extensive system, not necessarily tied to a specific technology, which in the next few years promises to evolve further in its qualitative and quantitative meaning. In this sense, Digital Manufacturing expresses well the renewal of the manufacturing system using digital technologies and 3D printing technologies, that are used in an integrated way in order to reach product innovation, testing, prototyping and the production of goods, allowing also the optimization of the manufacturing, marketing and distribution processes in a virtual environment (Pwc and Confartigianato imprese, 2015). It should be stressed that the 3D printing is just one of the technologies related to Digital Manufacturing; numerical control machines (CNC) and laser cutter technologies are digital technologies as equals, although already widely used and no longer directly related to the concept of innovativeness and renewal that it wanted to be described. Moreover CNC technologies and laser cutter ones are based on the concept of "subtractive manufacturing", and are aligned with the idea of classical manufacturing, that is to say from matter, by processes such as milling, pressing, cutting and others, is obtained the object; these technologies respect the sequential structure of production processes and have already spread so capillary in the economic system. On the contrary the 3D scanner is a useful tool to develop a project from an existing object. In this concept lies the big difference over other technologies: scanners 3D impact on the design, while numerical control machines, laser cutters and 3D printers provide alternative to series production. It is true that for many, significant, points of view additive technologies represent a discontinuity in the digitization process of manufacturing. 3D printers, in fact, are more flexible tools than traditional manufacturing technologies and allow to overcome many of the constructional limitations related to the geometric constraints imposed by other technologies. We talk about "free-form", a potential that enhances the creativity of the designers, who can imagine (and create) new geometries for optimize performance and the aesthetics of the objects. It follows that the 3D printing can make unnecessary some welding and many assembly tasks.

Note, however, that the 3D printing today entails very strict constraints considering the object dimensions (about one cubic meter for processing plastic and half a cubic meter for metal ones) (Beltrametti and Gasparre, 2015).

In conclusion it can be said that the word "Digital" connotes a wide range of Information Technologies and phenomena caused or affected by these technologies. The list can be shorter or longer, but experts, universities and consulting firms tend to converge in considering in it Mobile, Social Media Collaboration, Cloud Computing, Big Data and Internet of Things (IoT), along with the innovative 3D technology of AM (Pwc and Confartigianato imprese, 2015).

1.3.1 The main Additive Manufacturing production techniques

AM begins with CAD modelling software that takes a series of digital images of a design or object and sends descriptions of them to a professional-grade industrial machine. The machine uses the descriptions as blueprints to create the item by adding material layer-upon-layer. Layers, which are measured in microns, are added by hundreds or thousands until a three-dimensional object emerges. Raw materials may be in the form of a liquid, powder, or sheet and are typically plastics and other polymers[2], metals, or ceramics (Ford,

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[2] Polymer is a chemical compound made of small molecules that are arranged in a simple repeating structure to form a larger molecule. Examples of polymers often used in additive manufacturing are polycarbonate and high-density polyethylene. (Merriam-Webster Dictionary *http://www.merriam-webster.com/dictionary/polymer*).

2014). CAD technologies are available for assisting in the design of large buildings and of nano-scale microprocessors. CAD technology holds within it the knowledge associated with a particular type of product, including geometric, electrical, thermal, dynamic, and static behaviour. AM technology primarily makes use of the output from mechanical engineering, 3D Solid Modelling CAD software. It is important to understand that this is only a branch of a much larger set of CAD systems and, therefore, not all CAD systems will produce output suitable for layer-based AM technology. AM technology focuses on reproducing geometric form; and so the better CAD systems to use are those that produce such forms in the most precise and effective way (Gibson et al., 2010).

CAD technology has rapidly improved along the following lines (Gibson et al., 2010):

- *Realism*: with lighting and shading effects, ray tracing and other photorealistic imaging techniques, it is becoming possible to generate images of the CAD models that are difficult to distinguish from actual photographs. In some ways, this reduces the requirements on AM models for visualization purposes.
- *Usability and user interface*: early CAD software required the input of text based instructions through a dialog box. Development of Windows-based graphical user interfaces (GUIs) has led to graphics-based dialogs and even direct manipulation of models within virtual 3D environments. Instructions are issued through the use of drop-down menu systems and context-related commands. To suit different user preferences and styles, it is often possible to execute the same instruction in different ways.
- *Engineering content*: since CAD is almost an essential part of a modern engineer's training, it is vital that the software includes as much engineering content as possible. With solid modeling CAD it is possible to calculate the volumes and masses of models, investigate fits and clearances according to tolerance variations, and to export files with mesh data for Finite Element Analysis (FEA)[3]. FEA is often even possible without having to leave the CAD system.
- *Speed:* CAD systems are constantly being optimized in various ways, mainly by exploiting the hardware developments of computers.

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[3] **Finite Element Analysis (FEA)** is the modelling of products and systems in a virtual environment, for the purpose of finding and solving potential (or existing) structural or performance issues. FEA is the practical application of the finite element method (FEM), which is used by engineers and scientist to mathematically model and numerically solve very complex structural, fluid, and multiphysics problems. FEA software can be utilized in a wide range of industries, but is most commonly used in the aeronautical, biomechanical and automotive industries (source: www.plm.automation.siemens.com).

- *Accuracy*: if high tolerances are expected for a design then it is important that calculations are precise. High precision can make heavy demands on processing time and memory.
- *Complexity*: all of the above characteristics can lead to extremely complex systems. It is a challenge to software vendors to incorporate these features without making them unwieldy and unworkable.

As for the classification of AM technologies, there are numerous ways to classify these technologies. A popular approach is to classify according to baseline technology, like whether the process uses lasers, printer technology, extrusion technology, etc. (Kruth et l., 1998; Burns, 1993). Another approach is to collect processes together according to the type of raw material input (Chua and Leong, 1998). The problem with these classification methods is that some processes get lumped together in what seems to be odd combinations (like Selective Laser Sintering being grouped together with 3D Printing) or that some processes that may appear to produce similar results end up being separated (like Stereolithography and Objet). It is probably inappropriate, therefore, to use a single classification approach (Gibson et al., 2010).

The use of a technology rather than another is a choice to be made according to a number of very varied parameters: speed of production and the final cost of the piece, investment required for the printer (in case it is decided to buy it), mechanical resistance and finish surface desired. Classifying these technologies for 3D printing based on the materials used in the process and the way they are treated, in general they can be divided into three categories, based on the characteristics of consistency of the raw material: powder, liquid or solid (Advanced Manufacturing Office, 2012):

- the category of *powder* printers belong to those based on sintering or melting of powders (Selective Laser Sintering - SLS, Selective Laser Melting - SLM, Direct Metal Laser Sintering - DMLS, Electron Beam Melting - EBM) or deposition of chemically bonded on a homogeneous powder bed (3D Printing or binder jetting - 3DP);
- on the front of the *liquid* material technologies there are those which are based on curing by UV lamps (Stereolithography - SLA, Digital Light Processing - DLP) and secondly those who print with a jet (Ink Jet Modelling - IJM, Multi Jet Modelling - MJM);
- finally, the machines for 3D printing employing starting materials in the *solid* state (considering also filament and paste) are divided in models employing a stratified

based on sizing technique of sheets (Laminated Object Manufacturing - LOM), or extrusion of a solid material or semi solid (Fused Deposition Modelling - FDM).

The American Society for Testing Materials (ASTM)[4], in particular the International Committee F42 on AM Technologies, divides the AM technologies in seven families of processes (www.astm.org; Wong and Hernandez 2012; Munoz et al. 2013):

1. *Vat Photopolymerization*: an AM process in which a photopolymer sensitive to UV light, localized inside a tub, is solidified by a ultraviolet light source, layer by layer. The most widespread technology using this principle of operation is Stereolithography (SLA), the patented process from 3D System in 1986 which marked the beginning of rapid prototyping. The objects produced by this technology are characterized by an high resolution (often each layer is usually from 0.05 to 0.15 millimeters) and a very smooth surface finish. A variant of SLA is the Digital Light Processing (DLP), developed by the American company Texas Instruments. The fundamental difference with respect to the Stereolithography resides in the projection of UV light, operated not by a laser but by a projector.
2. *Material Jetting*: the principle of operation takes advantage of a print head similar to those of the two-dimensional Inkjet printers. The only substantial difference lies in the material with which the head is fed: instead of ink, wax acrylic resins or photopolymers are released. The main technologies that are based on this principle are called Multi Jet Modelling (MJM) and PolyJet. The MJM printers deposited wax, and acrylic resins, while the PolyJet printers fitted to the print head with a UV light source, able to activate and solidify a photopolymer previously deposited. These machines are suitable for office use because they are less invasive as regards noise and bad smell. These parts are made with a high aesthetic level and, in the case of some specific photopolymers and resins, possess medium-high mechanical properties.
3. *Binder Jetting*: even in this case it is provided the use of a print head, with a difference, that is to say it is not released material of construction but a chemical binder capable of combining in a progressive manner the individual grains of a homogeneous bed of powder. The materials used by this method are multiple:

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[4] The American Society for Testing and Materials (ASTM) is the American standardization body, founded June 16, 1898, in order to make companies of steel and rail transport cooperate together. Today it is among the major technical contributors of International Organization for Standardization (ISO) , it has a leadership role in the definition of materials and test methods in almost all industries. It has contributed substantially to define the terminology od Additive Manufacturing, beginning from the term itself that today identifies this group of technological processes.

plastic powders, composites and metal powders. Pieces made with this technology are generally very porous and quite fragile. However they are much cheaper compared to other printing technologies, and this makes them particularly suitable to be used as aesthetic models for demonstration purposes.

4. *Powder Bed Fusion*: it is an AM process which uses thermal energy to melt and solidify a region of a powder bed, layer by layer. This principle of operation is exploited by the technologies of Selective Laser Sintering (SLS), Selective Laser Melting (SLM) and Electron Beam Melting (EBM). While the SLS is usable with different families of materials, such as polymers, composite materials, ceramics and some metal alloys, SLM and EBM are usable with pure metal powders, not additivated. Some examples are steels and stainless steels, titanium, aluminium and chrome-cobalt alloys. A field of application of these technologies concerns the construction of orthopaedic implants: the biocompatibility of the ceramic and of the used metal (especially titanium) and the slight porosity of the pieces made, makes them an ideal solution for the graft within the Human Body.
5. *Material Extrusion*: the operating principle exploited by this technology is the extrusion. A malleable material in a semi-solid state is deposited, through the nozzle of an extruder, on a layer of underlying material deposited previously and already solidified. The deposition and the progressive hardening of the layers allows the fabrication of the object from the bottom upwards. The Fused Deposition Modelling (FDM) is the most widely used AM process that takes advantage of this principle. This is the 3D printing technology that has had the most widespread distribution, and it can also be of interest to an audience of people that are not necessarily linked to a professional context. Thanks to the high strength and high thermal stability of materials such as special resins, it is possible to build products and advanced equipment for the medical, automotive, aerospace and food sectors. In view of excellent chemical and mechanical properties, the finish surface of the products made with this technology appears rough, as the layers of filament are evident. The FDM printer can be very costly in the case of industrial machines; however it can also be very affordable if you use a "domestic" printer, which has a cost between 700 and 2000 euro.
6. *Sheet Lamination:* it is a process by which the material sheets are properly cut, stacked and united. It is a technique among the least popular. The sheets of material can be of various types: paper, plastic, cellulose, metals and reinforced composite

materials. Also the fixing agents are different: glue for the paper, glue or heat for the plastic materials, welding or bolts for metallic materials. One of the advantages of this technology is the ability to build objects of large dimensions, more of a large part of the current 3D printing technologies. However, the subsequent treatment is challenging because the extraction of the excess material is complex.

7. *Direct Energy Deposition:* a typical Direct Energy Deposition (DED) machine consists of a nozzle mounted on a multi axis arm, which deposits melted material onto the specified surface, where it solidifies. The process is similar in principle to material extrusion, but the nozzle can move in multiple directions and is not fixed to a specific axis. The material, is melted upon deposition with a laser or electron beam. The process can be used with polymers, ceramics but is typically used with metals, in the form of either powder or wire. The DED process can be used for prototype or production tooling in a variety of industrial applications, including direct metal prototypes, surface modification and coatings, aerospace and aircraft component repair.

Table 1.3 summarizes the Seven AM Process Categories defined by the American Society for Testing Materials (ASTM).

Table 1.3 The Seven AM Process Categories by ASTM (F42) (Source Munoz et al., 2013).

Classification	*Technology*	*Description*	*Materials*	*Developers*
VAT Photopolymerization	Stereolitography Digital Light Processing	*Builds part by using lights to selectively cure layers of material in a vat of photopolymer.*	Photoplymer Ceramic	3D systems (US) EnvisionTEC (Germany) DWS srl (Italy) Lithoz (Austria)
Material Jetting	Polijet Ink-jetting Thermojet	*Builds part by depositing small doroplets of build material, which are then cured by exposure to light.*	Photopolymer Wax	Stratasys (US) LUXeXcel (Netherlands) 3D systems (US)
Binder Jetting	3D printing Ink-jetting	*Creates objects by depositing a binding agent to join powdered material.*	Metal Polymer Ceramic	ExOne (US) VoxelJet (Germany) 3D systems
Powder Bed Fusion	Direct Metal Laser Sintering Selective Laser Melting Electro Beam Melting Selective Laser Sintering	*Creates objects by using thermal energy to fuse regions of a powder bed.*	Metal Polymer Ceramic	EOS (Germany) Renishaw (UK) Phenix Systems (France) Matsuura Machineri (Japan) ARCAM (Sweden) 3D system (US)

Material Extrusion	Fused Deposition Modelling	*Creates objects by dispensing through a nozzle to build layers.*	Polymer	Stratasys (US) Delta Micro Factory (China) 3D systems (US)
Sheet Lamination	Ultrasonic Consolidation Laminated Object Manufacture	*Builds part by trimming sheets of material and binding them together in layers.*	Hybrids Ceramic Metallic	Fabrisonic (US) CAM-LEM (US)
Direct Energy Deposition	Direct Metal Deposition Laser Deposition Laser Consolidation Electro Beam C^Direct Melting	*Builds part by using focused thermal energy to fuse materials as they are deposited on a substrate.*	Metal: powder and wire	DM3D (US) Irepa laser (France) Trumpf (Germany) Sciaky (US)

1.3.2 3D printing materials

Earlier AM technologies were built around materials that were already available and that had been developed to suit other processes. However, the AM processes are somewhat unique and these original materials were far from ideal for these new applications. For example powders used in laser melting processes degraded quickly within the machine and many of the materials used resulted in parts that were quite weak. As we came to understand the technology better, materials were developed specifically to suit AM processes. Materials have been tuned to suit more closely the operating parameters of the different processes and to provide better output parts. As a result, parts are now much more accurate, stronger, and longer lasting and it is even possible to process metals with some AM technologies. In turn, these new materials have resulted in the processes being tuned to produce higher temperature materials, smaller feature sizes, and faster throughput (Gibson et al., 2010).

Moreover usually, when objects are formed in moulds, they are generally formed in one homogeneous material. Even in the case of an overmoulded component, where there can be two or more homogeneous materials in one finished part, there is a definitive boundary between one material and the other. With some of the AM processes there is the potential to mix and grade materials in any combination that is desired, thus enabling materials with certain properties to be deposited where they are needed (Anon 2001; Jacobs 2002).

The overmoulding technique is a classic example of how design can be influenced by the availability of a manufacturing technique. Overmoulding allows designers, within limits, to produce parts that have added functionality and enhanced design. Indeed, the design of overmoulded components very often incorporates the different material combinations to accentuate the design to the extent that designers are able to exploit the delineation of the different materials used to produce design features as well as extra functionality (Hague et al., 2003).

As for the costs of the materials used for AM, analyses (Hopkinson and Dickens 2003; Atzeni et al. 2010) place material cost at around 30% of the unit cost for AM systems compared with an almost inconsequential amount (0.2–2.7%) for traditional methods. Differences in this regard are due largely to the extreme cost differentials that exist in the market between AM and more traditional material feedstock. According to industry analyses, thermoplastics and photopolymers for AM applications can cost $175–250 per kg, while those used for IM cost just $2–3 per kg; similarly, the steel powders used in AM applications are 100 times costlier than commercial grade. (Wohlers Associates 2013; Deloitte, 2014b).

Material recyclability drives cost as well. Assumptions of zero waste in AM applications seem inappropriate. Consensus on the amount of unprocessed material that can be recycled is hard to find. Some cite zero reuse for highly sensitive aerospace applications, while others suggest near-total reuse is possible (Allen 2006; Telenko and Seepersad 2011). Material recycle rates vary by process, system, and application and should be carefully evaluated as part of the business case (Hopkinson and Dickens 2003).

We present here below which are the main materials used for the Additive Manufacturing.

Thermoplastics

Thermoplastics, or polymers, are amongst the cheapest materials that can be used in AM and are the typical content for commercial 3D printers being sold for home use.

The main thermoplastics being used in Additive Manufacturing are (www.spilasers.com; www.sharemind.eu):

- Acrylonitile Butadiene Styrene (ABS): is the type of polymer which is the most widespread and can most easily be described as the type of plastic used for making Lego bricks. The ABS is lightweight, durable, and it is since a long time used in industry for the production of pipes, musical instruments, golf clubs, parts of car bodies and Lego bricks. The ABS is not biodegradable. The patterns printed in ABS are more or less opaque, resistant, relatively flexible, workable with subsequent mechanical processing (eg. Sanding, drilling, threading) and can be quite easily glued. The ABS can be painted, it can be filled with plaster etc. It is corroded by nail varnish remover, which is able to polish it and melt. ABS is fairly resistant to temperature, and can be printed at temperatures between 225 and 280 ° C.

- Polylactic Acid (PLA): is a crystalline polymer which is obtained by the fermentation of sugars, molasses (obtained for example from sugar cane, corn, potatoes, etc.) and whey, or alternatively the Bacillus coagulans; PLA tends to be a biodegradable material, obtainable from renewable resources. The models produced in PLA have a shiny, glassy appearance, highlighting layers and imperfections. They are poorly machined with mechanical machining; they are not easily paintable, and do not stick together. They resist only a little at high temperatures: hot tap water or exposure to sunlight deform them easily. The PLA is printed at a temperature comprised between 185 and 215 ° C.
- Polyvinyl Alcohol (PVA): is used as a material to create supports within the Additive Manufacturing process, and is entirely dissolvable. The PVA is used at a temperature of about 190 ° C, it is soluble in water, and can be used to print support materials in complex 3D prints. These supports can be removed once the final design is complete and being soluble can just be washed away.
- Polycarbonate (PC): is a thermoplastic polymer with good heat resistance and impact resistance. Unlike the plexi-glass, with which it is often confused, it can be folded and also formed, without showing cracks or particular deformations. The glass transition temperature is 150 ° C, while at 300 ° C, the fusion is manifested. Polycarbonate deforms very easily and to a greater extent compared to ABS and PLA.

Resins and ceramics

Also the resins can be used as materials for 3D printers, but the possibility of their use is limited by the possible need for support of the objects during the printing process.

The resin is a viscous material capable of cold or hot-hardening. Printers that use this material are more expensive, but able to provide more sophisticated results. The resin-based printer makes it possible to print very thin structures, making it easier to cut the structural supports if necessary. Considering ceramics materials, as normal ceramic, the use of these materials in 3D printing, such as aluminosilicates, allows food use and is waterproof: objects created with this material can therefore be used with food and drinks. This 3D printed ceramic is resistant to heat up to 500° C and is recyclable. Due to the process used, the glazing adds a small surface thickness that could change the appearance of some details of the object or be distributed unevenly (www.fabbricafuturo.it).

Metals

The variety of materials available for metal AM systems is continuously expanding. Common materials used are stainless steels, aluminium, nickel, cobalt-chrome and titanium alloys, with a number of machine manufacturers offering their own materials.

The common specifications of metal powders suitable for AM are the spherical geometry of the particles resulting from the gas atomisation and a particle size distribution according to the layer thickness, usually between 10-50 µm.

Material properties such as tensile strength, hardness and elongation, are important and often used as reference points for the decision about the right material (Frazier 2014; www.metal-am.com).

Glass

Designer and researcher Neri Oxman and her Mediated Matter group at Massachusetts Institute of Technology (MIT) Media Lab have developed a technique for 3D-printing molten glass. The group, based built an AM machine that extrudes molten glass - a process the team believes could be used to create architectural components and even entire building facades.

In the project, titled “Glass 3D printing”, Oxman's team have used the technique to produce a range of vases and bowls (Figure 1.7) but Oxman said that the new glass-printing technology could be used at an architectural scale.

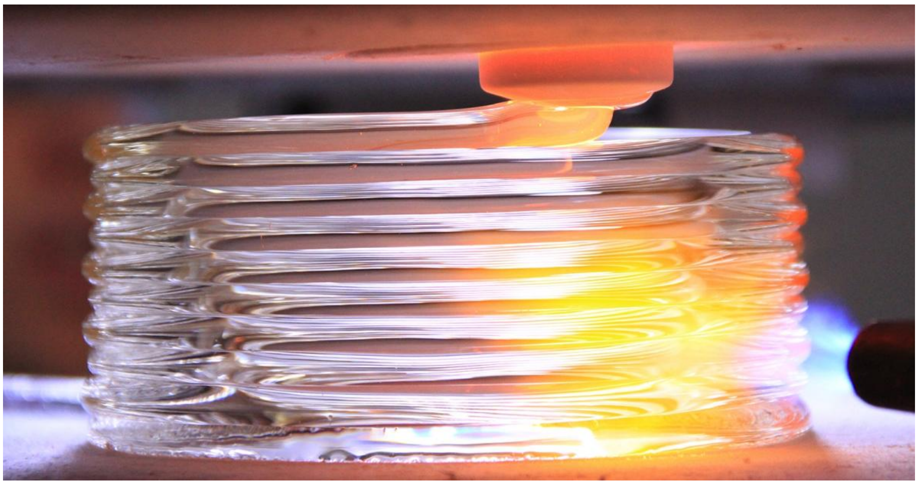

Figure 1.7 A 3D printer which print glass

"In this project we wanted to explore the possibility of creating that are at

once structurally sound, environmentally informed and have the potential to contain and flow media through them," she said, adding that glass could one day be printed to create *"a single transparent building skin"*. The Glass 3D printing printer has two insulated chambers, one above the other. The upper chamber serves as kiln, keeping molten glass heated to 1,900 degrees Fahrenheit (1,000 degrees Celsius).

This acts as the print cartridge, moving laterally to deposit a continuous stream of liquid glass into the lower chamber, that acts as the printer bed and anneals, or gradually cools, the glass as it builds up layer by layer. Annealing prevents the cooled glass from shattering when subjected to temperature change or impact (Klein et al., 2015).

Food

Among all the possible applications for 3D printing, food materials have been taken into account (Lipton et al., 2010), and even The National Aeronautics and Space Administration (NASA)[5] has decided to invest in creating a prototype that can print food in space. NASA and a Texas company are exploring the possibility of using a "3D printer" on deep space missions in a way where the "D" would stand for dining. NASA has awarded a Small Business Innovation Research (SBIR) Phase I contract to Systems and Materials Research Consultancy of Austin, Texas, to study the feasibility of using Additive Manufacturing for making food in space. Systems and Materials Research Consultancy will conduct a study for the development of a 3D printed food system for long duration space missions. As NASA ventures farther into space, the agency will need to make improvements in life support systems, including how to feed the crew during those long deep space missions. NASA's Advanced Food Technology program is interested in developing methods that will provide food to meet safety, acceptability, variety, and nutritional stability requirements for long exploration missions, while using the least amount of spacecraft resources and crew time. NASA is funding phase I of this project with six-month $125,000 study on 3D printing of foods to determine the capability of this technology to enable nutrient stability and provide a variety of foods from shelf stable ingredients (www.nasa.gov).

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[5] The National Aeronautics and Space Administration (NASA), since its inception in 1958, has accomplished many great scientific and technological feats in air and space. NASA technology also has been adapted for many nonaerospace uses by the private sector. NASA remains a leading force in scientific research and in stimulating public interest in aerospace exploration, as well as science and technology in general (www.nasa.gov).

Also the Columbia University is working on a new 3D food printer that can produce and cook a variety of dishes from frozen base ingredients. The team at Columbia University have opted for a technique that uses frozen ingredients in cartridges that they can use to print the food. There is obviously a second step, though, and the researchers are now looking for a way to cook the food, consistently, in a desktop format. The printer is capable of producing the gel-like substances we’ve seen from other manufacturers. So this machine will not try to replace traditional foods and will instead offer nutrient rich gel solutions that can then be cooked. It obviously comes with its own unique texture that the public might have to get used to (Hall, 2016).

Medical and Biomedical materials

AM processes have started to be used in the medical field: Bio-ink can be created from stem cells, which are then printed and layered like other materials, forming new tissue. Exciting results have been created from this technology, with bladders, blood vessels and kidney parts all having successfully been “printed”. It’s not just soft tissue that can be created in this way; new bone has successfully been grown too. By printing out a compound of a material made from calcium phosphate, silicon and zinc and combining this with bone cells, new bone growth was stimulated. The printed material was later dissolved, leaving just the new bone (Bartolo et al. 2012; Guo and Leu 2013).

Electrospinning is one of several fabrication methods that have been conventionally used for bone scaffold materials and is capable of fabricating bone replicate fibers that are submicrometer to nanometer in diameter. This fabrication technique relies on a high voltage power supply to electrospray a polymer feed solution containing nanoparticles of bone substitute from a nozzle onto a conductive rotating drum. Limitations with this method include the utilization of a high voltage (often >20 kV) as well as lack of control over scaffold geometry and porosity as is encountered with other traditional methods (Yeong et al., 2004; Wutticharoenmongkol et al., 2006; Gross et al., 2014).

Wood

The development of new materials, such as wood, has a good potential demand. This is because wood based materials are widely used in art, furniture prototypes and architecture mock up applications. Some furniture prototypes and architecture mock-ups required beauty and aesthetic value criteria. The beauty and aesthetic value could be presented in form of structure shape and appearance. Meanwhile, some of beauty and aesthetic criteria could be obtained through the usage of wood based material. The step in producing architecture mock up and furniture product is similar to that of industrial design and product manufacturing. Most of the product required CAD drawing development including 3D modelling. The 3D printing new material development process requires to undergo several studies such as powder formulation, binder selection, liquid binder formulation, powder binder interaction, printing process parameters, and specification of post-processing procedures (Utela, 2008). In recent years studies (Wahab et al. 2009; Saidin Wahab et al., 2013) started focusing on wood powders, which were taken from powder collector which was obtained from sanding process. In general, all wood material in the factory was chemically treated before it can be used for furniture, doors, wood tile and others. Therefore, the powder from the sanding process can be used directly without further treatment. This work has demonstrated that the wood powder is viable as a new 3D printing material and that the surface quality also can be further improved by having finer powder in the composition. Moreover in order to develop the sustainable materials of the future, the Swedish research institute *Innventia* has launched in 2015 an interdisciplinary consortium known as *"Would wood*" to develop integrated material and production concepts for the large-scale Additive Manufacturing of advanced wood-based structures. The project involves an innovative wood-based material for 3D printing as well as its manufacturing technique, which is aimed at producing furniture, structural elements, and in the long-term, large-scale construction projects for smart cities (http://www.3ders.org). The *Would Wood* project is made up of an interdisciplinary group of businesses, colleges, students, designers and architects. The project is looking to research and develop the sustainable materials and manufacturing processes of the future.

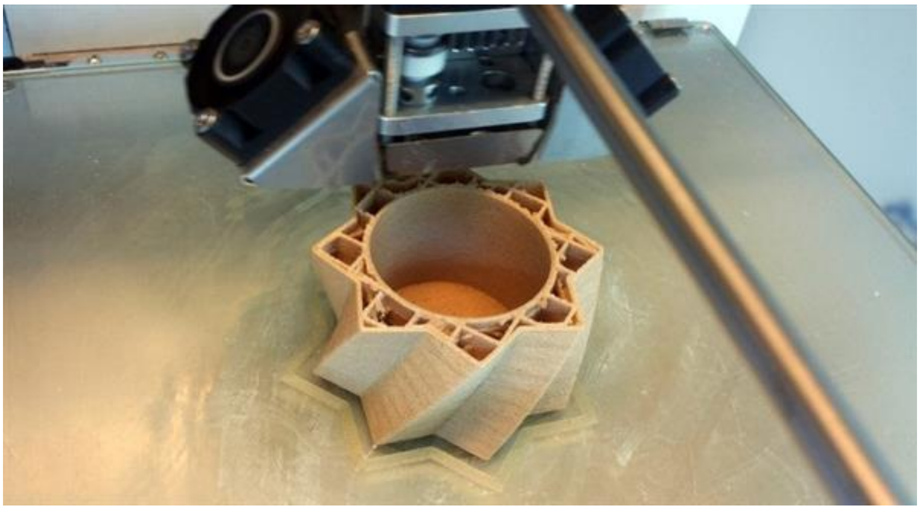

Figure 1.8 3D printing working on wood-materials

Their primary goal is to start by developing new 3D printing technologies and wood-based materials capable of manufacturing furnishings and small-scale structural elements.

However, they envision longer-term goals that will include scaling up their research to produce medium- and large-scale 3D printed wood structures and construction projects that can be used to make future more sustainable and eco-friendly cities (https://3dprint.com).

1.3.3 Fields of application for 3D printing

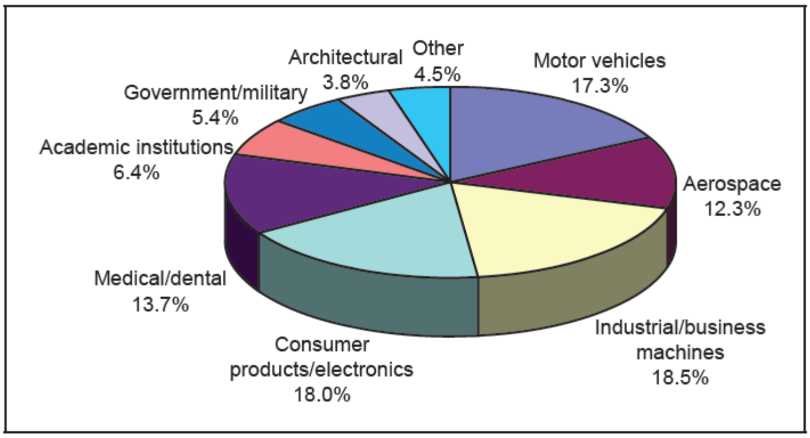

Figure 1.9 Industries served by AM manufacturers and service providers

The evolution of 3D printing technologies and the consequent increase of materials available have greatly expanded the range of product applications and process solutions. Considering the fields of application for Additive Manufacturing, Wohlers Associates conducted a survey of twenty-nine manufacturers of professional-grade, 125 industrial AM systems (those that sell 126 for $5k or more) and 82 service providers worldwide for their 2014 report on AM (Wohlers Report, 2014).The survey asked each company to indicate which industries they serve and the approximate revenues (as a percentage) that they receive from each. Figure 1.9 shows the results. The "Other" category includes a wide range of industries, such as oil and gas, non-consumer sporting goods, commercial marine products, and various other industries that do not fit into named categories.

To date, the possible uses of this technology are many and range from the production of highly specialized mechanical components to the printing of personal household. Here we present the major fields of application.

Prototyping and tooling

The most widely use of 3D printing, especially in Italy, is for the production of prototypes. This technology allows for fast and low-cost operations to clarify ambiguities in the design drawings, test the functionality of some components, to make changes to the project and develop it further in order to reach the optimal solution (Pricewaterhouse and Confartigianato imprese varese, 2015). For example filming for the movie "Skyfall" (Mendes, 2012) it has been made use of copies of the Aston Martin of the protagonist printed with the Binder jetting technology. The models were obtained by assembling 18 shares, then painted and chrome plated so as to obtain replicas perfectly identical to the original, but with the inclusion of the damage required by the script, such as some bullet holes (www.dailymail.co.uk).

As for tooling today, the development and manufacturing of tooling is one of the most expensive and time consuming steps within any manufacturing process. This is mainly due to complex geometries of final parts that require high accuracy and reliability, low surface roughness, and strong mechanical properties. Furthermore, tooling strongly depends on its further application, as different applications require different materials, part volume, size etc. Within recent years, more and more companies have identified AM to be a promising technology to save time and money in tooling. The 3D printing can be used in two different ways for the production of tools and utensils; the first is an indirect approach that involves the construction of molds and dies with various materials (rubber, wax, plastic, metals and others) acts in the manufacture of components or the product itself. The second use consists in the use of Additive Manufacture for the direct production of tools or product components.

Architectural Modeling

Creating an architectural model can be very difficult for architects. Architects usually build their models with hand techniques, but when complex models are on their minds making a physical model can be a very hard task. Modeling is very important for the architects to study the models and their functionality. They are also needed for architects to explain them to their customers and convince them to make the project a reality. Additive Manufacturing technologies can provide architects a very powerful tool for their business, by being able to

create a physical model faster without worrying about the complexity of their design. It also achieves a better resolution than other processes used in architecture. Architects work with CAD software, so there is no need for them to adapt to anything because file used for 3D printing is created from a CAD file. Stereolithography is a process very suitable for the architectural modeling because of the materials used and the printing resolution (Semetay, 2007; Rengier et al., 2010; Wong and Hernandez, 2012).

The construction sector

A sector close to that of architecture is that of the construction, in which there are interesting developments such as the construction in situ of dwellings, the introduction of finishes and structural elements printed with special materials, such as quick-drying cement, glass fibers, wet clay, sandstone powder and steel (Pricewaterhouse and Confartigianato imprese varese, 2015). In Netherland in 2014 it has been developed a project called “"3D Printed Canal House" that expect the construction of the first 3D printed house in the world. The house will have thirteen rooms that will be built piece by piece through a huge 3D printer assembled at the construction site. The idea is of a study of Dutch architecture, called DUS. The 3D printer has been created in collaboration with Ultimaker, a Dutch company specialized in 3D printing, and it can create objects of the maximum size of 2 meters wide and 3.5 meters high. It has been estimated that between labor and materials it will spend about a third less than with traditional methods. Moreover the fact of being able to build everything on site also means breaking down pollution and traffic. Finally, the plastic that is used is fully recyclable (100%); it is a real zero km building project (Pennacchioni, 2014).

Medical applications

Additive Manufacturing printing technologies have vast applications in the medical world. They are transforming the practice of medicine through the possibilities of making rapid prototypes and very high quality bone transplants and models of damaged bone of the patients for analysis. Additive Manufacturing printing methods permit to scan and build a physical model of defective bones from patients and give doctors a better idea of what to expect and plan better the procedure, this will save cost and time and help achieve a better result (James et. al, 1998). Bone transplants now can be done by printing them and Additive Manufacturing methods make it possible to have a transplant that is practically identical to the original. Because of the limitless form or shape of what could be built, doctors have the option to create a porous-controlled material that will permit osteoconductivity or to create a precise metal transplant identical to the original depending on the bone to be replaced (Makovec, 2010; Fielding et al., 2012). Additive Manufacturing is a very good tool also for dentists because they can easily build a plaster model of a patient’s mouth or replace the teeth, which have a unique form with process like stereolithography, selective laser sintering and electron beam melting (Hollister, 2005; Van Noort, 2012).

Aerospace applications

Despite current limitations, particularly with materials and structural integrity, aerospace companies are exploring 3D printing for manufacturing various parts of their products. Boeing has already used the technology to manufacture interior pieces of airplanes while NASA has used it to build rocket engines and parts for satellites. Companies in the sector are actively investing in the technology either by purchasing companies, like GE Aviation did when it acquired Morris Technologies, an engineering firm specializing in advanced fabrication techniques for jet engine production; or investing in partnerships with research centres, like Pratt & Whitney[6] which invested millions in an advanced Additive Manufacturing centre in collaboration with the University of Connecticut (PricewaterhouseCoopers, 2013).

Aerospace is also one of the most research-intensive sectors using 3D printing. It has used the

technology to build demonstration units, used by governments to evaluate functionality and hull design concepts. Research also includes developing complex parts, such as satellites parts or components of NASA’s rovers, including flame-retardant vents and housings, camera mounts and large pod doors (Munoz et al., 2013). In 2013, Airbus, a leading aircraft manufacturer, announced plans for an airplane that will include 3D printed components that are significantly lighter but as strong as traditional machined parts (PricewaterhouseCoopers, 2013).

Food applications

One area where we have the highly marketable applications is the culinary one: the more printable ingredients are chocolate and sugar. In 2012 the first 3D printer extruding the chocolate resulting in any form was marketed. Recently, Barilla has announced the winners of the contest launched in collaboration with Thingarage for choosing the design of pasta to be printed with 3D printings, thus revealing future strategy for the integration of this technology in its development plan (www.webnews.it). Other projects for the food releases were carried out by Cornell University in collaboration with the French Culinary Institute

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[6] Pratt & Whitney, United Technologies Corp. company (NYSE:UTX), is a world leader in the design, manufacture and service of aircraft engines and auxiliary power units. Frederick Rentschler founded Pratt & Whitney in Hartford, Connecticut, in 1925. Pratt & Whitney has built a long and distinguished record of providing top-of-the-line military engines to 31 armed forces around the world. Their military engines power front line fighters, such as the F-15 Eagle, F-16 Fighting Falcon, F-22 Raptor and F-35 Lightning II, as well as the C-17 Globemaster III military transport and Boeing's KC-46, the U.S. Air Force's new airlift tanker.

in New York and by the company Natural Machines, which is undertaking the commercialization of Foodini printer (from the merger of Food and Houdini[7]) for packaging pizza, crackers, cookies, etc, with fresh and wholesome ingredients (Pricewaterhouse and Confartigianato imprese varese, 2015).

Automotive applications

Today, the automotive industry is already a major user of Rapid Prototyping equipment: AM technologies are being applied for manufacturing of functional prototypes and for small and complex parts for luxury and antique cars (Gausemeier et al., 2011). It's mainly because new product development is critical for the automotive industry, but developing a new product is often a very costly and time-consuming process. The automotive industry has been using AM technology as an important tool in the design and development of automotive components because it can shorten the development cycle and reduce manufacturing and product costs(Guo and Leu, 2013). Especially, the motorsport sector constitutes an important field for the application of AM-technologies, as here high performance and low weight play a central role (Gausemeier et al., 2011). Within the automotive industry, increasing competition reinforces the pressure for reducing the time-to-market. This challenges the automotive industry to secure and further expand the market share. Against this background, the automotive industry can derive great benefits from the application of AM technologies, as these technologies enable a rapid production of complex parts, including a wide range of material properties. In 2013, the automotive industry contributed 17.3% to the total AM market volume (Figure 1.9). This corresponds to approximately $531 million US dollars (Wohlers Report, 2014).

Chemical aspects

Also the pharmaceutical industry is starting to become more interested in the ability to use Additive Manufacturing to make drugs and medications more cheaply. Inkjet-based 3D printing has been used extensively in the fabrication of drug delivery devices, as it allows for more control of the design and fabrication of implants that can be used for direct treatment. 3D printed drug implants are fabricated via the printing of binder (a solution that

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[7] Houdini is a 3D animation application software developed by Side Effects Software based in Toronto. Side Effects adapted Houdini from the PRISMS suite of procedural generation software tools. Its exclusive attention to procedural generation distinguishes it from other 3D computer graphics software (www.wikipedia.it).

is able to solubilize the chosen powder) onto a matrix powder bed, facilitating controlled drug release by providing a barrier between tissue and drug, or printing of binder onto a powder bed of drug in an additive manner, resulting in layers that are typically 200 μm thick. In this manner, a number of different drug delivery devices have been designed that allow for various drug release profiles (Gross et al., 2014; www.spilasers.com)

Design

Italian design with the advent of the Digital Fabrication has undergone a conceptual transformation of great importance: not more "*MADE* in Italy" but *"THOUGHT in Italy"*. It revolutionizes the world of design from conception through to the design, it changes the skills, the cultural and methodological approaches that lead to the finished project, and also the costs, accessibility to products and process timelines changes (Pricewaterhouse and Confartigianato imprese varese, 2015). First of all the 3D printing is applied to the interior design sector and therefore the design of furniture, objects for the home and office accessories. RepRap offers BIGRep ONE, a 3D printer capable of printing furniture or large items.

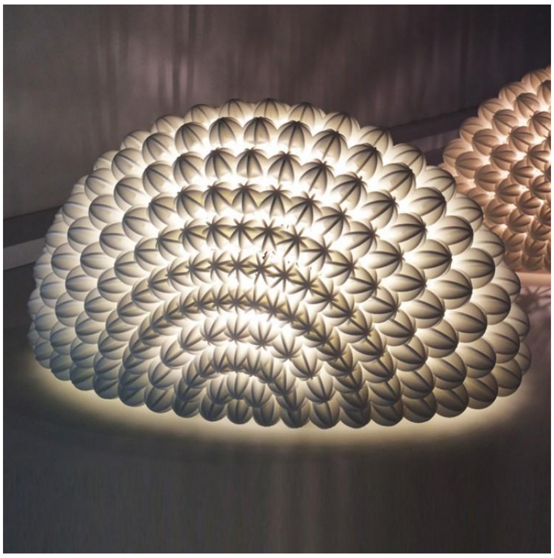


Figure 1.10a Example of 3D printing applied to interior design from the Italian company Exnovo

Figure 1.10b Example of 3D printing applied to accessories from the Italian company .Bijouets

Two significant Italian cases of companies that combine “Made in Italy” with the technologies of Additive Manufacturing transforming their production in "Thought in Italy" are Exnovo and Bijouets. Exnovo was born in 2010, and was the first company in Italy and among the first in Europe to use the Additive Manufacturing technologies for the production of designer collections by professional 3D printing. Exnovo creates, designs and manufactures lighting accessories and decorative objects, highly customized products, in limited series or unique pieces (Figure 1.10a). They pose the innovative technology of 3D printing at the craft service: thus collections of manufacturing excellence that are the expression of an unlimited and unpredictable creativity, impossible to achieve with conventional production processes. They call themselves part of a new generation that moves in between high technology and craftsmanship: deep roots in the Italian know-how - combined with the ability to move on a global scale and to communicate directly with the end customers - leading to new ways of thinking and design, produce and distribute (http://www.exnovo-italia.com).

Bijouets is a brand of jewellery and contemporary accessories with an exclusive modern and cosmopolitan design, Made in Italy with 3D printing technology.

The brand combines modernity and technological innovation with extraordinary craft skills: all jewellery and accessories ".bijouets", made of sintered polyamide, are in fact finished and hand-colored, becoming so real unique pieces (Figure 1.10b).

Bijouets claims to use light technology, which has a lightweight and sustainable impact. The ideas are turned into products through an almost immaterial process that is the synthesis of culture, passion and skills acquired over the years, thus reducing waste and emissions and respecting the environment (http://bijouets-italia.com).

Jewellery

The jewellery products are often distinguished by complex geometries. Furthermore, jewellery can be differenced by value: one extreme encompasses exclusive, hand-crafted individual pieces made from expensive materials; the other extreme includes costume jewelleries, which are cheap and produced in high lot sizes. Thus, the jewellery market is split into two market segments. Within the first market segment, the focus is on very high quality products; within the second, the time to market or the creativity of the design are the crucial success factors. Here, the quality is subordinate. Today, AM already match a number of requirements of the jewellery industry, such as the processability of high-value materials and the creation of any geometry. A central challenge is the still limited availability of materials that can be used for AM. In addition, the surface quality of additively manufactured parts still cannot be guaranteed; post-processing is still required. AM provides value creation potential within the jewellery industry. First, unique geometries can be designed, as digital development does not set any limits. Second, the digital sketches can easily be transferred to suppliers all over the world. Third, hand-crafted manufacturing processes can be replaced by AM, as AM-machines enable the manufacturing of highly individual parts. Thereby, personnel costs can be reduced significantly, and recycling costs of material decrease as almost no powder is wasted. Figure 1.11 shows the changes in the value chain of jewellery (Gausemeier et al., 2011).

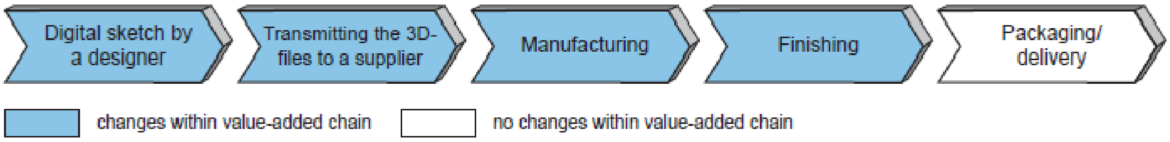


Figure 1.11 Changes in the value chain of jewellery

An example is the jewellery Uptown Diamond which works with 3D Systems to improve its business. In fact, setting up a granular type printer, they are now able to create 50 profiles in 10 hours and to satisfy every need, even the most particular, of its customers (www.3dsystems.com).

Textile and fashion

Textiles are present in various area of life; the applications range from clothes and household textiles to technical textiles. The textile industry is a very short-lived industry. Every season, new design trends, such as new colours, new cuts, etc. penetrate the market and force many manufacturers to change their product portfolios. Therefore, short product development processes are essential within the textiles industry. In addition, the industry must respond to an increasing demand for functional high-performance textiles. Moreover, customers are demanding for customized, body-fitting clothes.

The production of conformal textile articles is connected with restrictions. On the one hand, restrictions are imposed from the manufacturing of the textile itself, as individual production systems are needed. On the other hand, restrictions result from the design and the production of the garment, as production systems cannot proceed every kind of material. Against this background, AM is suitable to be applied within the textiles industry. Until today, the penetration of the market within the textiles industry is still limited to experimental purposes (Gausemeier et al., 2011). This is mainly due to the fact that conventional technologies already meet a number of the required abilities of textiles. However, the following products have already been manufactured additively:

Figure 1.12 Example of shoe made with 3D printing: Nike "Vapor Laser Talon”

- handbags and wristwatch bands;
- clothing garments;
- shoes;
- gloves.

For example Nike launched "Vapor Laser Talon" the first 3D printed shoe made by means of sintering technology. It has developed a product that provides maximum traction between the shoe and the ground, allowing athletes to shoot without losing grip during the initial push (www.nike.com).

Toys

The toys and collectibles market is known for its' high level of individual demand. The main target group of the toys and collectibles industry is represented by children. Children like to be creative and adults support their creativity by letting them make objects, as this promotes the creative growth. Previously children have made this with clay or similar materials. Today, children have the possibility to create 3D digital content (Bourell et al., 2009). For instance, action figures and custom dolls with one's own face can be easily printed with a 3D printer. However, adults also represent a target group for the collectibles' market, as e.g. older toys can also become collectibles. Due to this and based on the fact that these consumer goods are often small-sized and with low strength requirements, the toy and collectibles industry can significantly benefit from AM. AM has already been used for a number of applications within the toys and collectibles industry, such as action figures, video game avatars, land and air vehicles, custom dolls, individualized model cars and tin soldiers (Gausemeier et al., 2011).

1.3.4 Producing and user countries of 3D printing

The market of 3D printers is rapidly expanding as new companies and printer models are emerging in ever shorter time sequences (Frauenfelder, 2013). While still a nascent market, the speed of development and rise in buyer interest are pressing hardware manufacturers to offer easier-to-use tools that produce consistently high-quality results (Gartner, 2013a).

Thirty-one manufacturers from around the world produced professional-grade industrial Additive Manufacturing machines in 2011, compared to 32 in 2010 and 35 in 2009. In 2010 and 2011, 9 of these companies sold more than 100 machines each. Firms that produce Additive Manufacturing machines range from those that produce and sell fewer than 10 per year, to those that sell hundreds of machines per year (Ford, 2014; Wohlers Report 2012). The United States leads in the production and sales of professional-grade industrial Additive Manufacturing machines, with 35,753 units sold between 1998 and 2011. Israel and Germany made 4,556 and 3,980 units, respectively, during the same period. Powder bed fusion and binder jetting are the most common processes used by leading vendors, more of whom (70 percent) use metal than any other material. Table 1.4 presents several leading vendors that manufacture machines, an overview of processes and applications, and the most frequently used materials for each process (Ford, 2014).

Table 1.4 Leading worldwide vendors for 3D printing (source Ford, 2014)

Vendors/Production Sites	*Processes/Applications*	*Materials*
3D Systems* (US, AUS, NED, ITA)	Binder jetting material jetting vat photopolymerization powder bed fusion	Plastic, polymer, metal
Beijing Tiertime (CH)	Material extrusion	Polymer
DWS (ITA)	Vat photopolymerization	Polymer
Envisiontec (GER, US)	Vat photopolymerization material extrusion	Biomaterial, ceramic, polymer
EOS (GER)	Powder bed fusion	Ceramic, metal, polymer
ExOnea (US, GER, JPN)	Binder jetting	Ceramic, polymer, metal
Objetb (ISR, US, GER, Asia)	Material jetting	Biomaterial, polymer
Solidscape (US)	Material jetting	Plastic
Stratasys, (US, GER, IND)**	Material extrusion	Polymer
Z Corp. (US)	Powder bed fusion	Plastic, metal

* 3D Systems acquired Z Corp. in 2012.

** Stratysys acquired Solidscape in 2011, and merged with Objet in 2012.

The United States has several advantages in manufacturing in general, and in Additive Manufacturing in particular. For example, U.S. R&D spending for total manufacturing in 2011 was $415.0 billion, the highest among the countries for which Structural Analysis (STAN) data from the Organisation for Economic Co-operation and Development are available (OECD, 2013). Additionally, the technology was predominantly developed in the United States, where several leading producers of Additive Manufacturing machines, including Stratasys and 3D Systems, are based. In 2011, the United States accounted for 38.3% of the cumulative installed industrial Additive Manufacturing systems (figure 1.13). The same year, the United States accounted for 64% of all industrial AM systems sold worldwide; other countries with significant stocks of industrial Additive Manufacturing machines in this year included Japan (10.2% of global total), Germany (9.3%), and China (8.6%) (Ford, 2014; Wohlers Report 2012).

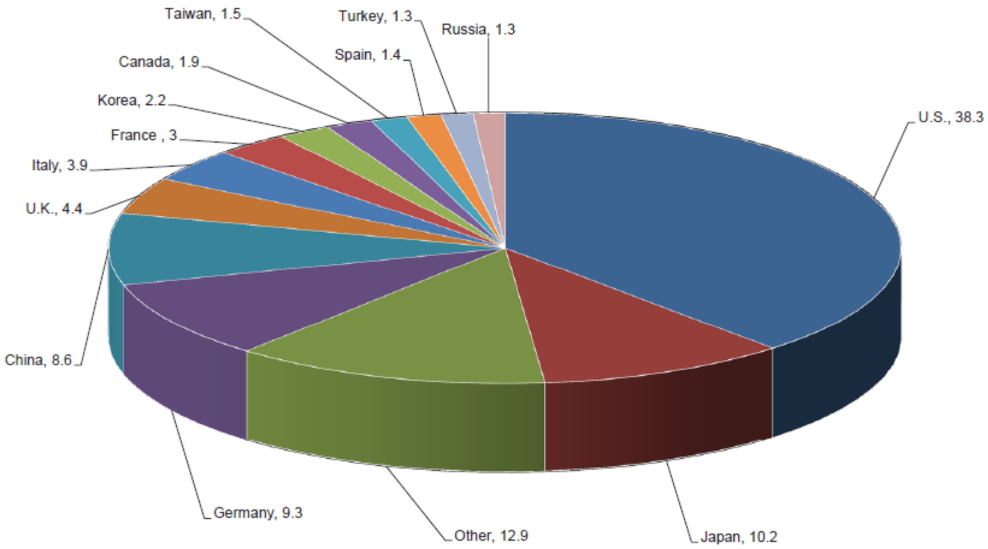


Figure 1.13 Cumulative additive manufacturing machines, installed by country, 1988-2011, (percent of global total) (Source Ford, 2014; Wohlers Report 2012).

As for 3D printing investments, these keeps on increasing all over the world. Germany is the most involved European country in terms of 3D printing investment, with an AM strategy through creating links between science and industry. A €3.4 million of project funds were provided by that German State to match additional industry funding.

The UK has also seen a significant investment in AM in a number of industry sectors. The UK Government has invested £30 million with an equal industry match for a seven year period for the development of a new aerospace technology. According to the International Data Corporation (IDC) 3D printing spending in Asia Pacific excluding Japan will grow at a 23% compounded annual growth rate (CAGR) from $1.5 billion to $4.3 billion by 2019.

In Japan, according to a 2014 study, 4 billion yen ($38.6 million) were spent in funding for various national 3D printing projects. Eighty percent of this funding is targeting the research and development of 3D printers capable of producing end-use products in metal for industrial use. Another 15% will go toward developing super-precision 3D printing technology, including Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), as well as technology for post-processing and powder recycling. The remainder will be used for developing new 3D measurement devices and image processing software (IDC, 2016).

In South Korea, according to the 3D Printing Industry Development Council, the plan includes a goal to train 10 million creative makers by 2020. Making some real examples, The American company General Electrics has started to invest in 2016 $3.5 billion in new equipment and will continue over the next five years to produce advanced components using additive manufacturing. Alcoa, the third bigger aluminum companies in the United States invested in 2016 $60 million in order to create a manufacturing center specializing in advanced 3D printing techniques and materials.

European companies are also on the go. The Sweden company Siemens opened a $23.8-million additive manufacturing production facility for metal parts.

Germany’s leading aeroplane engine manufacturer racked up more than $1 billion of orders at a single air show and 3D printing is driving the future.

Ford, Lockheed Martin (LMT), Airbus (EADSY), NASA, United Technologies’ (UTX) Pratt & Whitney and Rolls Royce are also becoming big users of 3D technology.

In Japan, companies such as Hitachi, Toshiba and Mitsubishi are the companies investing the most in 3D printing (www.sculpteo.com).

1.4 3D printing: the size of the phenomenon

It cannot be said that the AM technology is a new technology if Chuck Hull, which is considered the father of AM, founded its 3D Systems, as mentioned earlier, in the mid-80s. In any case the terms "3D Printing" and "Additive Manufacturing" have only recently become very popular and over a rather short period of time: for example, placing equal to 100 the maximum number of searches on Google of the term "3D printing" in the world, it is noted that even in the summer of 2010, this index stood at 5 and it stood at 21 in March 2012; the highest peak in the world took place in March 2015 with a value of 100, which was followed by a sharp decline until the end of the year, which has also seen a recovery in 2016 and to date in June 2016 we have a value of interest for the argument equal to 87 (Figure 1.14).

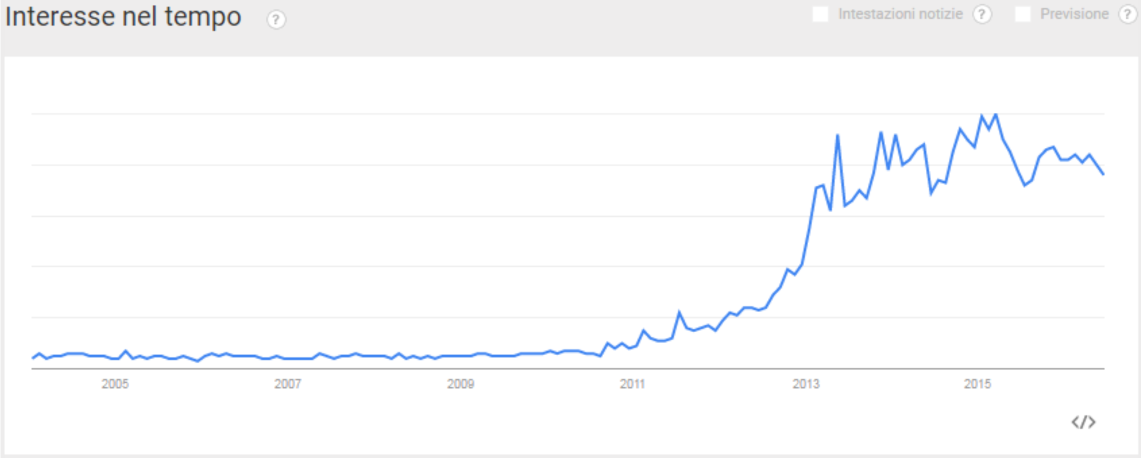
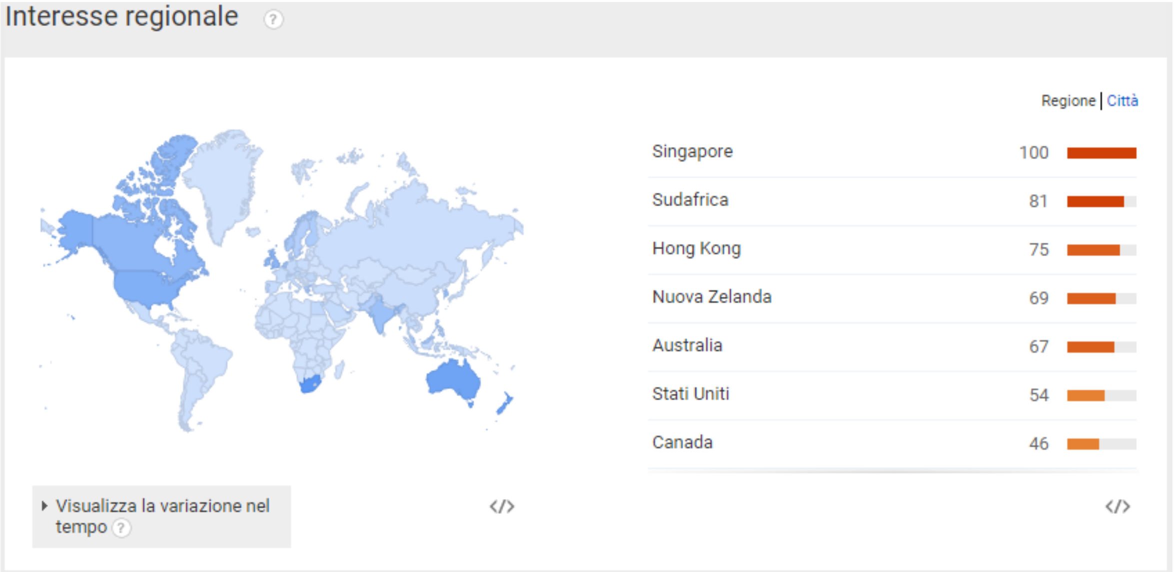


Figure 1.14 World index of interest of the term "3D printing" updated at June 2016. Source: Google Trends (www.google.it/trends/)

Moreover Google Trends (June, 2016) shows the regional interest in the phenomenon of 3D printing; as we can see from Figure 1.8 among the top ten countries that have an interest in the topic there are Singapore (with a value of 100), South Africa (83), Hong Kong (75), New Zealand (70), Australia (67), United States (54), Canada (47), United Kingdom (45), Ireland (42) and the United Arab Emirates (39). In this ranking Italy is among the last with a value of 8 (Figure 1.15).



Singapore	100
Sudafrica	81
Hong Kong	75
Nuova Zelanda	69
Australia	67
Stati Uniti	54
Canada	46

Figure 1.15 Regional index of interest of the term "3D printing" updated at June 2016. Source: Google Trends (www.google.it/trends/)

These considerations made on the data obtained from Google Trends must keep in mind that in Italy the search term most commonly used might be the Italian term “stampa 3D” from the eponymous English term; for this reason it has been carried out from Google Trends an analysis of this second term. Always placing equal to 100 the maximum number of searches on Google of the term "stampa 3D " in the world, it can be seen, as conceivable, that the term was of interest only in Italy and the maximum peak of interest until today (June 2016) has been reached on November 2014 (Figure 1.16).

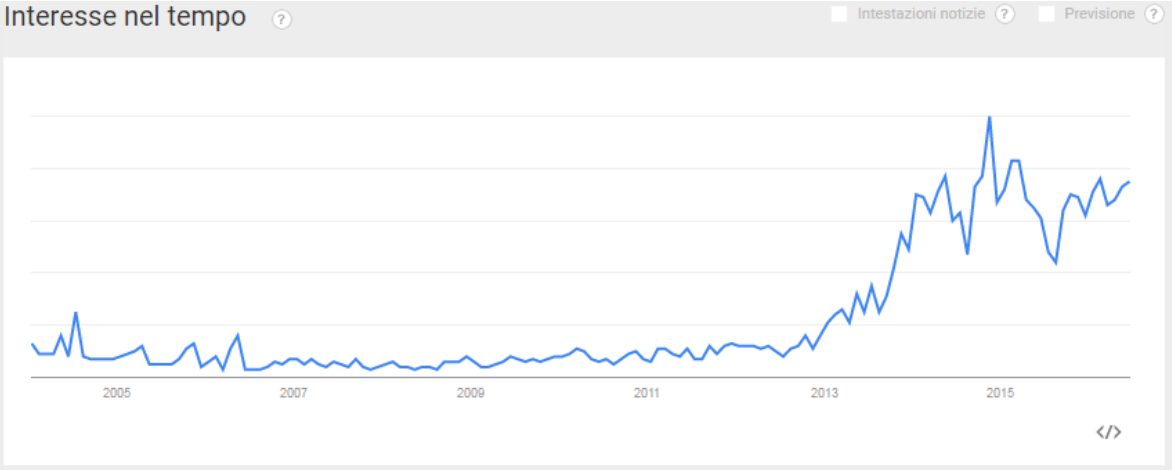
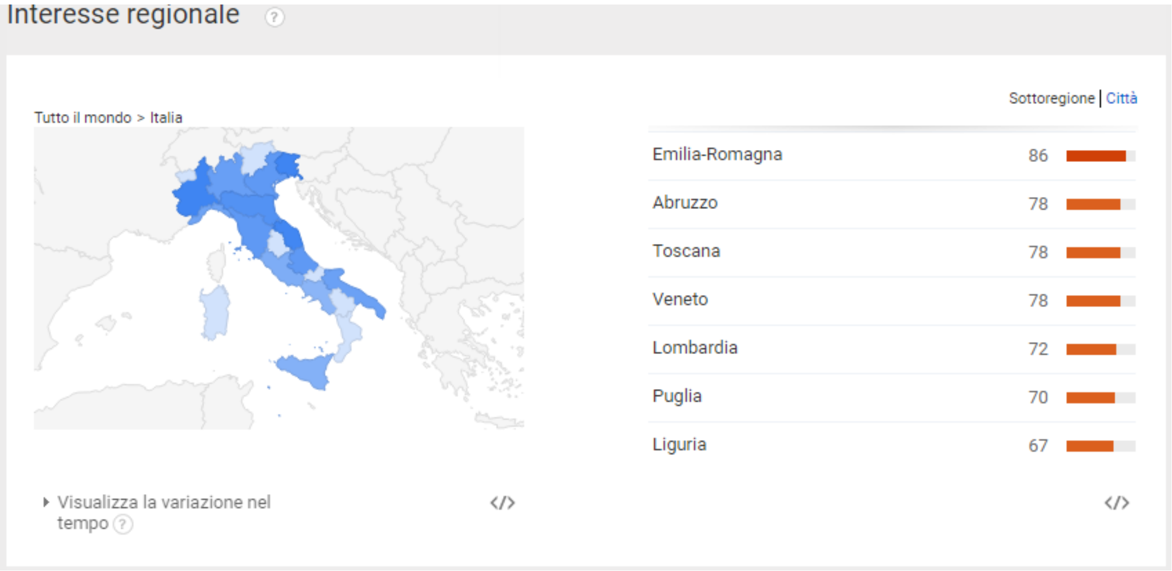


Figure 1.16 World index of interest of the term "stampa 3D" updated at June 2016. Source: Google Trends (www.google.it/trends/)

Always placing equal to 100 the maximum number of searches on Google of the term "stampa 3D" the ten principal Italian regions interested in this theme, as shown in Figure 1.10, are Piemonte (100), Friuli Venezia Giulia (100), Marche (98), Emilia Romagna (78), Abruzzo (78), Toscana (78), Veneto (78), Lombardia (72), Puglia (70), Liguria (67) (Figure 1.17).



Emilia-Romagna	86
Abruzzo	78
Toscana	78
Veneto	78
Lombardia	72
Puglia	70
Liguria	67

Figure 1.17 Regional index of interest of the term "3D printing" updated at June 2016. Source: Google Trends (www.google.it/trends/)

According to Beltrametti and Gasparre (2015), in an historical moment in which the media exposure of this technology is very high it is questionable whether such popularity is attributed to a real revolutionary potential of the underlying technological innovations or if we are in the presence of a media bubble, designed to deflate as soon as it will be realized that the real scope of these innovative technologies is below the expectations.

In the following two paragraphs it will considered first the international dimension of the 3D printing phenomenon and then a focus on the state of art of AM in the Italian economic environment will be made.

1.4.1 The international context

Despite what Beltrametti and Gasparre (2015) said about the real revolutionary potential of AM, the statistics on the growth of the phenomenon seem comforting. 3D printing is an innovation that has a few decades but it is showing its most economically interesting applications only recently and for some aspects it is still at a stage of development and testing.

Columbus (2015) in Forbes[8] cites data of the Wohlers Report 2014, saying that in 2014 Wohlers Associates[9], which has been tracking the 3D printing industry since the 1980s, recently revised its growth forecasts for the burgeoning industry by a significant factor. According to Wohlers Report 2014, the worldwide 3D printing industry is now expected to grow from \$3.07 billion in revenue in 2013 to \$12.8 billion by 2018, and exceed \$21 billion in worldwide revenue by 2020 (Figure 1.18).

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[8] **Forbes** is an American business magazine. Published bi-weekly, it features original articles on finance, industry, investing, and marketing topics. Forbes also reports on related subjects such as technology, communications, science, and law. Its headquarters is located in Jersey City, New Jersey. Primary competitors in the national business magazine category include Fortune and Bloomberg Businessweek. The magazine is well known for its lists and rankings, including its lists of the richest Americans (the Forbes 400) and rankings of world's top companies (the Forbes Global 2000). Another well-known list by the magazine is the The World's Billionaires list.

[9] **Wohlers Associates, Inc.** is a 29-year old independent consulting firm based in Fort Collins, Colorado. The company provides technical and strategic consulting on the new developments and trends in rapid product development and Additive Manufacturing. Much of this guidance has dealt with industrial applications, what works and what does not, hidden costs, industry trends, and growth forecasts. The company also helps to identify opportunities in mergers and acquisitions, provides advice on product positioning and competitive issues, and offers expert testimony in litigation. Wohlers Associates has provided advice to 150 companies in the investment community, most being institutional investors that represent mutual funds, hedge funds, and private equity valued at billions of dollars (Source: wohlersassociates.com)

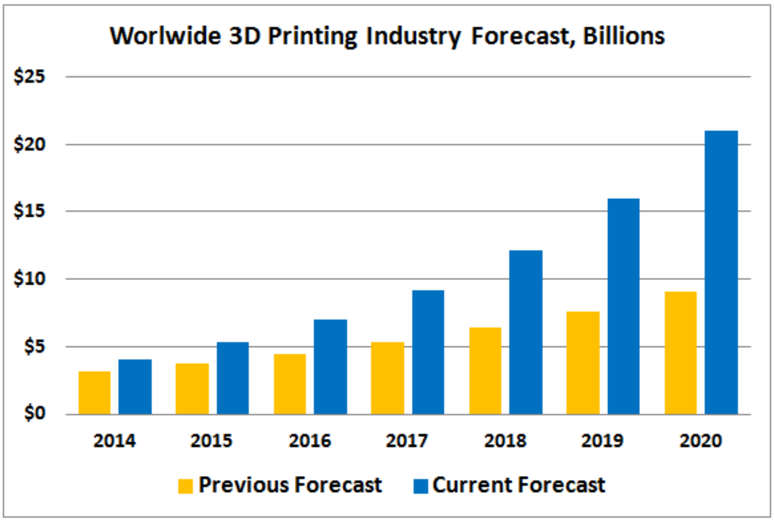

Figure 1.18. Forecast on 3D printing evolution (www.forbes.com)

As far as 3D printing stocks are concerned, the industry's growth trajectory could offer a tremendous runway for growth, assuming companies can grow alongside the industry and deliver on the potential for long-term fortunes - neither of which are guaranteed.

According to a survey made by Gartner[10] (2014), 60% of organizations said high start-up costs are a main factor in the delay of implementing 3D printing strategies, however, the survey also found that early adopters of the technology are finding clear benefits in multiple areas; *"3D printing has broad appeal to a wide range of businesses and early adopter consumers and while the technology is already in use across a wide range of manufacturing verticals from medical to aerospace, costs remain the primary concern for buyers,"* said Pete Basiliere, research director at Gartner.

The survey also shows that prototyping (24,5%), product development (16,1%) and innovation (11,1%) are the three most common reasons international companies are pursuing 3D printing, even if this technology is widely used also in manufacturing applications (Figure 1.19).

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[10] **Gartner, Inc.** is an American research and advisory firm providing information technology related insight. Its headquarters are in Stamford, Connecticut, United States. Research provided by Gartner is targeted at Chief Information Officers (CIOs) and senior Information Technologies (IT) leaders, marketing leaders and supply chain leaders. Gartner clients include large corporations, government agencies, technology companies and the investment community. The company consists of Research, Executive Programs, Consulting and Events. Gartner uses Hype Cycles and Magic Quadrants for visualization of its market analysis results.
In the second quarter of 2014, Gartner conducted a worldwide survey to determine how organizations are using or planning to use 3D printing technologies. Survey participants were 330 individuals employed by organizations with at least 100 employees that are using or planning to use 3D printing.

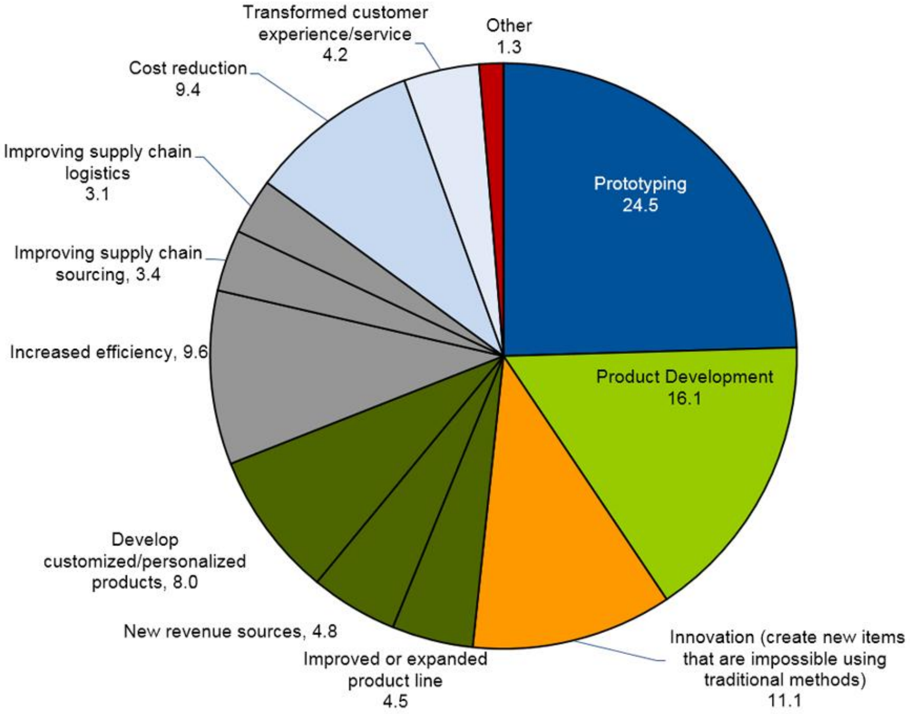

Figure 1.19 Reasons for pursuing 3D printing (www.gartner.com, November 2014)

Moreover Gartner (2014) projects the 3D printing market will globally grow from 1,6$ Billion in 2015 to 13,4$ Billion in 2018 attaining a 103,1% Compound Annual Growth Rate (CAGR), while Allied Market Research[11] (AMR) projected in 2014 that the 3D printing market will grow from $2.3B in 2013 to $8.6B in 2020, attaining a CAGR of 20.6% (www.alliedmarketresearch.com). Pete Basiliere, Research Director at Gartner, speaks in this way of the results of their International survey:

> *"The market is emerging from its nascent stage as organizations move beyond design and prototyping applications of 3D printing toward creating short run production quantities of finished products. Based on these results and the answers to other survey questions, we predict that by 2018, almost 50 percent of consumer, heavy industry and life*

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[11] Allied Market Research (AMR) is a full-service market research and business consulting wing of Allied Analytics LLP based in Portland, Oregon. Allied Market Research provides global enterprises as well as medium and small businesses with unmatched quality of "Market Research Reports" and "Business Intelligence Solutions". AMR has a targeted view to provide business insights and consulting to assist its clients to make strategic business decisions and achieve sustainable growth in their respective market domain. They results we speak about are written in their 2014 report called "World 3D Printing Market".

> *sciences manufacturers will use 3D printing to produce parts for the items they consume, sell or service. An interesting finding was that respondents felt overwhelmingly that using a 3D printer as part of their supply chain generally reduces the cost of existing processes, especially research and product development costs. The mean cost reduction for finished goods is between 4.1% and 4.3%, which is an impressive figure. It shows that early adopters of the technology are finding clear benefits, which are likely to drive further adoption. Clearly there is much room for future growth in this market, but vendors need to work on tools and marketing that show how the technology can be applied and drive competitive advantage. 3D printing vendors that take the time to articulate the value of their product in terms that align with their clients' needs will be well-positioned to capitalize on any future growth."*
>
> *P. Basiliere, Research Director at Gartner*
> *(Press Release, EGHAM, U.K., December 9, 2014)*

While according to Allied Market Research (2014):

> *"The increasing adoption of 3D printing in various application segments such as consumer products, industrial products, aerospace, automotive, defense, healthcare, education & research, architecture and arts are facilitating the growth of 3D printing market. The key industry segments such as healthcare and aerospace, which are growing at a promising rate, have witnessed significant penetration of 3D printing technology. Consumer product industry remains the largest application segment with about 22% of the market*

> *share, while defense sector is expected to exhibit the fastest growth at a Compound Annual Growth Rate (CAGR) of 17.2% during the forecast period. North America leads the 3D printing market with about 43.9% revenue share in 2013, followed closely by European region. The dominance of North American market is attributed to the growth in healthcare, consumer, aerospace and automobile industry. Asia-Pacific would be the fastest growing market, having a CAGR of 51.9% during 2014-2020, due to faster adoption of 3D printing in the developing industrial sectors."*
>
> *AMR, World 3D printing market, 2014*

Another survey from PricewaterhouseCooper[12] (2014a) concerning more than 100 international industrial manufacturers, reveals that two-thirds of them were already using 3D printing. Most were just experimenting or using it only for rapid prototyping, which has been 3D printing's center of gravity for most of its history (Figure 1.20)

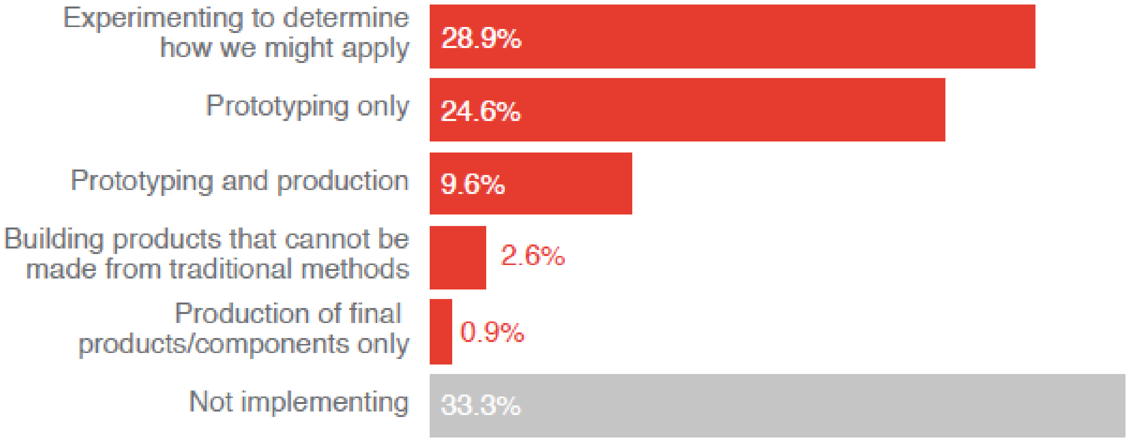

Figure 1.20 How is your company currently using 3D printing technology? (Source PwC and ZPryme survey and analysis, conducted in February 2014)

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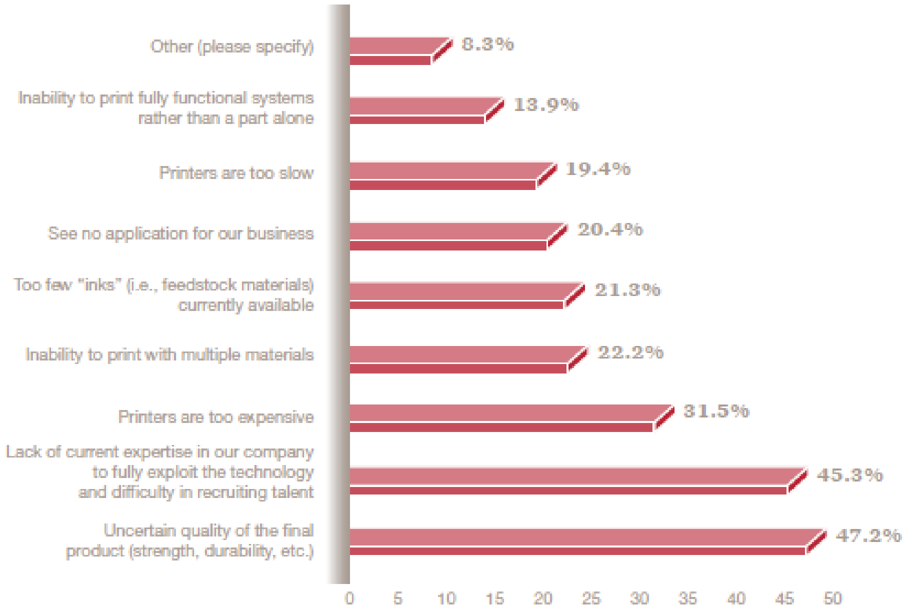
[12] **PricewaterhouseCoopers** (**PwC**) is a multinational professional services network headquartered in London, United Kingdom. It is the largest professional services firm in the world, and is one of the Big Four auditors, along with Deloitte, EY and KPMG. They made a report called Technologyforecast in 2014 on the issue: "The future of 3-D printing: moving beyond prototyping to finished products".

3D printing can accelerate new product development cycles, which ultimately could translate into getting new products to market more quickly and frequently, especially when prototyping complex products. Moreover 3D printing is also opening the doors to the “lot of one” model, allowing companies to avoid producing products that are unpopular and only print those products that are making inroads to customization of popular products. The technology could also impact the after-market of products, particularly for manufacturers of products with long lives and a high demand for parts replacement and repair and even for obsolete parts. According to PricewaterhouseCooper (2014b) survey, 70% of respondents believe that in the next three to five years, 3D printing will be used for obsolete parts while 50% believe it’s likely that the technology will be used for production of after-market products.

As for the barriers perceived, almost half (47%) of the manufacturers surveyed identified the top barrier to implementing a 3D printing strategy is the uncertainty of a 3D printed products’ quality, followed by lack of talent to exploit the technology (45%). Intellectual property protection is another potential concern, where CAD-files, 3D scanners and printers could open the door to patent infringement. In addition, manufacturers are wary about how well printed parts or components can perform, and whether they will gain certificate or approval for use by regulated bodies (Figure 1.21).



Number of respondents: 108

Source: PwC and Zpryme survey and analysis, "2014 Disruptive Manufacturing Innovations Survey," conducted in February 2014.

Figure 1.21 Barriers to in-house adoption of 3D printing

Other forecasts for growth of the AM market by equity research analysts range from: $7 billion by 2020, on 18% CAGR (Paul Costerof JP Morgan), to bull market scenarios as high as $21.3 billion by 2020, on 34% CAGR (Ben Uglowof Morgan Stanley) as stated by Cotteleer and Joice (2014a). Furthermore **Siemens predicts that 3D printing will become 50% cheaper and up to 400% faster in the next five years** (Figure 1.22**)**. Siemens is also predicting 3D Printing will be a €7.7 billion ($8.3 billion) global market by 2023. They say *“although Additive Manufacturing won’t replace conventional production methods, it is expected to revolutionize many niche areas. Exponential growth is on the horizon”* (www.siemens.com).

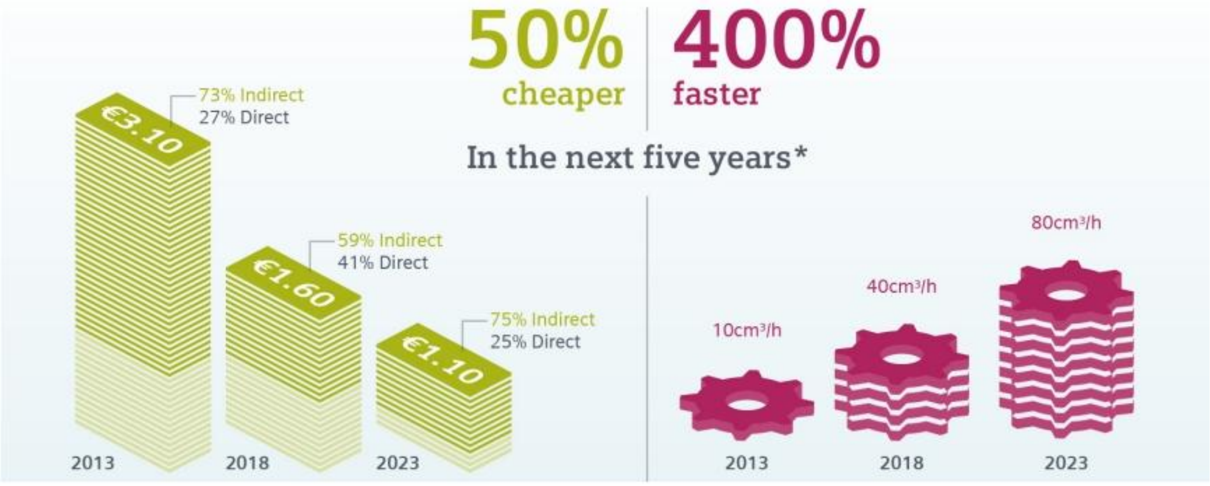


Figure 1.22 Siemens’ forecast on AM evolution (www.siemens.com)

Considering subsequently the industries served and the approximate revenues (by percent) for AM, data of the Wohlers Report (2013) cited by Deloitte (2014a) shows that AM systems are sold into a wide range of sectors. Industrial and consumer products (19% and 18%) are the ones which contributed most to double-digit sales of AM systems in 2013, while also Automotive, Medical, and Aerospace lead (43%) among targeted sectors (Figure 1.23).

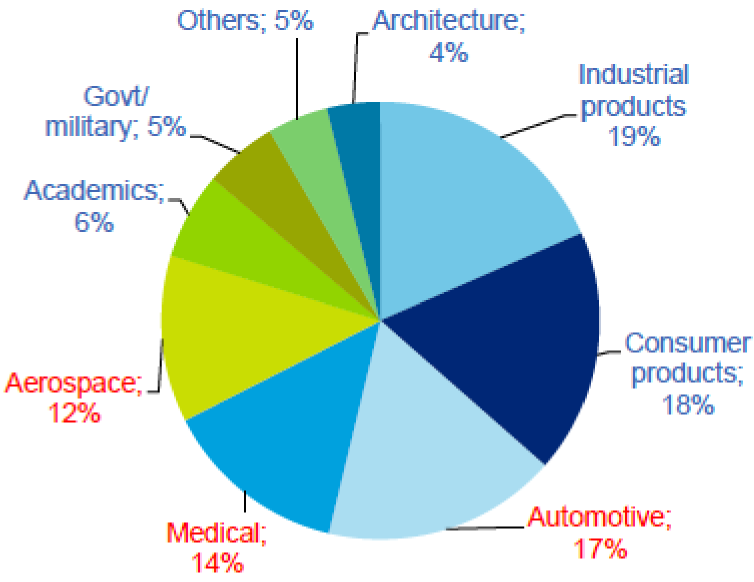


Figure 1.23 AM system sales revenue to various sectors: 2013. (Source Deloitte 2014, from Wohlers Report 2013).

Finally Gartner (2015) in the study “The Hype Cycle for Emerging Technologies” has published a focus only catered specifically to the 3D printing sector. But what is an “Hype Cycle”? Gartner explains that Gartner Hype Cycles provides since 1995 a graphic representation of the maturity and adoption of technologies and applications, and how they are potentially relevant to solving real business problems and exploiting new opportunities. Gartner Hype Cycle methodology gives a view of how a technology or application will evolve over time, providing a sound source of insight to manage its deployment within the context of a specific business goals; it permits to highlight the common pattern of overenthusiasm, disillusionment and eventual realism that accompanies each new technology and innovation. The Hype Cycle drills down into the five key phases of a technology's life cycle (Figure 1.24):

- the phase of *“Technology Trigger”* is when a potential technology breakthrough kicks things off; during this phase early proof-of-concept stories and media interest trigger significant publicity and often no usable products exist and commercial viability is unproven.
- The phase of *“Peak of Inflated Expectations”* is when early publicity produces a number of success stories — often accompanied by scores of failures. Some companies take action; many do not.

- The phase of *"Trough of Disillusionment"* is when interest wanes as experiments and implementations fail to deliver. Producers of the technology shake out or fail. Investments continue only if the surviving providers improve their products to the satisfaction of early adopters.
- The phase of *"Slope of Enlightenment"* is characterized by more instances of how the technology can benefit the enterprise and this one become more widely understood. Second and third generation products appear from technology providers. More enterprises fund pilots while conservative companies remain cautious.
- The phase of*"Plateau of Productivity"* begins when mainstream adoption starts to take off. Criteria for assessing provider viability are more clearly defined. The technology's broad market applicability and relevance are clearly paying off (www.gartner.com)

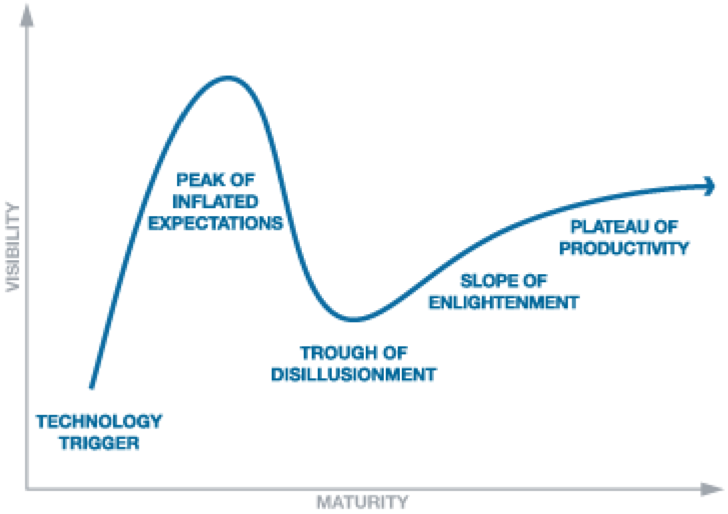


Figure 1.24 How Gartner Hype cycle works: an explanation. (Source www.gartner.com)

Since 3D Printing is getting into every single sector of manufacturing, from automotive to regenerative medicine, Gartner (2015), has published a study only catered specifically to the 3D printing sector (Figure 1.25). Gartner's 2015 Hype Cycle for 3D Printing reveals that 3D printing of medical devices has reached the Peak of Inflated Expectations, but certain specialist applications are already becoming the norm in medical care. In the healthcare industry, 3D printing is already in mainstream use to produce medical items that need to be tailored to individuals, such as hearing aids and dental devices. All of the major hearing aid manufacturers now offer devices that are personalized to the shape of the customer's ear. This is evidence that using 3D printing for mass customization of consumer goods is now viable, especially given that the transition from traditional manufacturing in this market took less than two years. Routine use of 3D printing for dental implants is also not far from this level of market maturity. Looking further out, at least five to 10 years to mainstream adoption, there is bioprinting. 3D bioprinting has two categories in this Hype Cycle: one focused on producing living tissues for human transplant, the other for life sciences' research and development (R&D). There is still rapid advancement outside of medical fields. While 3D prototyping has for many years been the only mainstream use of the technology, within the next two to five years it is likely to be joined by many technologies that will spur much wider use of 3D printing outside of specialist fields. *"Advancements outside of the actual printers themselves may prove to be the catalyst that brings about widespread adoption"*, said Mr Basiliere, research director at Gartner. Technologies such as 3D scanning, 3D print creation software and 3D printing service bureaus are all maturing quickly, and all have the potential to make high quality 3D printing more accessible and affordable. Moreover the emergence of 3D printing service bureaus also continues to accelerate. This enables enthusiasts and organizations to test and experiment with the capabilities of advanced 3D printing systems in situations where an investment in purchasing a 3D printer would be hard to justify. As this ecosystem matures around the printers, so market demand and competition will keep increasing and more use cases will become commonplace (Gartner, 2015).

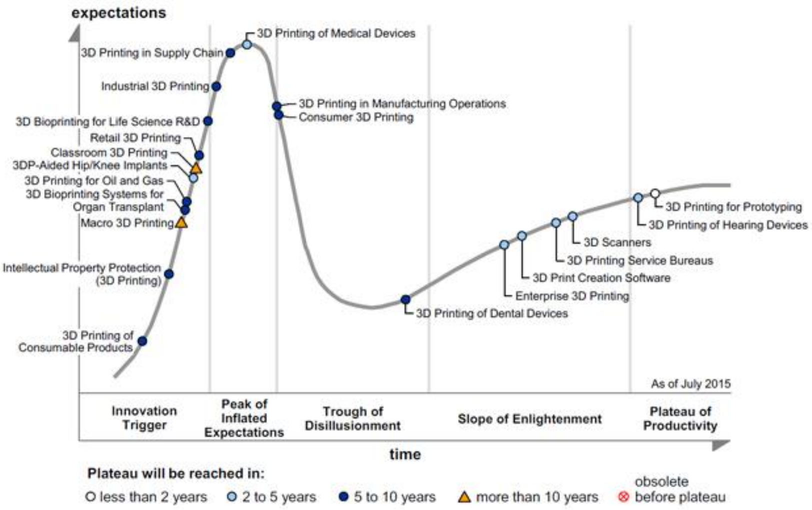


Figure 1.25 Gartner Hype Cycle for 3D printing 2015. (Source www.gartner.com)

1.4.2 Countries initiatives for Additive Manufacturing

In the USA, Additive Manufacturing receives significant attention from policy and companies. For instance, President Barack Obama emphasized in his 2013 State of the Union the huge, revolutionary potential he sees in AM technology by changing the way we make almost everything. The politics in the US aim to create an environment of thinkerers and makers, which drives this emerging movement in order to create new jobs. In this context, the government supports start-ups with the program for advanced manufacturing providing entrepreneurs access to more than $5 billion (Shear, 2014).

One of the nation's first publicly funded National Additive Manufacturing Innovation Institute called "America Makes" is located in Youngstown, Ohio (Molitch-Hou, 2014). It was established in 2012 and is led by the National Center for Defense Manufacturing and Machining (NCDMM). The Institute includes 50 firms, 28 university and research labs, as well as 16 other organizations. The government supports the institute with US-$ 50 million with the aim to increase national manufacturing competiveness and to enhance the adoption of 3D printing technologies and Additive Manufacturing in the U.S. manufacturing sector (Advanced Manufacturing Portal, 2014). The institute offers multiple events like an International Forum, Technology Shows or 3D Printing Summits (Bechthold et al., 2015).

As for China, it is exploring how 3D printing can be integrated into its manufacturing-driven economy. The Beijing-based Asian Manufacturing Association (AMA) is one of the main drivers behind this exploration. Members of the AMA include representatives of China's manufacturing industry, researchers and professors of technological universities, economists and party officials. In May 2013, the AMA announced plans to found ten 3D printing innovation institutes in China with an initial investment of $ 3.3 million each (Mu, 2013).

In May 2013, the AMA organized the World 3D Printing Technology Industry Conference, which was attended by 500 representatives of the international 3D printing industry (Ye, 2013). In the course of this conference and in cooperation with international industry and research representatives, Luo Jun, the Chief Executive Officer (CEO) of the AMA, initiated the foundation of the World 3D Printing Industry Association. In 2014, the World 3D Printing Industry Alliance hosted the second World 3D Printing Technology Industry Conference in Qingdao, a city in the northern Shangdong province. More than 110 3D printing company representatives attended the event, including companies such as 3D Systems, EOS and Voxeljet (The World 3D Printing Industry Association, 2014; Bechthold et al., 2015).

Considering the European Union, already 15 years ago, the European Commission funded a program which was an European thematic network of research institutions, universities, and industry partners working with rapid tooling (Beaman et al., 2004). After completion, a new seven-year program, the Network of Excellence in Rapid Manufacturing (NEXTRAMA), funded by the European Union's Sixth Framework Program (FP6), followed the project. NEXTRAMA's goal was to achieve efficient and sustainable rapid manufacturing industrial processes through a broadly coordinated effort to create a permanent support organization. Shared work, facilities knowledge, and experience helped define the primary development themes and related research goals. Annual funding levels of over €1.29 million per year were granted to the organization and management of the project (Beaman et al., 2004).

Around 20 active EU FP7 projects include work streams focused on Additive Manufacturing. Moreover, the EU has recognized the need for uniform standards and processes in the area of Additive Manufacturing and initiated the so-called SASAM project, an initiative for Support Action for Standardization in Additive Manufacturing.

SASAM's mission is to drive the growth of AM to efficient and sustainable industrial processes by integrating and coordinating standardization activities for Europe (SASAM, 2014). Further European initiatives such as the European Additive Manufacturing Group (EAMG) have been formed during the past years, laying the basis for the further adoption of AM in Europe (EPMA, 2014).

Also the European Union's "Horizon 2020" program seeks to support and promote research and innovation in advanced manufacturing and processes. What is more, MANUFUTURE, an industry lead initiative, was set up in 2004 and launched the European Factories of the Future Research Association (EFFRA) in 2009. Under "Horizon 2020", EFFRA aims at encouraging research on production technologies by engaging in a Public-Private Partnership (PPP) with the European Union called "Factories of the Future" (Bechthold et al., 2015). Within Europe, the United Kingdom strives for the pioneering role in 3D printing research and development activities. This is manifested in the UK's superior financial input to AM research as well as the great number of AM-related research publications (Dickens et al., 2012). But what is the role played by Italy in this manufacturing revolution?

1.4.3 Italy and 3D printing

Since 3D printing is particularly useful in the production of unique and complex items or small series, and of medium/high value, it could be suitable to improve the competitiveness of many industries of Made in Italy that produce valuable items in small quantities, such as artisans (digital craftsmanship), musical instruments, objects of design, decoration and furniture, jewellery and watches, fashion (shoes, clothing, clothing accessories), renovation (furniture, statues, architectural details, car, motorbike, boat), motorcycle industry, automotive, aerospace, mechanical engineering and new materials, medical industry (dentures, dental, hearing aids), architecture and building, food industry (sweets, pasta), marketing, promotional items and toys (gifts, gadgets).

The traditional manual skills of Italian craftsmen, combined with their imagination and their creativity, with the contribution of new technologies and new materials can afford to make a quantum leap and revive manufacturing in Italy by creating jobs and development, promote youth self-employment and create an advanced digital craftsmanship. According to Rusconi (2015) the 3D printing is a strong growing phenomenon, already quite widespread in Italy, with further potential of development.

An example of the Italian development of 3D printing is Sharebot, a start-up founded in a garage in Nibionno, in the province of Lecco, in 2012, with the idea to ride the paradigm "of do it yourself 3D printing". Today Sharebot has installed about 2 thousand 3D printers among Italy (most) and foreign countries with a catalogue populated by different models that take advantage of printing technologies such as Fused Deposition Modelling (FDM), extrusion of thermoplastic filament (FFF) and UV rays - to print objects of small dimensions (10x10 cm) and larger (70x20 cm) ones. Sharebot produces machines that cost from less than a thousand Euros to a few thousands, and professionals and companies are the classes of more sensitive users (www.sharebot.it).

Considering the use of 3D printers in Italy, Italian companies, at the end of 2014, had about 5 thousand professional printers in operation, equal to about 4% of those installed globally. For instance, Italy is at the level of Great Britain and France, above Spain and just below Germany, which has a market share of 9% and is the leader in the world if we consider only the AM of metals. These data are consistent with the findings from a recent study by which the Rise Lab[13] has analyzed seven technologies considered disruptive (including the Internet of things and the augmented reality) of a sample of about one hundred Italian manufacturing companies (in mainly mechanical and instrumental industry). Research has shown specifically how 3D printing is by far the most established and widely used technology. About a quarter of the surveyed companies are in fact carrying out technical-economic feasibility analysis aimed at 3D printing implementation, and a similar portion already uses it on a daily basis to support research and development (rapid prototyping) and production for support equipment and small series of finished components.

The benefits obtained by manufacturing companies who have already embraced the 3D printing confirmed that the impact of this technology is already significant, as well as measurable: there is a substantial reduction in time-to-market of the products (in some cases even by 30%) and of production costs, an improvement of performance in exercise and a reduction of waste materials. By contrast, investments in mainly machinery and equipment and, skills seem to restrain a development even more massive of the phenomenon (Rusconi, 2015).

Considering the estimates of the "First report on the impact of digital technologies in the Italian manufacturing system", produced by Fondazione Nord Est and Prometeia for the Foundation Make in Italy, on a sample of one thousand representative companies of the Made in Italy with revenues in excess of one million euro (in 2013)[14], 3D printing and robotics begin to take root among those companies of the Made in Italy, making them more

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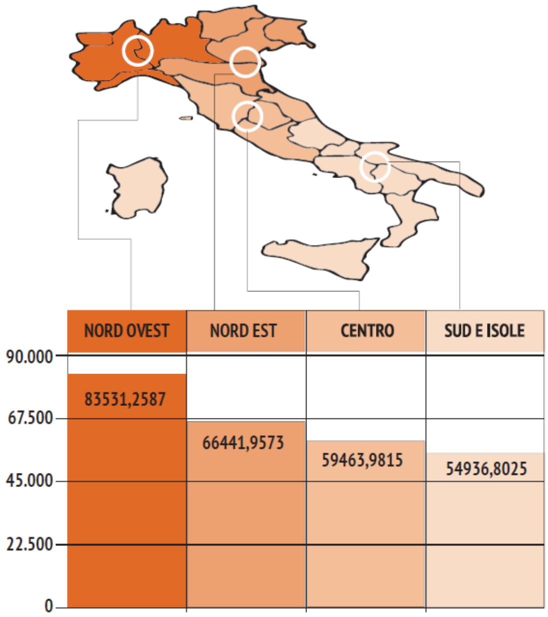
[13] The RISE Laboratory (Research & Innovation for Smart Enterprises) was born in 2008 as an ASAP Research Center, and it became Laboratory on Supply Chain & Service Management (SCSM). It aims to support the competitiveness of Italian companies developing innovative knowledge, that is strict and usable to develop the innovation of products, processes and business models. Particular attention is paid to the awareness of enterprises, to the transfer of knowledge from research to industry, and to the practical application of the main innovations developed in the research world. On the subject of Additive Manufacturing, RISE has developed a paper titled "The Digital Manufacturing Revolution - What prospects for manufacturers Italian ?", which deals closely with the possible development of digital technologies in Italy.

[14] The survey examined capital companies with 2013 revenues of more than 1 million Euro. The universe of reference thus defined consists of 42.096 enterprises, slightly higher than the 10% of the total of manufacturing enterprises in Italy. The population sampled is the set of Italian company active in the sectors of textile, clothing, articles in leather, wood industry, furniture, rubber and plastic, non-metallic minerals, metallurgy, metal products, computer and electronic products, electrical appliances, machinery and equipment, motor vehicles, trailers and semi-trailers, other means of transport, jewelery and precious stones, musical instruments, tools and medical and dental supplies and other manufacturing industries with revenues in 2013 more than 1 million euros. Enterprises have been extracted from those present in the Aida database - Bureau Vand Dijk. The sample was broken down by geographical area (North West, North East, Centre and South and Islands), macro-sector of economic activities such as textile, clothing, footwear, wood and furniture, rubber, plastic and non-metallic minerals, metallurgy and metal products, machinery, electrical equipment, transportation, other manufacturing industries, and size class (from 1 to 9.999 million Euro, from 10 to 49.999 million Euro, and over 50 million Euro). The sample amounted in total to 1.000 units.

competitive on the international market: about one in three is already using these technologies. Technological progress, if extended to all small and medium enterprises in the Made in Italy, may be worth 8.6 billion euro of annual growth of industrial output value, 39 thousand new jobs and an additional added value of 4.3 billion euro (Longo, 2015).

The Make in Italy (2015) report aims to show the degree of penetration of the new technologies of digital manufacturing in the Italian production system. The analyzes aim to highlight how new production technologies are able to improve, in the medium term, the Italian business performances in the sectors of Made in Italy.

As for the geographical distribution of Italian enterprises (Figure 1.26) which work for Made in Italy, it can be said that the 77% of the production of Made in Italy is concentrated in the northern regions. In fact in these regions the 56.3% of Italian companies have its headquarter, and their size is approximately double compared to those active in the rest of the country (12 employees).



Fonte: Prometeia - Db Strut 2013

Figure 1.26 Made in Italy, number of businesses by geographic area (Source Prometeia, in Make in Italy 2015).

The ability of the Made in Italy enterprises to satisfy an increasingly diverse and complex world demand supported export growth in recent years. Foreign sales account for about the 46% of the turnover of the sector by giving an essential contribution to the manufacturing total balance (119 billion euros in 2014).

Considering in detail the dissemination of AM technologies in the sector (Figure 1.27), the Make in Italy (2015) report says that the 25.8% of companies are using 3D printing and 3D scanning “in house” or from external service; this share reaches the 33.3% among large companies (revenues of over 50 million).

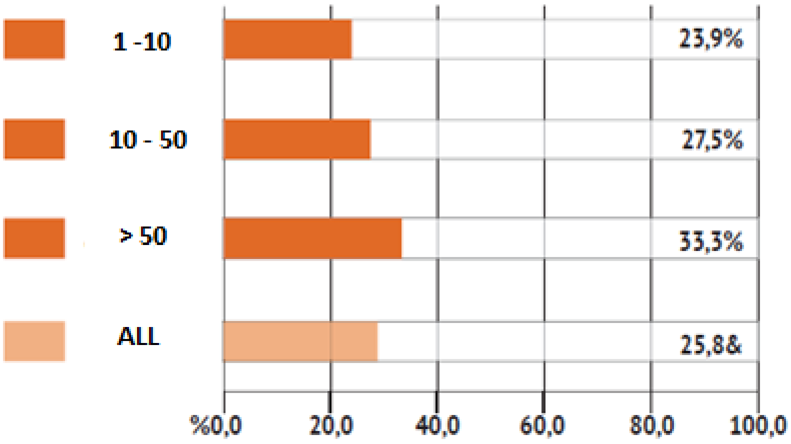
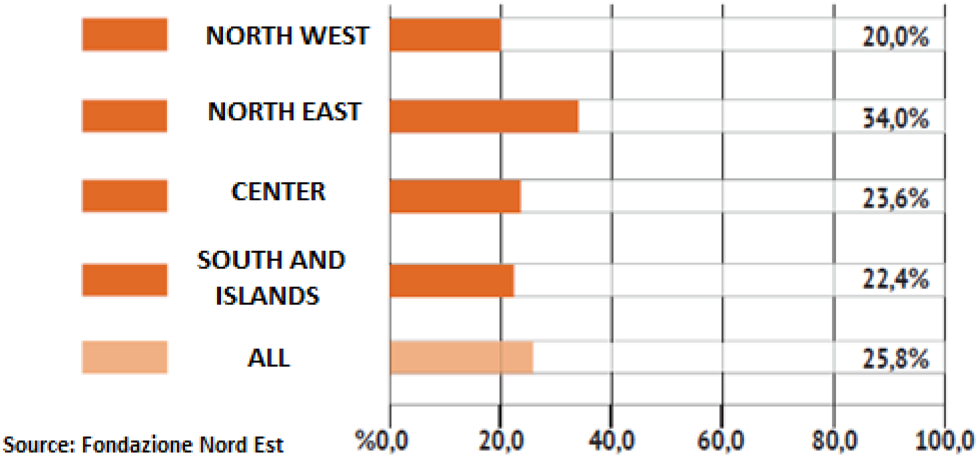


Figure 1.27 Use of digital technologies in Italy by company size (Source Prometeia in Make in Italy 2015).

At a geographical level among those companies with headquarter in the North East the percentage reaches 34% (Figure 1.28).



Source: Fondazione Nord Est

Figure 1.28 Use of digital technologies in Italy by geographical area (Source Fondazione Nord Est, in Make in Italy 2015)

The research shows that the use of 3D scanning and 3D printing among Italian companies is more widespread in the industry of jewels and precious stones as well as in dental sector 42.6%, followed by the machinery and transport sector (32,4%). In the field of wood furniture less than one company in four uses 3D printers (Figure 1.29).

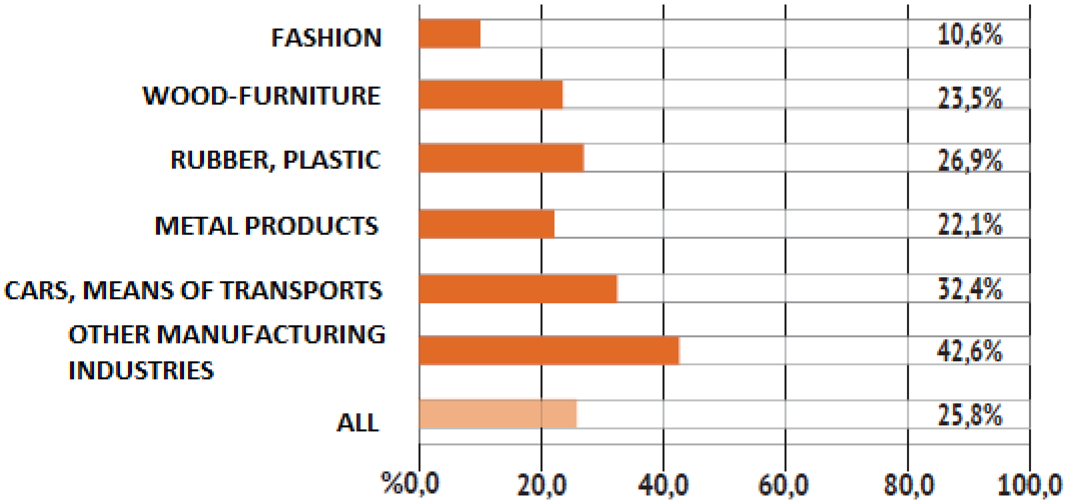


Figure 1.29 Use of digital technologies in Italy by sector (Source Make in Italy 2015)

Considering sectors, the companies of the Technological Made in Italy are using these technologies at a higher intensity than the average (27.7% compared to 25.8%). Furthermore among those who use 3D printing the 55.6% relies on external service (Make in Italy, 2015).

Moreover those businesses that do not use 3D technologies motivate their choices stating that it is a technology that does not support their business (74.7%); the 13.5% do not know the technology and the 11.8% knows it and is evaluating the purchase (Figure 1.30).

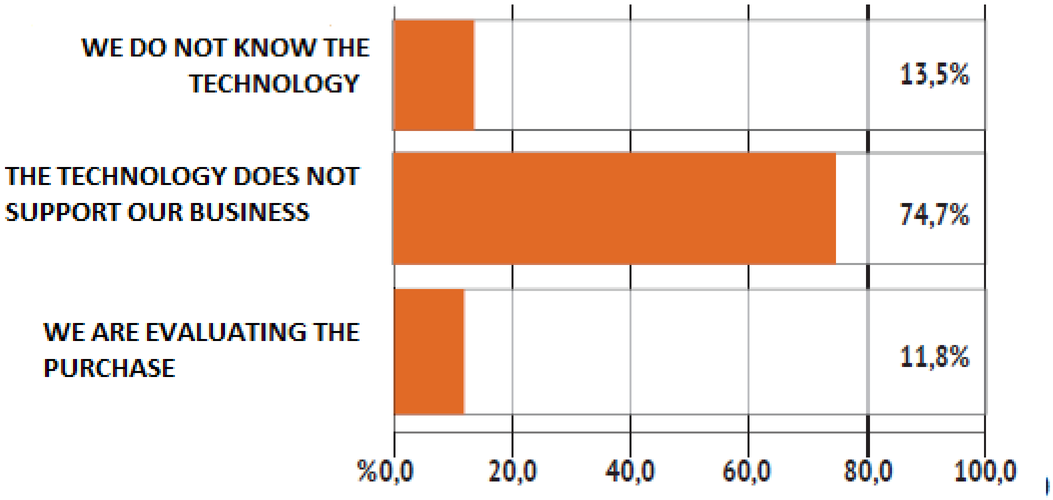


Figure 1.30 Reasons for non-using 3D technologies

The greatest benefit areas expected by Italian companies and, shown by the Make in Italy (2015) report, concern the design, in particular the reduction of design time and prototyping (40.2%), the acquisition of 3D model of existing objects (29.7%), the possibility of producing objects with shapes and geometries not possible before (28.9%) and the creation of specific 3D models for the customer (28.9). the possibility of moving the manufacturing to retail outlets (4,7%) appears unimportant.

As for the real benefits perceived among those companies that use 3D printing and 3D scanning in first place there is the reduction of the time of design and prototyping (77.5%), followed by the greater involvement of the customer in the design (55.6%) and the implementation of customer-specific 3D models (56.3%). Among the factors that prevent or slow the spread of 3D printing at the top there is the limitation of workable materials (43.3%), followed by the investment required for equipment (42%) and for the software (38.1%).

Finally, studies on the impact of these technologies perceived by the Italian companies show that 30% of companies which are using 3D printing, argues that the adoption of these technologies has a significant impact. Almost half, however, (47.5%) said they have a limited impact and in 14.4% of cases the introduction of 3D printing does not appear to have any significant impact.

The research shows as companies using 3D printing and robotics highlight in the period 2000-2014 a greater capacity for growth. In particular, after the fall index occurred in 2008-2009, the gap between 3D and robotics businesses and the ones that does not use this technology of choice has gradually widening. As for 2012, the profitability of companies who have invested in 3D and robotics is higher both in terms of Return on Sales (ROS) and Return on Investments (ROI). Even in terms of added value, companies that have invested in 3D technologies and robotics are much more performing against companies in their fields which do not adopt none of the digital manufacturing technologies (Make in Italy, 2015).

In the next section some cases of Italian companies of Made in Italy that have opened to the reality of AM will be shown, changing traditional craftsmanship of Made in Italy in digital craftsmanship worthy of being appointed as Italian.

Italian National Plan for the 4.0 industry

The 21st September 2016 was presented in Milan by the Italian Prime Minister Matteo Renzi, the National Plan for the 4.0 industry, to boost investment and Italian companies; it has come into force in the budget law in 2017 and it will have a medium-long term perspective for the period 2017-2020. The national plan was developed in line with the one developed in American and called "Manufacturing USA", the French "Industrie du Futur" and the German plan"Industrie 4.0."

The plan provides an increase of 10 billion Euro in private investment in innovation in 2017 (from 80 billion to 90 billion), 11.3 billion Euro more of private spending in the three years from 2017 to 2020 for research and development, an increase of 2,6 billion Euro of private funding, especially in the *early stage*, that is, the initial investment period. Moreover it will foresee a public commitment of 13 billion Euros, distributed in seven years between 2018 and 2024 to cover private investments made in 2017 and investments supported by the investment tax credit for research.

Among the strategic lines of action, there is that of promoting private investment in technologies and assets 4.0, increasing private spending on research, development and innovation and strengthen the financial support for 4.0 industry, venture capital and start-up.

As for skills and training, the plan wants to spread a 4.0 culture through (Piano Nazionale Industria 4.0, 2016):

- digital school and Alternating School Work;
- University paths and Technical Superiors Institutes dedicated;
- strengthening of Cluster and doctorates;
- the creation of a Competence Center and Digital Innovation Hub.

As for the benefits expected from the Industry 4.0 Plan, these are (Piano Nazionale Industria 4.0, 2016):

- more flexibility through the production of small batches at large scale costs;
- more speed from prototype to mass production through innovative technologies;
- increased productivity through reduced set-up times, reduced errors and machine downtime;
- better quality and reduced waste by means of sensors that monitor the production in real time;
- higher product competitiveness through increased functionality arising from the Internet of Things (IoT).

These Public support tools are designed with the aim to ensure private investment, support large investments in innovation, strengthen and innovate the supervision of international markets and support the wage-productivity trade through the company decentralized bargaining.

1.5 Additive Manufacturing: a change in companies’ strategies and business models

The first big change that AM is bringing in economy is due to the fact that AM impacts the economics of production by reducing minimum efficient scale, that is the point at which the average cost of each unit of production is minimized. Where minimum efficient scale is high (i.e., where there are large capital costs required to initiate production) the number of production facilities will be small. In some cases, AM may allow consumers to satisfy their individual needs without the significant labor or capital investments that might have previously been required. Research supports this conclusion. Multiple economic studies illustrate that minimum efficient scale for AM can be achieved at low unit volumes—as low as one. This cost performance contrasts with that of traditional manufacturing methods that face higher initial costs for tooling and setup (Allen, 2006; Ruffo et al. 2006; Atzeni and Salmi, 2012). Figure 1.31 illustrates a prototypical set of cost curves for AM and traditional manufacturing methods drawn from existing studies. The cost curves illustrate the change in average cost for each incremental unit of production. Breakeven between two alternative production approaches occurs where these curves cross. Figure 1.31 illustrates the achievement of minimum efficient scale for AM manufacturing, in this case, at one unit. In essence, the average cost curve is flat, suggesting that marginal cost does not change with volume. More traditional production methods may as yet yield cost advantages at higher volumes, as suggested by the declining cost curve. The research concludes that AM production, using a variety of materials, can provide an efficient alternative for low-to-medium-sized production runs (Ruffo et al., 2006; Cotteleer and Joice, 2014a).

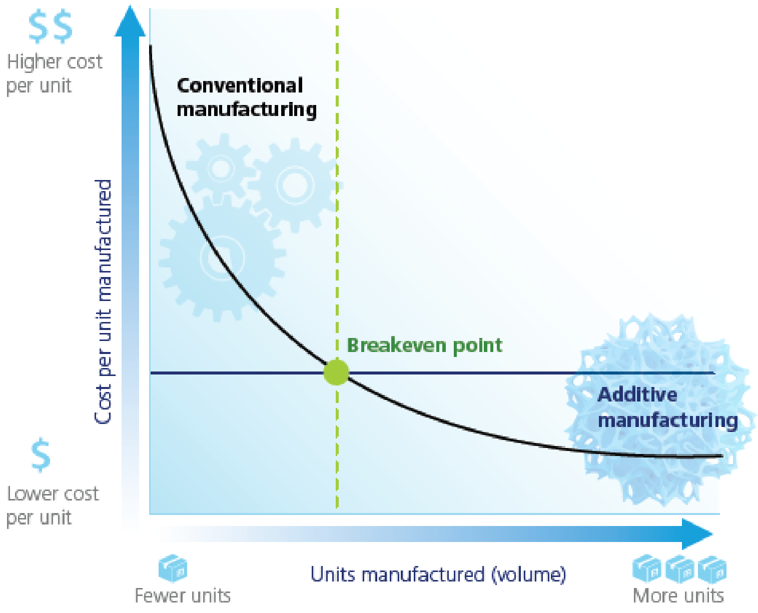


Figure 1.31 Breakeven analysis comparing conventional and additive manufacturing processes. (Source Cotteleer and Joice, 2014)

The impact of AM technologies on scope economics may exceed their impact on scale. In fact AM is known to be extremely versatile in its ability to produce different product configurations with reduced changeover time and cost (Baumers et al., 2012). Economy of scope refers to the inherent flexibility of a unit of capital. Specifically, scope economies deliver advantage by allowing for the production of multiple different end products using the same equipment, materials, and processes (Chandler, 1990). The scope impact of AM is a result of the technology's flexibility. In many cases, no changes to tooling are required to shift the AM device from producing one object to producing a totally different object (i.e., AM could sequentially produce a sword and then a plowshare without alteration to the production equipment) (Allen, 2006; Ruffo et al. 2006; Atzeni and Salmi, 2012). The implication of changes in scale and scope economies is that manufacturers may be able to produce products with potentially dramatically lower capital costs. These conclusions have direct practical implications for managers. In essence, it allows them to evaluate the applicability of AM to their operations by framing the choice relative to its impact on a company's supply chain and/or its products. In other words, companies can use AM to reconsider the ways they move products through their supply chains, and they can use these technologies to create new products or reengineer processes for making existing products (Cotteleer and Joice, 2014a).

According to Cotteleer and Joice (2014) framing the AM investment choice in this way presents companies with four tactical paths to follow as they deploy these technologies across their businesses:

1. ***Stasis***: companies will not seek radical alterations in either supply chains or products, but they may retain interest in exploring AM technologies to improve value delivery for current products within existing supply chains. It is on this stasis path that the technology has gained its foothold and contributed value over the past 30 years, being most commonly deployed for modeling, prototyping, tooling, and short-run production. Key performance enhancement offered by AM is the ability to streamline and accelerate the design process. The result of this can be a reduced time to market, improved product quality, and reduced cost.
2. ***Supply chain evolution***: companies take advantage of scale economics offered by AM as a potential enabler of supply chain transformation for the products they offer. Primarily, the derived benefits come from AM's ability to significantly reduce minimum efficient scale in production locations, alter traditional supply chains, and reduce working capital requirements. Among the key promises of AM

in redefining supply chain operations is the potential to impact field service operations and “long tail” inventory. These applications can simultaneously deliver performance improvement on all three drivers of value: profit (cost), risk, and time. Evolution in supply chains is also evidenced at the business-to-consumer level with multiple big-box retailers and other service providers leveraging scale and scope economies to deliver on-demand printing at local sites. It is the specific shifts in minimum efficient scale enabled by AM that enables this business model. In the long run, such shifts in supply chain structure may represent a key growth vector, as firms large and small try to capitalize on the ability to deliver faster, cheaper, and more precisely than their competitors. The capabilities delivered by AM, in some cases, allow for the creation of physical products that cannot be produced by other means.

3. ***Product Evolution***: companies take advantage of scope economics offered by AM technologies to achieve new levels of performance or innovation in the products they offer. AM technologies are increasingly allowing the use of multiple materials and the ability to embed sensors, electronics, and other technologies within components and products. The product evolution also presents some opportunities to improve performance. Current applications suggest that performance value is derived as much or more from the mitigation of risk as from the enhanced speed and profitability that factor so heavily along *Stasis* and *Supply chain evolution* paths. This opportunity comes from the ability to improve product fit, customize tooling, and monitor the build process in ways that are not possible using other methods.
4. ***Business model evolution***: companies alter both supply chains and products in pursuit of new business models. They try to apply AM in either sequential or simultaneous transformations of both products and the supply chains that deliver them. In essence, they seek to combine the tactics and value embedded in *Supply chain evolution* and *Product evolution* paths to achieve not only the operational advantages that define new levels of competition, but also to create new business models. In many cases these simultaneous efforts represent attempts to create new ways of delivering value in an effort to deliver growth opportunities in a manner that either creates new markets or impairs competitors’ ability to compete. It is reasonable to posit that the route to *Business model evolution* runs through the product innovation goals that characterize path III. The delivery of innovative

products may require new or revised approaches to supply chains and distribution, or it may present opportunities to disrupt competitors and markets when combined with supply chain innovation (e.g., highly customized dental crowns being manufactured at the dentist’s office). This may be particularly true where AM and digital technologies are deployed to increase the level of collaboration between producers and end users. Figure 1.32 shows the model defined by (Cotteleer and Joice, 2014)

Path III: Product evolution
- **Strategic imperative:** Balance of growth, innovation, and performance
- **Value driver:** Balance of profit, risk, and time
- **Key enabling AM capabilities:**
  - – Customization to customer requirements
  - – Increased product functionality
  - – Market responsiveness
  - – Zero cost of increased complexity

Path IV: Business model evolution
- **Strategic imperative:** Growth and innovation
- **Value driver:** Profit with revenue focus, and risk
- **Key enabling AM capabilities:**
  - – Mass customization
  - – Manufacturing at point of use
  - – Supply chain disintermediation
  - – Customer empowerment

Path I: Stasis
- **Strategic imperative:** Performance
- **Value driver:** Profit with a cost focus
- **Key enabling AM capabilities:**
  - – Design and rapid prototyping
  - – Production and custom tooling
  - – Supplementary or “insurance” capability
  - – Low rate production/no changeover

Path II: Supply chain evolution
- **Strategic imperative:** Performance
- **Value driver:** Profit with a cost focus, and time
- **Key enabling AM capabilities:**
  - – Manufacturing closer to point of use
  - – Responsiveness and flexibility
  - – Management of demand uncertainty
  - – Reduction in required inventory

Figure 1.32 Framework for understanding AM paths and value (Source Cotteleer and Joice, 2014)

1.5.1 Benefits and costs of AM

The costs of production can be categorized in two ways (Young, 1991). The first involves those costs that are “well-structured” such as labor, material, and machine costs, while the second involves “ill-structured costs” such as those associated with build failure, machine setup, and inventory. In the literature, there tends to be more focus on well-structured costs of AM than ill-structured costs; however, some of the more significant benefits and cost savings in AM may be hidden in the ill-structured costs. Moreover considering AM in the context of lean production might be useful.

A key concept of lean manufacturing is the identification of waste, which is classified into seven categories:

1) *Overproduction*: it occurs when more is produced than is currently required by customers;
2) *Transportation*: transportation does not make any change to the product and is a source of risk to the product;
3) *Rework/Defects*: discarded defects result in wasted resources or extra costs correcting the defect;
4) *Over-processing*: occurs when more work is done than is necessary;
5) *Motion*: unnecessary motion results in unnecessary expenditure of time and resources;
6) *Inventory*: is similar to that of overproduction and results in the need for additional handling, space, people, and paperwork to manage extra product;
7) *Waiting*: when workers and equipment are waiting for material and parts, these resources are being wasted.

Additive Manufacturing may impact a significant number of these categories. For example, AM may significantly reduce the need for large inventory, which is a significant cost in manufacturing. In 2011, there was an average of $208 billion or the equivalent of 14% of annual revenue held in inventory for medium- and high-tech manufacturing with an estimated cost of $52 billion or 3% of revenue. Reducing inventory frees up capital and reduces expenses (Douglas and Stanley, 2014). Moreover trying to understand the benefits and costs of the adoption of AM, inventory and transportation are two important factors. At the beginning of 2011, there were $537 billion in inventories in the manufacturing industry, which was equal to 10% of that year's revenue. The resources spent producing and storing these products could have been used elsewhere if the need for inventory were reduced. Suppliers often suffer from high inventory and distribution costs. Additive Manufacturing provides the ability to manufacture parts on demand. For example, in the spare parts industry, a specific type of part is infrequently ordered; however, when one is ordered, it is needed quite rapidly, as idle machinery and equipment waiting for parts is quite costly. Being able to produce these parts on demand using AM reduces the need for maintaining large inventory and eliminates the associated costs. As for transportation, Additive Manufacturing allows for the production of multiple parts simultaneously in the same building, making it possible to produce an entire product. Traditional manufacturing often includes production of parts at multiple locations, where an inventory of each part might be stored. Douglas and Stanley

(2014) summarize three different alternatives for AM defining a fourth one. The first is where a significant proportion of consumers purchase AM systems or 3D printers and produce products themselves (Reeves, 2008). The second is a copy shop scenario, where individuals submit their designs to a service provider that produces goods (Neef et al., 2005). The third scenario involves AM being adopted by the commercial manufacturing industry, changing the technology of design and production. They consider a fourth scenario: since AM can produce a final product in one building, there is limited exposure to hazardous conditions, and there is little hazardous waste (Huang et al., 2013). For this reason there is the potential to bring production closer to the consumer for some products (i.e., distributed manufacture). For example, currently, a more remote geographic area may order automotive parts on demand, which may take multiple days to be delivered. Additive Manufacturing might allow some of these parts or products to be produced near the point of use or even onsite (Holmstrom et al., 2010). Further, localized production combined with simplified processes may begin to blur the line between manufacturers, wholesalers, and retailers as each could potentially produce products in their facilities.

AM can also bring some changes in the supply chain of a company: the supply chain includes purchasing, operations, distribution, and integration. Purchasing involves sourcing product suppliers. Reducing the need for these activities can result in a reduction in costs. Some large businesses and retailers largely owe their success to the effective management of their supply chain. They have used technology to innovate the way they track inventory and restock shelves resulting in reduced costs. Additive Manufacturing may have significant impacts on the manufacturing supply chain, reducing the need for supply chain management. This technology has the potential to bring manufacturers closer to consumers, reducing the links in the supply chain (Douglas and Stanley, 2014). Moreover always Douglas and Stanley (2014) argue that if AM reduces the

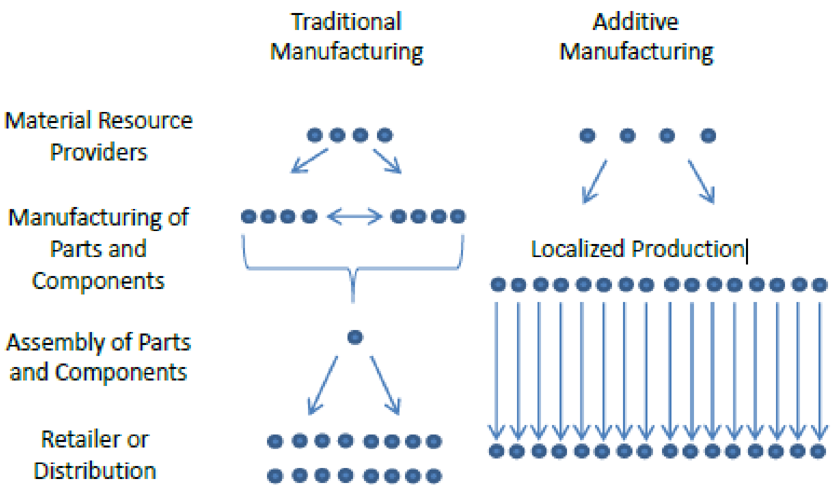


Figure 1.33 Example of Traditional Supply Chain Compared to the Supply Chain for Additive Manufacturing with Localized Production (Douglas and Stanley, 2014)

number of links in the supply chain and brings production closer to consumers, it will result in a reduction in the vulnerability to disasters and disruptions. Comparing traditional manufacturing with AM (Figure 1.33), it can be seen that under traditional manufacturing, material resource providers deliver to the manufacturers of parts and components, who might deliver parts and components to each other and then to an assembly plant. From there the assembled product is delivered to a retailer or distributer. A disruption at any of the points in manufacturing or assembly may result in a disruption of deliveries to all the retailers or distributers if there is not redundancy in the system. Additive Manufacturing with localized production does not have the same vulnerability. First, there may not be any assembly of parts or components; second, a disruption to manufacturing does not impact all of the retailers and distributors.

Furthermore with geometric freedom, AM allows products to be produced using less material while maintaining the necessary performance. Products can be produced at the level of performance needed rather than significantly exceeding the necessary performance level because of limitations in traditional manufacturing. Currently, however, the price of materials for AM can often exceed those of traditional manufacturing.

As discussed previously, metal and plastic are the primary materials used for this technology. Atzeni and Salmi (2011) showed that the material costs for a selected metal part made from aluminium alloys was €2.59 per part for traditional manufacturing and €25.81 per part for AM using selective laser sintering; thus, the Additive Manufacturing material was nearly ten times more expensive. The material costs of AM are significant; however, technologies can often be complementary, where two technologies are adopted alongside each other and the benefits are greater than if they were adopted individually. One example is computer aided design and computer aided manufacturing, as both are needed to be utilized for the other to be valuable (Douglas and Stanley, 2014). Additive Manufacturing and the raw materials that are used may be a condition where they are complementary (Baumers, 2012). All AM requires raw materials, and according to Stoneman (2002) this may create a feedback loop. Increasing adoption of AM may lead to a reduction in raw material cost through economies of scale. In addition to material costs, machine cost is one of the most significant costs involved in AM. The average selling price of an industrial AM system was $73,220 in 2011 (Wohlers Report, 2012); moreover large differences remain between the costs for polymer-based systems and metal-based systems, and the tremendous growth in sales of low-cost, polymer-based systems during this time has strongly influenced the average selling price of AM systems.

Subsequently also build time is a significant component in regard to estimating the cost of AM. There tends to be two approaches to estimating build time: the first one is detailed analysis and the second one is parametric analysis (Di Angelo and Di Stefano, 2011). Detailed analysis utilizes knowledge about the inner workings of a system, while parametric analysis utilizes information on process time and characteristics such as layer thickness. Build time estimations tend to be specific to the system and material being used (Douglas and Stanley, 2014).

Finally among the factors that could influence AM costs and benefits there are energy consumption and labor. Energy consumption, however, is an important factor in considering the cost of AM compared to other methods of manufacturing, especially in terms of examining the costs from cradle to grave. Energy studies on AM, however, tend to focus only on the energy used in material refining and by the AM system itself (Hopkinson and Dickens, 2003; Baumers et al., 2011; Morrow et al., 2007; Telenko and Seepersad, 2012). As for labor, it tends to be a small portion of the AM cost. Labor might include removing the finished product or refilling the raw material among other things. Hopkinson and Dickens (2003) estimate labor at 2% of the cost, while Ruffo et al. (2006) estimate it between 2% and 3%. It is important to note that additional labor is built into the other costs such as the material cost and machine cost, as these items also require labor to produce. Table 1.5 summarizes the major benefits and costs of AM discussed above.

Table 1.5 Main AM benefits and costs

AM Benefits	***AM costs***
Total freedom of design **(geometric complexity)**	**Self production**: threat for the manufacturing industry
Product customization **(this lead to major customer satisfaction)**	**Purchase cost of 3D printers**
Reduction in production cost: **- cancellation of production lines;** **- elimination of production waste,**	**Procurement costs of materials** (in relation to the procurement of production raw materials)
Ability to print parts and mechanisms already assembled: **- reduction of labor costs for assembly.**	**Greater production times with lower production volumes**
Economies of scope	**No economies of scale**
Reduced environmental impact: **- there are no waste production to recycle;** **- tons of material reduction;**	**Heavier quality control?** (See par. 1.5.2)

- recycling of biodegradable products; **- reduction of exhaust gas and fuel savings.**	
Reducing in time-to-market: **- production of small batches to be sent immediately on the market in order to verify their effectiveness.**	**Purchase and update of CAD systems**
Ability to serve niche markets	**Air pollution during 3D printing production?** (See Chapter 4)
Reduced inventory costs: **- on demand products;** **- Just-in-Time inventory;**	-
Reducing transportation costs: **- the product is sent electronically to the customer.**	-

1.6 Is there a need for standardization in Additive Manufacturing?

Additive Manufacturing produces objects by layering materials such as metals, composites, or polymers to produce a three-dimensional part rather than, for example, machining parts from blocks of raw material, as with conventional manufacturing. However, while companies have widely explored AM's potential to shrink the scale and scope necessary for manufacturing, bring to life previously impossible designs, and alter the makeup of organizational supply chains, several significant hurdles prevent its wider adoption. One of the most important barriers is the qualification of AM-produced parts (AlGeddawy and ElMaraghy, 2011). This issue is so crucial, in fact, that many characterize Quality Assurance (QA) as the single biggest hurdle to widespread adoption of AM technology, particularly for metals. Many manufacturers and end users have difficulty stating with certainty that parts or products produced via 3D printing, whether all on the same printer or across geographies, will be of consistent quality, strength, and reliability. Without this guarantee, many manufacturers will remain leery of AM technology, judging the risks of uncertain quality to be too costly a trade-off for any gains they might realize (Wing et al., 2015).

Quality Assurance (QA) presents a multifaceted challenge, encompassing both the scale and scope of production. Indeed, quality doesn't just exist on one dimension, and each area should be addressed for parts qualification, and AM's potential, to be more fully realized.

In order to address the challenge of certifying quality for AM-produced parts along these four facets, manufacturers can develop capabilities that will enable them to:

- ***Identify*** the level of QA their products need, and what level of risk they are willing to assume;
- ***Accurately predict*** whether parts will meet specifications when built under "idealized" conditions;
- ***Ensure repeatability, consistency, and reliability*** across different AM machines and geographies;
- ***Incorporate the appropriate technologies and capabilities*** necessary to qualify AM-produced parts, based on the target QA level.

In order to reach these targets International Standardization bodies such as the International Organization for Standardization (ISO) and The American Society for Testing and Materials (ASTM) are cooperating to create international recognized standards on Additive Manufacturing, in order to cover the lack of supporting framework and industrial standards. In fact it is difficult for AM to compete with traditional techniques; for companies looking for a rejection rate of just a few parts per million, there is no way AM can come close to that. This is because a set of standards can help guarantee a level of reproducibility, and give business and manufacturers the much needed assurance that AM processes, materials and technologies are safe and reliable. Klas Boivie, Convenor of ISO/TC 261's working group WG 1 for AM terminology, explained that the appetite for AM standards is relatively recent. The initiative came from the AM community, where it was very clear that this technology had the capability for much wider industrial application, but the industry was slow and skeptical about using it, unless for very special or non-critical applications. This motivated a group of key actors within the international AM community to initiate a discussion for the creation of technical standards for AM. However, since this group could not be certain to gather a wide enough international support, the initiative was brought to ASTM International, which led to the creation of *ASTM committee F42* for Additive Manufacturing technologies in 2009. While this debate was going on, the Association of German Engineers (VDI) was hard at work on a series of guidelines for what was then called "rapid technologies". These guidelines eventually led to the creation of ISO/TC 261, in 2011, whose secretariat is held by the Deutsche Institut für Normung (DIN)[15] , the ISO member for Germany.

With the international AM community being so small, many of the experts invited to review the standard proposal were already involved with ASTM F42. The creation of ISO/TC 261 raised serious concerns about work duplication, or worse, the development of competing standards, but the two organizations decided to cooperate and developed an ASTM/ISO partnership agreement. The two organizations agreed in giving priority to terminology and general principles, which will provide the bedrock for the development of any future standards (Tranchard and Rojas, 2015 in www.iso.org). The standard on general principles has been developed and published yet on 15th February 2015 under the name of ISO/ASTM 52915:2016. The two organizations are now still working together in developing other AM standards and at the same time they are producing and have produced other AM standards independently (www.iso.org; www.astm.org).

Figure 1.34 shows the list of AM technology standards developed by ASTM, while Figure 1.35 shows the standards developed by ISO, in detail 17296 part 2, 3 and 4. Finally Figure 1.36 shows the standards and projects under development under the direct responsibility of ISO/TC 261 Secretariat.

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[15] Deutsches Institut für Normung (DIN) is the German national Organization for Standardization and is the German ISO member body. DIN is a German Registered Association with headquartered in Berlin. There are currently around thirty thousand DIN Standards, covering nearly every field of technology.

Design

Designation	Title
ISO / ASTM52915 - 16	Standard Specification for Additive Manufacturing File Format (AMF) Version 1.2

Materials and Processes

Designation	Title
F2924 - 14	Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion
F3001 - 14	Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion
F3049 - 14	Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes
F3055 - 14a	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion
F3056 - 14e1	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion
F3091 / F3091M - 14	Standard Specification for Powder Bed Fusion of Plastic Materials

Terminology

Designation	Title
ISO / ASTM52900 - 15	Standard Terminology for Additive Manufacturing – General Principles – Terminology

Test Methods

Designation	Title
F2971 - 13	Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing
F3122 - 14	Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes
ISO / ASTM52921 - 13	Standard Terminology for Additive Manufacturing-Coordinate Systems and Test Methodologies

Figure 1.34. List of ASTM standards on Additive Manufacturing

ISO/TC 261 - Additive manufacturing

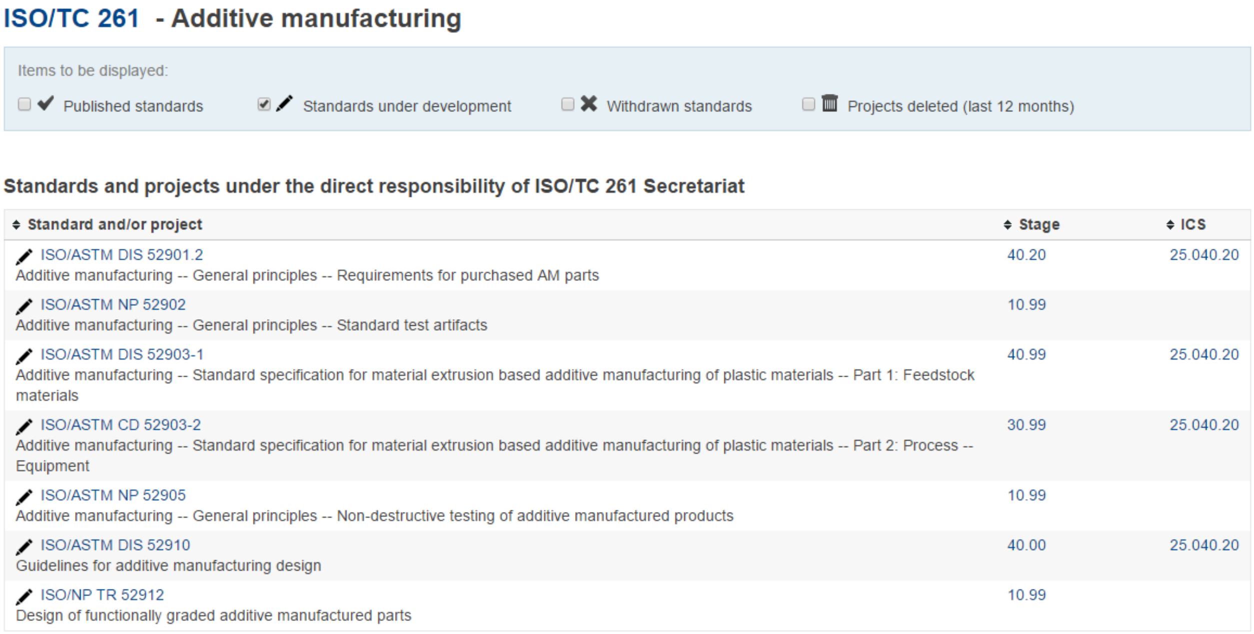
Items to be displayed:

☑ ✓ Published standards ☐ Standards under development ☐ ✖ Withdrawn standards ☐ Projects deleted (last 12 months)

Standards and projects under the direct responsibility of ISO/TC 261 Secretariat and its SCs

Standard and/or project	Stage	ICS	TC
✓ ISO 17296-2:2015 Additive manufacturing -- General principles -- Part 2: Overview of process categories and feedstock	60.60	25.040.20	ISO/TC 261
✓ ISO 17296-3:2014 Additive manufacturing -- General principles -- Part 3: Main characteristics and corresponding test methods	60.60	25.040.20	ISO/TC 261
✓ ISO 17296-4:2014 Additive manufacturing -- General principles -- Part 4: Overview of data processing	60.60	25.040.20	ISO/TC 261
✓ ISO/ASTM 52900:2015 Additive manufacturing -- General principles -- Terminology	60.60	01.040.25 25.040.20	ISO/TC 261
✓ ISO/ASTM 52915:2016 Specification for additive manufacturing file format (AMF) Version 1.2	60.60	35.240.50 25.040.20	ISO/TC 261
✓ ISO/ASTM 52921:2013 Standard terminology for additive manufacturing -- Coordinate systems and test methodologies	60.60	25.040.20	ISO/TC 261

Figure 1.35 List of ISO standards on Additive Manufacturing



ISO/TC 261 - Additive manufacturing

Items to be displayed:

☐ ✓ Published standards ☑ ✎ Standards under development ☐ ✗ Withdrawn standards ☐ 🗑 Projects deleted (last 12 months)

Standards and projects under the direct responsibility of ISO/TC 261 Secretariat

Standard and/or project	Stage	ICS
✎ ISO/ASTM DIS 52901.2 Additive manufacturing -- General principles -- Requirements for purchased AM parts	40.20	25.040.20
✎ ISO/ASTM NP 52902 Additive manufacturing -- General principles -- Standard test artifacts	10.99	
✎ ISO/ASTM DIS 52903-1 Additive manufacturing -- Standard specification for material extrusion based additive manufacturing of plastic materials -- Part 1: Feedstock materials	40.99	25.040.20
✎ ISO/ASTM CD 52903-2 Additive manufacturing -- Standard specification for material extrusion based additive manufacturing of plastic materials -- Part 2: Process -- Equipment	30.99	25.040.20
✎ ISO/ASTM NP 52905 Additive manufacturing -- General principles -- Non-destructive testing of additive manufactured products	10.99	
✎ ISO/ASTM DIS 52910 Guidelines for additive manufacturing design	40.00	25.040.20
✎ ISO/NP TR 52912 Design of functionally graded additive manufactured parts	10.99	

Figure 1.36 ISO standards and projects under development under the direct responsibility of ISO/TC 261 Secretariat

1.7 The future: 4D printing

The advancement on 3D printing are flowing now on a new technology that is taking the name of 4D printing. In literature it is said that 3D printing technology is maturing creeping up in the background and creating four-dimensional (4D) printing (Pei, 2014b). It is not about how long it takes for a part to be printed; but rather the fact that the 3D printed object still continues to “shape shift” and evolve over a period of time (Pei, 2014a). The main difference is that conventional 3D printing produces parts that are generally static and inanimate, whereas 4D printing involves carefully designed geometries with precisely controlled deposition of different materials or active fibres that can reshape when subject to external stimuli. Think about the bi-metallic strip that we are all familiar with in school textbooks. The strip consists of two different metals that expand at different rates when heated. One side will bend one way when hot and the other side will curve in the opposite direction when cold. Pei (2014b) makes the example of having a bi-metallic strip being 3D printed where it will react to the environment, which in this case ambient heat is the stimuli. If this is applied to a practical product such as a 3D printed window blind, it will bend and close to shade the home; or if one desires, opens when the sun is up. Therefore for 4D printing to occur, three aspects must be fulfilled. The first is the use of stimuli-responsive composite materials that are blended or incorporate multi-materials with varying properties being sandwiched layer upon layer. The second is the stimulus that will act on the material. Examples of stimuli include heating, cooling, gravity, ultraviolet (UV) light, magnetic energy, wind, water or even humidity. The last aspect to be fulfilled is the amount of time for the simulation to occur, and the final result is the change of state of the object (Pei, 2014b). Khoo et al., (2015) define these materials used for 4D printing as smart materials, that is to say materials that would either change their shape or properties between different physical domains in a useful manner under the influence of certain stimuli from the environment. Due to the ability of smart materials, the 3D fabricated components consisting of such materials would be able to evolve in a predefined manner over time. Hence, this gives rise to a new term called "4D printing" (Tibbits et al. 2013). However, not all 3D printing processes that produce animate components such as printed living hinges are categorised as 4D printing since they do not demonstrate "smart" behaviour such as self-sensing, self-actuating and shape changing (Bogue 2014; Pei, 2014). Hence, in order to differentiate 3D printing from 4D printing, the definition of 4D printing needs to be properly defined. According to Pei (2014), 4D printing is *"the process of building a physical object using appropriate Additive Manufacturing technology, laying down successive layers of stimuli-responsive composite or multi-material with varying properties. After being built, the object reacts to stimuli from the natural environment or through human intervention, resulting in a physical or chemical change of state through time"*. On the other hand, Tibbits et al. (2013) stated 4D printing as a new process that *"entails multi-material prints with the capability to transform over time, or a customised material system that can change from one shape to another, directly off the print bed"* with *"the fourth dimension described here as the transformation over time, emphasising that printed structures are no longer static, dead objects; rather, they are programmably active and can transform independently"*. Thus, according to these two definitions, the main difference between them is that Pei (2014) considered 4D printing to incorporate either a physical or chemical change of state while Tibbits et al. (2013) only considered shape changes. As a result of these two definitions Khoo et al. (2015) defined 4D printing is *"an AM process that integrates smart materials into the starting form of the printing material for 3D printed structures/components. After fabrication, the 3D object would respond in an intended manner to external stimuli from the environment or through human interference, resulting in a change in shape or physical properties over time"*.

Over the past few months, we have seen a plethora of projects exploring potential applications of 4D printing with proof-of-principle prototypes being demonstrated. Very recently, MIT researchers revealed a "bakeable robot" made up of printed components that fold into a prescribed 3D structure when subjected to heat (Hardesty, 2014). This requires exact control of angles at which the heated sheet would fold. The material structure is composed of a polyvinyl chloride (PVC) sheet sandwiched between two films of rigid polyester. When hot, the PVC layer contracts and the edges fold, leading to the pre-determined geometry being formed. Other projects are those cited in the articles of Byoungkwon and Rus (2012), Ge *et al.* (2013), University of Pittsburgh (2013).

However multi-material printing at this time is still limited and one of the most widespread commercial systems in the market is PolyJet printing from Stratasys that was patented in early 2000s. In principle, the technology is similar to how inkjet printers work. The Objet Connex 3D printer, which uses this technology, jets layers of UV-curable liquid photopolymerm onto a printing bed, which allows composite materials with predetermined mechanical properties known as “digital materials” to be produced. Nevertheless another area for growth potential in 4D printing, along the whose direction researches are going, is fused deposition modelling (FDM) (Espalin et al., 2014).

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FABRICATION LABORATORIES: WHERE 3D PRINTING COMES TO LIFE

"Give ordinary people the right tools, and they will design and build the most extraordinary things."

ABSTRACT

Chapter 2 deals with the places where digital manufacturing technologies and 3D printing take shape, that is, Fabrication Laboratories (Fab Labs). They are defined as a platform for learning and innovation: a place to play, to create, to learn, to mentor, to invent. After describing the born of the International Maker Movement, the chapter describes the typical layout of these digital manufacturing spaces, where makers operate; the tools and machines used in it and the people that appeal to it. Subsequently the Italian economic reality of Fab Labs is taken into account, describing the diffusion and typology of laboratories present in the territory, and making a comparison with the other major European and American ones.

2.1 Digital Manufacturing and the International Maker Movement

The meaning of the word "manufacture" is historically linked to that of "craftsman"; shops and large manufacturing industries often have a common past made up of creativity, inspiration, dedication and manual work. Almost always the distinctive element, between industry and craftsmanship, is concretized in size and production capacity on the one hand and in uniqueness and specialization on the other. Digital Manufacturing brings us back to technology-induced change. This change, if applied to reality where design, personalization and work on the single product are particularly relevant, stimulates and paves the way for digital craftwork. With the gradual adoption of Digital Manufacturing's own technologies, there is a gradual process of convergence and approach between the model of creation, design and handicraft production, and the manufacturing model on a large scale. Digital Manufacturing represents for large-scale manufacturing the opportunity to approach the customer's specificity and product uniqueness, while maintaining the dimensional characteristics that are typical of industrial production. Digital, artisan or industrial manufactures offer the ability to design and produce new product solutions by following innovative manufacturing processes that are developed through market dynamics stimulated by a constantly changing demand. In this way, the world of handicrafts and manufacturing is also approaching consumers who are not usually involved because of cultural, economic and/or logistical barriers (Pricewaterhouse and Confartigianato Imprese Varese, 2015).

In this context lies the definition of Maker Movement which consists of a growing culture of hands-on making, creating, designing, and innovating. It has been with the launch of MAKE Magazine in 2005, that Dale Dougherty and his team provided the catalyst for a tech-influenced Do-It-Yourself (DIY) community that has come to be identified as the Maker Movement (Dougherty, 2012) . A hallmark of the maker movement is DIY mindset that brings together individuals around a range of activities, including textile craft, robotics, cooking, woodcrafts, electronics, digital fabrication, mechanical repair, or creation, making nearly anything. Despite its diversity, the movement is unified by a shared commitment to open exploration, intrinsic interest, and creative ideas. It’s spreading through Online maker communities, physical makerspaces, and Maker Faires are popping up all over the world and continually increasing in size and participation (Dougherty, 2013; Peppler and Bender, 2013).

The maker movement refers broadly to the growing number of people who are engaged in the creative production of artifacts in their daily lives and who find physical and digital forums to share their processes and products with others (Halverson and Sheridan, 2014).

According to Manzo and Ramella (2015), makers might be called the new craftsmen of the digital era. Many of them are hobbyists and amateurs. Werner Sombart (1916) would have classified them as «sunday inventors». Others, however, are proto-entrepreneurs who use their creative and professional skills to launch new products and activities. These, would have been defined by Sombart (1916) as “weekday inventors” or “inventors of anything”.

Makers are often young people with a passion for personal fabrication: they combine DIY with the use of digital technologies, thus giving rise to new economic phenomena. In some cases, these are activities that are not primarily motivated by reasons of acquisitiveness and are not aimed at producing goods for the market: they follow a different logic, based on cooperation, the dissemination and sharing of knowledge and the application of open source principles to the manufacture of material objects. In other cases, these are activities that do not exclude commercial purposes, generating productive and entrepreneurial phenomena that collocate them partly in the context of the sharing economy and partly in that of the market economy (Manzo and Ramella, 2015).

It is believed that the maker movement has the potential to transform how and what people learn in Science, Technology, Engineering, and Mathematics (STEM) and arts disciplines (Peppler and Bender, 2013). President Obama spoke about it in his remarks on the Educate to Innovate campaign, saying *"see the promise of being the makers of things, and not just the consumers of things"* (Obama, 2009). This orientation toward personal fabrication rather than blind consumerism is also seen as the foundation for a new, more prosperous economy.

Always president Obama, at the first ever White House Maker Faire in 2014, declared *"I am calling on people across the country to join us in sparking creativity and encouraging invention in their communities"* (White House, 2014).

Chris Anderson (2012), former editor-in-chief of *Wired* magazine, defines the movement as "a new industrial revolution." He distinguishes between the maker movement and tinkerers, inventors, and entrepreneurs of prior eras by referencing three key characteristics: the use of digital desktop tools, a cultural norm of sharing designs and collaborating online, and the use of common design standards to facilitate sharing and fast iteration.

Mark Hatch (2014), Chief Executive Officer (CEO) and cofounder of TechShop, one of the first and most successful makerspaces, has also proposed a "Maker Movement Manifesto" that describes makers' activities and mind-sets organized around nine key ideas: make, share, give, learn, tool up (i.e., secure access to necessary tools), play, participate, support, and change. Like Anderson, Hatch highlights the importance of the construction of physical objects as a feature of the maker movement that makes it distinct from the earlier computational and Internet revolutions. Hacth's Manifesto is the following:

> **MAKE**
>
> Making is fundamental to what it means to be human. We must make, create, and express ourselves to feel whole. There is something unique about making physical things. These things are like little pieces of us and seem to embody portions of our souls.
>
> **SHARE**
>
> Sharing what you have made and what you know about making with others is the method by which a

maker’s feeling of wholeness is achieved. You cannot make and not share.

GIVE

There are few things more selfless and satisfying than giving away something you have made. The act of making puts a small piece of you in the object. Giving that to someone else is like giving someone a small piece of yourself. Such things are often the most cherished items we possess.

LEARN

You must learn to make. You must always seek to learn more about your making. You may become a journeyman or master craftsman, but you will still learn, want to learn, and push yourself to learn new techniques, materials, and processes. Building a lifelong learning path ensures a rich and rewarding making life and, importantly, enables one to share.

TOOL UP

You must have access to the right tools for the project at hand. Invest in and develop local access to the tools you need to do the making you want to do. The tools of making have never been cheaper, easier to use, or more powerful.

PLAY

Be playful with what you are making, and you will be surprised, excited, and proud of what you discover.

PARTICIPATE

Join the Maker Movement and reach out to those around you who are discovering the joy of making. Hold seminars, parties, events, maker days, fairs, expos, classes, and dinners with and for the other makers in your community.

SUPPORT

This is a movement, and it requires emotional, intellectual, financial, political, and institutional support. The best hope for improving the world is us, and we are responsible for making a better future.

CHANGE

> Embrace the change that will naturally occur as you go through your maker journey. Since making is fundamental to what it means to be human, you will become a more complete version of you as you make.
>
> *In the spirit of making, I strongly suggest that you take this manifesto, make changes to it, and make it your own. That is the point of making (Hatch, 2014).*

Hatch (2014) said that *"The real power of this revolution is its democratizing effects. Now, almost anyone can innovate. Now almost anyone can make. Now, with the tools available at a makerspace, anyone can change the world"* (Hatch, 2014, p. 10).

The celebration of the Maker Movement is a large scale event called Maker Faire. It defines itself as *"part science fair, part county fair, and part something entirely new, Maker Faire is an all-ages gathering of tech enthusiasts, crafters, educators, tinkerers, hobbyists, engineers, science clubs, authors, artists, students, and commercial exhibitors."* All of these "makers" come to Maker Faire to show what they have made and to share what they have learned.

The launch of Maker Faire in the Bay Area in 2006 demonstrated the popularity of making and interest among legions of aspiring makers to participate in hands-on activities and learn new skills at the event. 200,000 people annually attend the Maker Faires in the Bay Area and New York. It is a family-friendly event, in fact 50% of people attend the event with children. In 2017, over 190 independently-produced "Mini Maker Faires" plus over 30 larger-scale Featured Maker Faires will have taken place around the world, including Tokyo, Rome, Shenzhen, Taipei, Seoul, Paris, Berlin, Barcelona, Detroit, San Diego, Milwaukee, and Kansas City. Maker Faire is primarily designed to be forward-looking, showcasing makers who are exploring new forms and new technologies. But it's not just for the novel in technical fields; Maker Faire features innovation and experimentation across the spectrum of science, engineering, art, performance and craft (http://makerfaire.com/makerfairehistory/; Peppler and Bender, 2013). According to Dougherty (2012) at Maker Faire, *"we see innovation "in the wild." It hasn't been "domesticated" or controlled, you have to look for it, and to turn a corner at any of our Faires is to see something you haven't seen before."*

2.2 Fabrication Laboratories

The Fab Foundation[16] defines a Fabrication Laboratory (Fab Lab) as an *"educational outreach component of Massachussetts Institute of Technology's (MIT) Center for Bits and Atoms (CBA)[17], an extension of its research into digital fabrication and computation. A Fab Lab is a technical prototyping platform for innovation and invention, providing stimulus for local entrepreneurship. A Fab Lab is also a platform for learning and innovation: a place to play, to create, to learn, to mentor, to invent. To be a Fab Lab means connecting to a global community of learners, educators, technologists, researchers, makers and innovators - a knowledge sharing network that spans 30 countries and 24 time zones. Because all Fab Labs share common tools and processes, the program is building a global network, a distributed laboratory for research and invention."* (http://fabfoundation.org).

This international network was founded by MIT professor Neil Gershenfeld, who opened the CBA in 2001. The name of the centre clearly illustrates the idea that inspired the Fab Labs: the setting up of places where information technology meets productive activity – where, in other words, new objects are created using digital design interacting with machines that operate on physical materials. In short, then, laboratories where bits interact with atoms. The Fab Lab project builds on the success with MIT students of an experimental course launched by Gershenfeld in 1998 called "How to Make (Almost) Anything", the intention of which was to bring together personal and digital fabrication, individual creativity and group collaboration (Manzo and Ramella, 2015).

Gershenfeld (2008), in his book, *"Fab, the coming revolution on your desktop - from personal computers to personal fabrication*", tells where and how the idea of creating the first Fab Lab was born with these words:

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[16] The **Fab Foundation** is a foundation formed in 2009 to facilitate and support the growth of the International fab lab network as well as the development of regional capacity-building organizations. The Fab Foundation is a US non-profit organization that emerged from MIT's Center for Bits & Atoms Fab Lab Program. The mission of the foundation is to provide access to the tools, the knowledge and the financial means to educate, innovate and invent using technology and digital fabrication to allow anyone to make (almost) anything, and thereby creating opportunities to improve lives and livelihoods around the world. Community organizations, educational institutions and non-profit concerns are our primary beneficiaries. The Foundation's programs focus on: education, organizational capacity building and services and business opportunity.

[17] The **Massachussetts Institute of Technology's (MIT) Center for Bits and Atoms (CBA)** is an interdisciplinary initiative exploring the boundary between computer science and physical science. CBA studies how to turn data into things, and things into data. It manages facilities, runs research programs, supervises students, works with sponsors, creates startups, and does public outreach. CBA's projects involve collaborations with researchers from across MIT's campus and around the world. (http://cba.mit.edu/about/).

“ To develop real working personal fabricators that can operate on a larger scale, my colleagues at MIT and I assembled an array of machines to make the machines that make machines [...]The problem we quickly ran into was that it would take a lifetime of classes for students to master all of the tools, and even then the students would get little practical experience in combining these tools to create complete working systems. So, we thought, why not offer a single-semester course that would provide a hands-on introduction to all the machines? In 1998 we tried teaching “How To Make (almost) Anything” for the first time. The course was aimed at the small group of advanced students who would be using these tools in their research. Imagine our surprise, then, when a hundred or so students showed up for a class that could hold only ten. They weren’t the ones we expected, either; there were as many artists and architects as engineers. And student after student said something along the lines of “All my life I’ve been waiting to take a class like this,” or “I’ll do anything to get into this class.” Then they’d quietly ask, “This seems to be too useful for a place like MIT—are you really allowed to teach it here?” Students don’t usually behave that way. Something had to be wrong with this class, or with all the other classes I taught. I began to suspect the latter. [...]The increasing accessibility of space and time means that a relatively modest facility (on the scale of the MIT class) can be used to create physical forms as fine as microns and program logical functions as fast as microseconds. Such a lab needs more complex consumables than the ink required by a printer, including copper-clad boards to make circuits and computer chips to embed

into projects. But, as the students found at MIT, these capabilities can be combined to create complete functioning systems. [...]This thought led to the launch of a project to create field "Fab Labs" for exploring the implications and applications of personal fabrication in those parts of the planet that don't get to go to MIT. As you wish, "Fab Lab" can mean a lab for fabrication, or simply a fabulous laboratory. [...] a Fab Lab is a collection of commercially available machines and parts linked by software and processes we developed for making things. The first Fab Labs have a laser cutter to cut out two dimensional shapes that can be assembled into three-dimensional structures, a sign cutter that uses a computer-controlled knife to plot flexible electrical connections and antennas, a milling machine that moves a rotating cutting tool in three dimensions to make circuit boards and precision parts, and the tools for programming tiny high speed microcontrollers to embed logic. [...] This is not a static configuration; the intention over time is to replace parts of the Fab Lab with parts made in the Fab Lab, until eventually the labs themselves are self-reproducing.

Starting in 2002, the first Fab Labs went to rural India, Costa Rica, northern Norway, inner-city Boston, and Ghana. The equipment and supplies for each site initially cost about twenty thousand dollars. Knowing that this cost will come down as the technology progresses, the first Fab Labs weren't meant to be economically self-sustaining. One of the first surprises from the field was the demand for duplicating the labs even at that cost. In keeping with the Fab Lab project's goal of discovering which tools

> *and processes would be most useful in the field, we started setting up these labs long before we knew how best to do it. The response in the field was as immediate as it had been at MIT. We ended up working in so many far-flung locations because we found a demand for these capabilities around the world that was every bit as strong as that around campus.” (Gershenfeld, 2008, pp. 12 e 17-19).*

The rapid proliferation of Fab Labs in many countries over the past decade must be understood against this background. Figure 2.1 shows the actual maps of Fab Labs present all over the world. These are in total at present (September 2017) 1176.

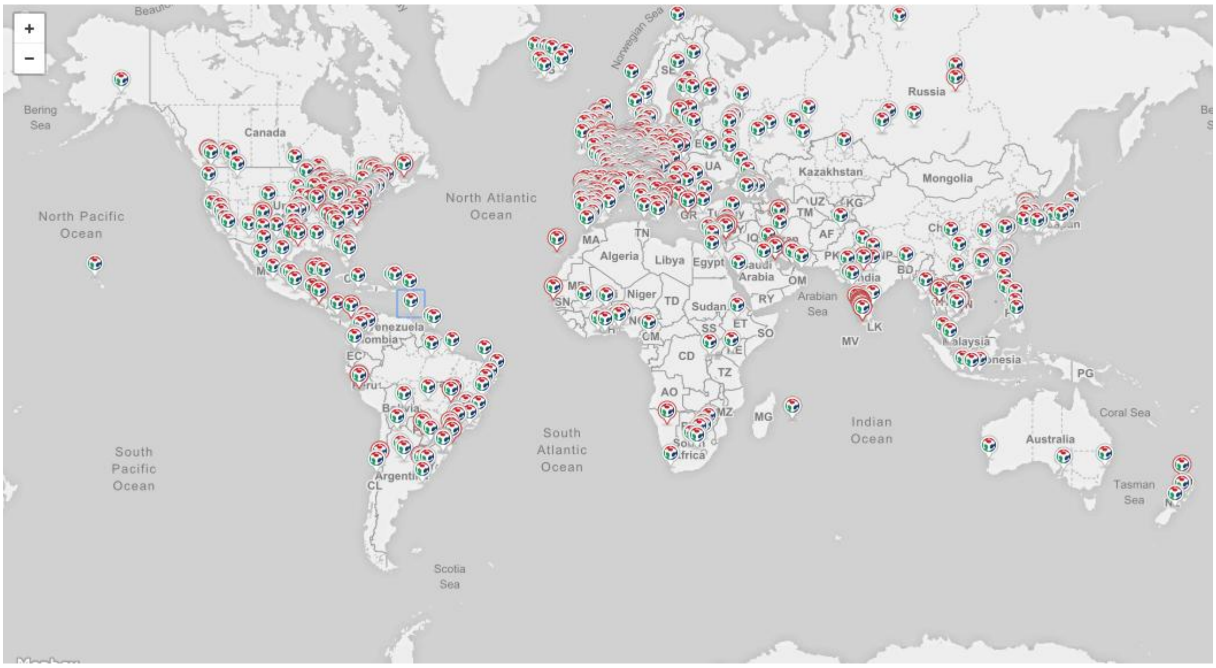

Figure 2.1 Maps of Fab Labs present in the world (https://www.fablabs.io/labs)

These laboratories work with the typical mechanisms of the sharing economy: they provide a space with tools and equipment for digital manufacturing, making them available to individual users, small businesses and schools. There are three main objectives (Manzo and Ramella, 2015):

a) training;
b) the promotion of digital fabrication;
c) the development of open-innovation.

Fab Labs have certain distinctive features, such as a strong specialisation in digital technologies for rapid prototyping; the sharing of certain guiding principles and the membership of an international network of laboratories that employ the same procedures and equipment. They are small laboratories open to the public, with digital manufacturing equipment and services and possessing two main profiles: a) on the one hand they are a *technical platform* for innovation, aimed at stimulating local entrepreneurship; b) and on the other they are a *social platform* for innovation, designed to stimulate learning, creativity and peer-to-peer collaboration (Manzo and Ramella, 2015).

The Fab Foundation describes four essential features that registered Fab Labs must have (http://fabfoundation.org/ what-qualifies-as-a-fab-lab/):

1. **Public access** to the Fab Lab is essential. A Fab Lab is about democratizing access to the tools for personal expression and invention. So a Fab Lab must be open to the public for free or in-kind service/barter at least part of the time each week, that's essential.
2. Fab Labs have to support and subscribe to the **Fab Charter**. This document is the following:

The Fab Charter

What is a Fab Lab?

Fab Labs are a global network of local labs, enabling invention by providing access to tools for digital fabrication

What's in a Fab Lab?

Fab Labs share an evolving inventory of core capabilities to make (almost) anything, allowing people and projects to be shared

What does the Fab Lab network provide?

Operational, educational, technical, financial, and logistical assistance beyond what's available within one lab

Who can use a Fab Lab?

Fab Labs are available as a community resource, offering open access for individuals as well as scheduled access for programs

What are your responsibilities?
safety: not hurting people or machines
operations: assisting with cleaning, maintaining, and improving the lab
knowledge: contributing to documentation and instruction

Who owns Fab Lab inventions?
Designs and processes developed in Fab Labs can be protected and sold however an inventor chooses, but should remain available for individuals to use and learn from

How can businesses use a Fab Lab?
Commercial activities can be prototyped and incubated in a Fab Lab, but they must not conflict with other uses, they should grow beyond rather than within the lab, and they are expected to benefit the inventors, labs, and networks that contribute to their success

(http://fabfoundation.org/ the-fab-charter/)

3. Fab Labs have to **share a common set of tools and processes**. A prototyping facility is not the equivalent of a Fab Lab. A 3D printer is not a Fab Lab. The idea is that all the labs can share knowledge, designs, and collaborate across international borders. *"If I make something here in Boston and send you the files and documentation, you should be able to reproduce it there, fairly painlessly. If I walk into a Fab Lab in Russia, I should be able to do the same things that I can do in Nairobi, Cape Town, Delhi, Amsterdam or Boston Fab Labs."* The Fab foundation defines a list of critical machines and materials and of open source software and freeware to use.
4. Fab Labs must **participate in the larger, global Fab Lab network**, that is, you can't isolate yourself. This is about being part of a global, knowledge-sharing community. The public videoconference is one way to do connect. Attending the annual Fab Lab meeting is another. Collaborating and partnering with other labs in the network on workshops, challenges or projects is another way. Participating in Fab Academy is yet another way. The Fab Academy in particular is a distributed educational model providing a unique educational experience; It is a technical

training course held by Nail Gershenfeld himself streaming, whose practical exercises take place physically at the many local laboratories. The target of the Fab Academy, is to learn how to envision, prototype and document ideas through many hours of hands-on experience with digital fabrication tools, taking a variety of code formats and turning them into physical objects (http://fabacademy.org/about/).

2.2.1 Fab Labs' layout

The Fab Foundation describes in detail in its website, what is the stereotype of the perfect Fab Lab in the section "How to start a Fab Lab".

The lab used as an example of the perfect space is the **Chicago Fab Lab** at the Museum of Science and Industry (MSI). The Chicago lab has two of each of the machines in it and is about 77 square meters. For a laboratory with one of each machine, 140 square meters should be sufficient.

This lab is designed to accommodate larger groups of about 20-30 users at a time, so it includes double the number of machines and tools, therefore more expensive that the usual Fab Lab. Figure 2.2 shows the layout of the Chicago Fab Lab.

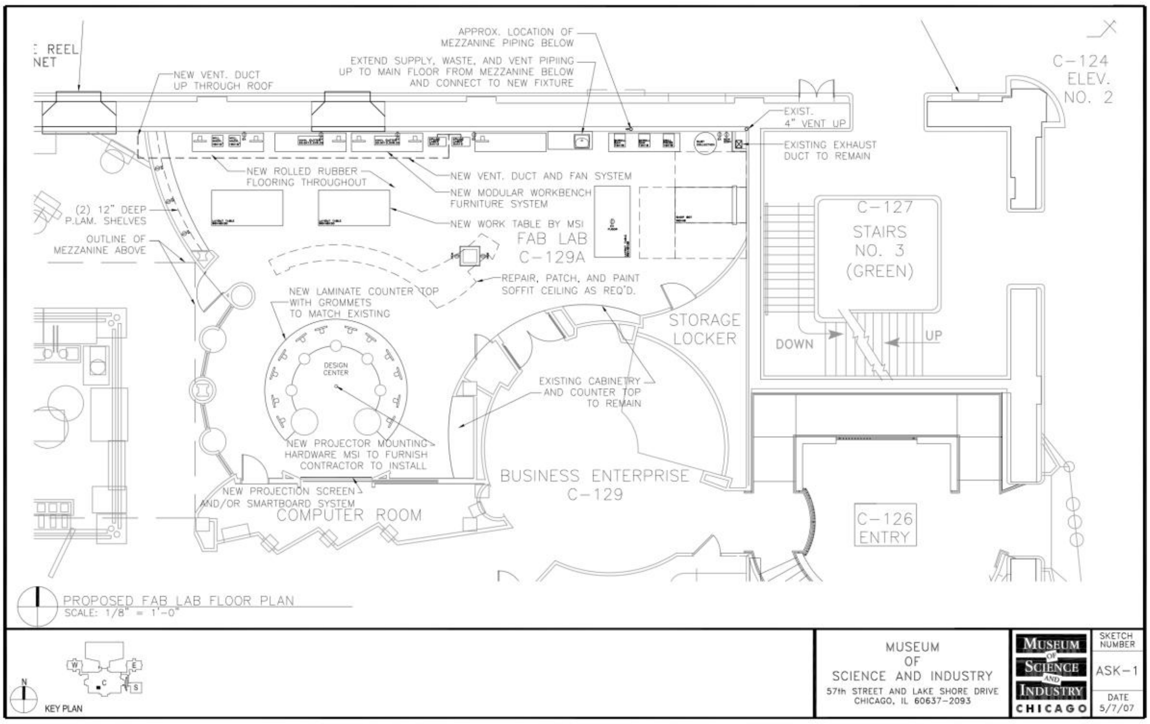

Figure 2.2 Layout of the Chicago Fab Lab at the Museum of Science and Industry

Describing the blueprint in Figure 2.2, it can be seen a large circular shape entitled Business Enterprise: this is a museum exhibit just outside of the Fab Lab. Adjacent to the circle is a semi-circle entitled "design center". As 90% of a student or user's time is spent designing on the computer, MSI invested in a design space for 12 users, plus a teacher or guru who can demonstrate using a projector and a powerful laptop computer on the screen at the front of the design center. This is also where videoconferencing for Fab Academy or meetings happens as well. Behind the design center/screen wall is a computer room for IT purposes. To the left of the design center there is another semicircular space. This is display space for the best or most interesting projects in the Fab Lab at the time. To the left and behind the design center there is the electronics workbench. That includes one set of bench test equipment, but two soldering stations and two programming stations (2 computers) and of course, electronic components and tools for two labs. Along the back wall are two Modelas for making circuits and molds for casting. There is a computer designated for each Modela (2 computers in total here). Also along the back wall there are two laser cutters, attached to 1 computer, and attached to an outside, roof ventilation system.

Toward the end of the back wall is a counter and sink with running water to handle casting projects and other projects that require water for processing or clean up. There are two long, empty counters along the back wall as well for work space and for use with some of the other kinds of tools, like a drill press and a scroll saw.

The right end of the lab, in the center of the lab there is a large open space for the ShopBot (large wood router) and the associated computer and filter/blower. This is the one item that has special electrical power needs.

And finally there are 2 or 3 large rectangles in the center of the room. These are purely workspace, places where students and users can spread out their projects as they work on them.

The Fab Foundation suggests not to underestimate the need for material and project storage. Some significant space devoted to storing large pieces of wood and other materials is needed, as well as cubby holes or shelving for student/user individual projects (http://fabfoundation.org/ fab-lab-form/).

Moreover Fab Labs have a recommended list of capabilities called "Fab Lab Inventory". These include a laser cutter for making 3D structures from 2D designs, a large Computer Numeric Control (CNC) mill for making furniture and housing, a Numeric Control (NC) knife and smaller mini-mill for making circuits and molds for casting, 3D printers, an electronics workbench, and a suite of tooling and materials that allows anyone, anywhere to make almost anything.

Equipping with all these machines will let the Fab Lab participate in Fab Academy, research collaborations and all the things a full Fab Lab is capable of doing. The computing environment of a Fab Lab should mostly work with the Linux partition, because of the belief in the open source approach, which aligns with the Fab Lab mission of democratizing access to the tools and knowledge for education and invention (http://fabfoundation.org/the-hardware-and-software/).

2.2.2 Fab Lab people

The Fab Foundation describes the kind of people needed to run a Fab Labs; firstly it has been said that a Fab Lab minimally need two figures (http://fabfoundation.org/fab-people/):

1. **Champion**: this is the local community leader who believes in and is passionate about the Fab Lab concept and what it can do for the community. This is a person who is closely connected to the community base in order to bring resources (financial and other) and commitment to the Fab Lab from within. This person may already be running a community center, and has a personal commitment to and community mission for that center, rather than performing merely an administrative role. A champion should find the commitment and resources to sustain the operation, and have enough vision to keep the community excited about it. Champions are critical to the success of the Fab Lab. This person does not need to be technical, just committed and passionate about the idea, and well connected within the community to sustain the operation. This person may or may not serve as administrative/managerial support for the lab.
2. **Technical Guru**: this is the person that makes the lab operate on a day to day basis. They must like to make things. That’s far and above the most distinguishing factor for a Fab Lab guru, they must love to make things. It helps a lot if they have either a mechanical or electrical engineering background, OR a background making things professionally. Electronics and programming are good skills to have as well. In the US, high school teachers who lead robotics competition design classes are perfect for this kind of job, since they are those with arts or architecture training, or training in industrial arts. This person is always multi-tasking, between

maintaining the equipment and supplies, to helping mentor people through projects, and training users on the design software and the fabrication hardware. It's a big job, and if you have a big lab, you need two of them. Most of all this person has to be open to new ideas, have a passion for making things, and patience and capability to teach users

Moreover it is important also the presence of:

3. **Fab Lab Director:** this figure must have:
   i) a technical degree and/or similar job experience.
   ii) Strong interpersonal and communication skills.
   iii) Desire to seek and pass on knowledge to others. Previous teaching experience is preferred.
   iv) Proficiency in common desktop applications (web browsing, word processing, image editing etc.).
   v) Familiarity with CAD/CAM and/or PCB Design software.
   vi) Experience with running and maintaining PCs and LANs. Familiarity or expertise in Linux is preferred.

   The Foundation says that The Fab Lab Director and the Fab Lab itself should cross the boundary of multiple disciplines including education, arts, mechanical engineering, electrical engineering, computer science and manufacturing engineering. The ideal candidate will likely have a background that could embrace new concepts and technologies when appropriate.
4. **Part time technical support person:** this person maintains the computers in the lab, the networking, internet access and other technical needs that come up in the lab. This should be a 1/3 to 1/2 time position.

Finally the Fab Foundation defines also a sample of the Fab Lab programme and the communities it could serve; these are (http://fabfoundation.org/sample-program/):

- **Public school children.**
- **Private school children.**
- **General public:** that is to say people who just want to make things or learn new skills or make products in the lab. This group could include college or university students who will want to work in the lab.

- **Artists/Crafters:** they should be encouraged to come and experiment with the tools and processes of the Fab Lab. The lab doesn't replace their traditional work, but it augments and broadens the palette of what they can do in their work. The foundation says it would be great to have artists experiment with the tools in the Fab Lab offering them one or two month program in which they have access to the entire lab with the technical gurus to help support them. If they produce some high level art or crafts for exhibit in the lab, and outside in public spaces, this will help the Fab Lab to show off the capabilities of the lab, get the artists' endorsements, and build the Fab Lab reputation in the public.
- **University Students:** they can bring great creativity and new approaches to making things to the environment. They can also be hugely useful as technical resources and as teachers.
- **Entrepreneurs:** this group includes the college or university students, and young entrepreneurs who are inventive and creative, need a space and a place and a community to support their invention. It might be interesting to offer also to entrepreneurs a one or two month program in which they have access to the entire lab with the technical gurus to help support them.
- **Government or Corporate Employees:** this might be a group who will find new uses for the lab, and new experts to volunteer and work in the lab for you, and they will spread the word about the lab to the larger community. Their endorsement and adoption of the lab can be important to the success of the Fab Lab.

2.2.3 Fab Labs and the development of new business models

According to Troxler and Schweikert (2010), a Fab Lab is a platform for technical prototyping for learning and innovation that provides important stimuli for local entrepreneurship and is based mainly on four key factors: openness, interdisciplinary collaboration, effectiveness and transferability.

The Fab Lab's concept is not an alternative to mass production in creating large-scale products, but is largely demonstrating its potential in modifying the manufacturing logic, offering individuals the ability to create customized products tailored to local and personal needs, in ways that would be considered inexpensive or economical according to the logic of mass production (Carrus et al., 2014).

A Troxler (2010) study indicates that, among the feasible business models, the one of the incubation is the most reacheable, configuring the lab as an infrastructure of support for small business owners. The main problem is that the Fab Labs are currently funded mainly by government agencies, universities or private companies and have not yet demonstrated complete economic self-sufficiency, and are therefore strongly unable to support the growth of new businesses within them. Conversely, the Fab Labs may be incubated by companies that are already mature, who intend to create laboratories with social, educational objectives, research and dissemination of their products and services.

A Fab Lab could take on different configurations, from the traditional "machine shop" to the most ambitious "innovation ecosystem". In particular, the Fab Lab conceived as an ecosystem of innovation allows its users a real innovation experience. Value creation in the innovation ecosystem is carried out through the linkage and exchange between actors holding a wealth of knowledge and diverse experiences, and through the ability to carry out rapidly and economically the many activities required in the innovation process (Carrus et al., 2014).

From a managerial point of view, analysis suggests that the open business model (Chesbrough, 2006) is the most suitable for explaining Fab Labs. Open organizations in fact generate value through internal and external channels, and their success is conditioned by the ability to create links with external actors in order to absorb different types of knowledge, improve innovative capacity and thus grow (Troxler and Wolf, 2010; Pisano *et al*., 2014; Cautela *et al*., 2014). In addition to this model there is an innovative element, the territorial presence of the Fab Lab, which is strongly integrated with local socio-productive resources, favoring the direct involvement of the end customer and overcoming intermediaries in distribution channels. Customer is the buyer, but it also becomes an important product effectiveness or ideas conceived tester in the lab. Digital manufacturing technologies also allow the development of different distribution strategies, including direct e-commerce and alliances for organized distribution (Carrus et al., 2014).

From a theoretical point of view, the encounter between the traditional manufacturing firm and the Fab Lab could develop a new evolutionary model, the one of open manufacturing, based on the collaboration between craftsmen holding manual knowledge, and new creative makers to exploit the innovations available to quickly and effectively prototype increasingly distinctive and unique objects (Yair et al., 1999). Open manufacturing is inspired by the philosophy of co-opetition (Brandenburger and Nalebuff, 2011) and contamination, and can be organized in the form of strategic networks (Zaheer et al., 2000) between manufacturing laboratories, small and medium enterprises and manufacturing startups, where laboratories make their own tools available to companies already in the market or support new start-ups.

2.3 The Italian Economic Reality of Fab Labs

The short history of the Italian Fab Lab is characterised by two important stages: a first stage that could be called *embryonic* and a second that could be labelled *explosion*. The diffusion process, was very quick, with the first Fab Lab born in 2012 in Turin (http://fablabtorino.org) and the *explosion* phase developed in the first half of 2014. The phenomenon has spread first in the North of Italy, via Reggio-Emilia, Trento and Milan, and then it reached the South (Aliazzo, 2014).

If the spread of Italian Fab Labs was very fast, it was still late taking off compared to the rest of Europe: the European *embryonic phase* occurred in 2008 (four years before the "Fab Lab Torino"), when two laboratories were opened in Barcelona and Amsterdam that are still a reference point for the global network (Manzo and Ramella, 2015).

In the years preceding the explosion phase, two major events involving the digital fabrication and maker world took place. The first took place in Turin in 2011, when, as part of the "Future Station" exhibition[18], "Fab Lab Italia" was created, a temporary digital fabrication laboratory. The theme of digital fabrication found fertile terrain in the city and, a few months after the exhibition closed, exactly February 14, 2012, the first Italian laboratory, the "Fab Lab Torino", was founded in former industrial buildings which housed the coworking *Toolbox* and *Officine Arduino*. The second major event occurred in 2013, when Rome hosted the first *Maker Faire, the European edition*, an exhibition connected to Make magazine, a point of reference for the Maker community.

According to the work of Manzo and Ramella (2015) the founders of Italian Fab Labs, in most cases, are men (11% being women) and are between 30 and 40 years of age (the average age being 35). Aliazzo (2014) found that about 80% of the tested realities were born on the initiative of individuals. Engineers, Architects, Industrial Designers and Informatics (these are the founders' profiles in all the cases analyzed) gathered to start an association in 44% of cases or to a private enterprise in 27%. Fab Lab is located in private

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[18] This exhibition was developed among the events for the 150th anniversary of the Unification of Italy. It has been developed in the Grand Reparations Offices in Turin from March 17 to November 20, 2011 (https://blog.arduino.cc/)

premises rented in 50% of the sample, but a high percentage is hosted by public premises (23%). Three different types of founders were defined (Manzo and Ramella, 2015):

1. ***the sharing-entrepreneurs***: for the sharing-entrepreneur, opening the laboratory is all about their passion to lead the way. Before opening the Fab Lab they have had other professional experiences related to information technology, electronics and design, but these have not completely satisfied their know-how and need for professional independence. The laboratory is seen as a kind of library, a place open to all, where freedom of access, common interests and experimentation come together to trigger a mechanism of contamination between skills and ongoing informal training. The sharing-entrepreneur believes that the Fab Lab, thanks to its particular features and potential, can become a real R&D laboratory external to companies.
2. ***The designer***: The Fab Lab represents an evolution of one part of the designer's professionalism: not a "new" starting point, as in the previous case, but something in a line of continuity with their work. It is not a private investment made exclusively to bring growth to their own studio: "collective" and pro-social objectives also exist, since the space is open to everyone. It does not represent a secondary activity in relation to their usual work, on the contrary, the two activities are strongly integrated, and in some cases it is the laboratory that tends to predominate.
3. ***The patchworker***: these are founders for whom the laboratory has become a (patch-like) "piece" of their professionalism. All have one or more jobs and, having always been passionate about electronics and new technologies, they decide to make a professional investment in a Fab Lab. They are not ready to leave their profession in order to devote themselves entirely to the laboratory, but the latter becomes a piece of the "patchwork" that makes up their professionalism. In these cases, the opening hours are influenced by the availability of free time of the founder and the other partners: they are usually open in the late afternoon and/or evening and at weekends. Amongst patchworkers, their main job does not satisfy their know-how in the field of technology.

With regard to machine equipment, the main tool used in the Fab Labs is 3D printer: about 95% of respondents claim to own and use 3D printers, there are on average 2.6 of them per laboratory. Along with 3D market printers, the amount of self-assembled and built-in

Arduino technology increases (this technology will be deepend explained and discussed in par. 2.3.1), accounting for about 30% of 3D printers in Fab Lab. Just Arduino circuits are the second technology in the Fab Lab, with 13.1 units present on average in over 83% of the interviewed realities. The high spread of Arduino control cards is a symptom of one of the pillars behind Fab Lab's philosophy: knowledge-based culture based on the spread of open source technologies that are subject to continuous evolution. In addition to highly innovative machineries and technologies (from 3D printers to Arduino, from Internet of Things (IoT) platforms to 3D scanners), Fab Lab's equipment also features traditional machines typical of craftsmanship (numerical milling machines, lathes, pantographs, instrumentation for carpenters) to prove how the Fab Labs are structuring to become laboratories in which the "new" craftsman experiments and adopts digital technologies to face the challenges imposed by innovation. Open Source technologies have a predominant presence in these realities (Aliazzo, 2014).

The services offered by Fab Labs can be categorized into three main areas (Aliazzo, 2014):

1. the first concerns services closely related to the design, prototyping, and production (in a low-scale) of products through 3D printers and the universe of corollary modelling software. 88% of Fab Labs deliver product printing services (mainly for the consumer world), and supports the user in product design and in designing new concepts.
2. The second is due to consultancy activities. It increases the use of skills of Fab Labs for choosing the right 3D printer for specific demand requirements (75% of Fab Labs outsourced this service); but also for the advice in terms of support in redefining production processes rather than material consulting (over 60% of sample Fab Labs have been involved in decisions in such areas).
3. Finally, always connected to the material theme, Fab Lab is often used as a reference operator for the supply of printable materials.

Often, the success of a Fab Lab is closely related to the competences within it: first of all, Arduino's programming skills on the platforms, but equally significant and widespread are the expertise in materials, hardware and self-assembled machines, software programming, knowledge of company processes and design software. Important, but not so widespread, the expertise of the companies or products in the field of IoT (Aliazzo, 2014).

2.3.1 Arduino's platform

Arduino is a platform, born in Italy, for open-source electronic prototyping based on an easy and intuitive hardware and software component to use (Figure 2.3).

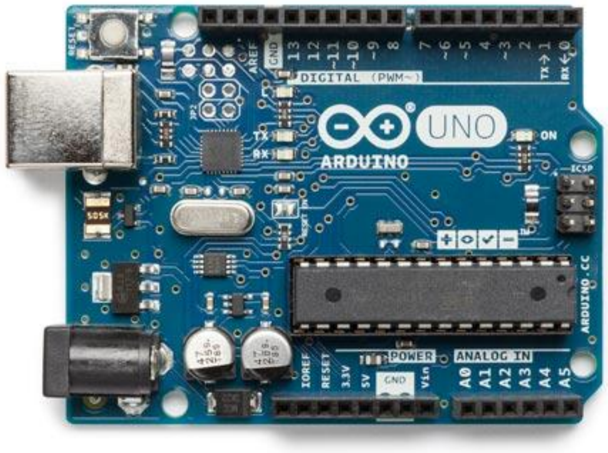
Figure 2.3 The open-source Arduino Platform

It's a object designed for artists, designers, hobbyists and anyone interested in create interactive tools or environments. The story of Arduino begins in 2001 with the creation by Olivetti and Telecom of the Interaction Design Institute of Ivrea. In its web site Arduino describes itself as:

> *The world's leading open-source hardware and software ecosystem. The Company which sells it, called Tinker.it, offers a range of software tools, hardware platforms and documentation enabling almost anybody to be creative with technology.*
>
> *Arduino is a popular tool for IoT product development as well as one of the most successful tools for STEAM education. Hundreds of thousands of designers, engineers, students, developers and makers around the world are using Arduino to innovate in music, games, toys, smart homes, farming, autonomous vehicles, and more.*
>
> *Originally started as a research project by Massimo Banzi, with the collaboration of David Cuartielles, Tom Igoe, Gianluca Martino, and David Mellis at the Interaction Design Institute of Ivrea in the early 2000s, it builds upon the Processing project, a*

language for learning how to code within the context of the visual arts developed by Casey Reas and Ben Fry as well as a thesis project by Hernando Barragan about the Wiring board.

The first Arduino board was introduced in 2005 to help design students, who had no previous experience in electronics or micro-controller programming, to create working prototypes connecting the physical world to the digital world. Since then it has become the most popular electronics prototyping tool used by engineers and even large corporations.

Arduino is the first widespread Open Source Hardware project and was set up to build a community that could help spread the use of the tool and benefit from contributions from hundreds of people who helped debug the code, write examples, create tutorials, supports other users on the forums and build thousands of groups around the globe. We are eternally grateful for being supported by such an amazing community.

Since the Arduino project's foundation, many new development boards and software libraries have been introduced, expanding the range of possibilities available to the community. Today, more than a decade later, Arduino continues to provide open source hardware and software to bring new ideas to life.

The openness and ease-of-use of the project has led to mass adoption of micro-controller based electronics projects and was a catalyst in the creation of the Maker Movement. Arduino has become the number one choice for electronics makers, especially for developing solutions for the IoT marketplace, which

> *has been predicted to become a $6 trillion market by 2021 (https://www.arduino.cc/en/Main/AboutUs).*

The price of Arduino cards is about thirty euros and so far, around twenty different cards have been made. It goes from model One dedicated to beginners, up to the little Nano at Lilypad, made to be sewn inside the fabrics. Arduino has developed on a new business model: a society based on the idea of giving it all. Only the name of the Arduino card is patented. Anyone would download project data, send specifications to a Chinese company, and begin marketing its own microprocessor, and that's exactly what *Tinker.it* hopes to do. Massimo Banzi[19], one of Arduino's founders describes it as a "Lingua Franca"[20] and says:

> *In the last 12 years Arduino has grown to be the "lingua franca" of microcontrollers, a set of Application Program Interface (API) implemented on a large number of different architectures making it very easy for people of every skill level to learn to write embedded code and to port code from one processor to another (https://massimobanzi.com/)*

An Arduino version, "Arduino Pro", is even devoted to being inserted into art objects. In 2011 Paola Antonelli, senior curator of the Department of Architecture and Design at the Museum of Modern Art (MoMA) in New York, made the show "Talk to me", and most of the works is based on Arduino.

> *Talk to Me explores the communication between people and things. All objects contain information that goes well beyond their immediate use or appearance. In some cases, objects like cell phones and computers exist to provide us with access to complex systems and networks, behaving as gateways*

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[19] Massimo Banzi is the co-founder of the Arduino project. He is an Interaction Designer, Educator and Open Source Hardware advocate. He has worked as a consultant for clients such as: Prada, Artemide, Persol, Whirlpool, V&A Museum and Adidas. Massimo started the first FabLab in Italy which led to the creation of Officine Arduino, a FabLab/Makerspace based in Torino. He spent 4 years at the Interaction Design Institue Ivrea as Associate Professor (https://massimobanzi.com/about/).

[20] A "Lingua Franca" is a language systematically used to make communication possible between people who do not share a native language or dialect. www.wikipedia.it

> *and interpreters. Whether openly and actively, or in subtle, subliminal ways, things talk to us, and designers help us develop and improvise the dialogue.*
> *The exhibition focuses on objects that involve a direct interaction, such as interfaces, information systems, visualization design, and communication devices, and on projects that establish an emotional, sensual, or intellectual connection with their users. Examples range from a few iconic products of the late 1960s to several projects currently in development—including computer and machine interfaces, websites, video games, devices and tools, furniture and physical products, and extending to installations and whole environments (https://www.moma.org/.)*

Another project developed with Arduino is *MusicInk*, a project by Gilda Negrini and Riccardo Vendramin, two students from the Politecnico of Milano (Figure 2.4). This is a device that plays children's drawings. A particular ink acts as a sensor that transmits signals to Arduino, which switches them to music.
It is defined as:

Figure 2.4 MusicInk Project

> *MusicInk is a project spawned from the idea of looking into the world of music teaching, creating a new way to understand music and interact with musical instruments.*
> *MusicInk is a toy that leads you to an innovative approach to music, allowing children not only to*

> *draw musical properties, but also to turn them into a real symphony.*
> *Our project main characteristic is the use of a unique electrically conductive paint that allows children to play their own drawings [...]The game is based on the use of a particular electrically conductive and non-toxic ink with which the children will realize drawings representing the different properties of sound (http://musicink.co/).*

2.4 Fabrication Laboratories: The development of new business models with new digital technologies. An empirical analysis around Europe and America

The aim of this paper is to analyze where DIY comes to life, investigating the economic reality of Fab Labs. These laboratories work with the typical mechanisms of the sharing economy: they provide a space with tools and equipment for digital manufacturing, making them available to individual users, small businesses and schools. In detail the aim is to make a comparison between laboratories developed in different economic realities, that is the European and the American ones, highlighting their potential strength and weaknesses and identifying their role both towards consumers and businesses in the Industry 4.0 era. The work tries to cover a literary gap, since only few and specific qualitative works have been done on Fab Labs. The novelty resides in the issue considered and the experimental techniques used. Some qualitative case studies have been developed in the field, but no previous quantitative analysis have been developed on a large sample of Fab Labs, developing comparisons between European and American realities of these digital laboratories. Italy has been taken as reference reality and has been deeply investigated, and compared to France, Germany, Spain and The Netherlands for Europe and to the American ones.

The greater value of the paper relies on this direct comparison of Fab Labs born in different economic realities.

Therefore, the research questions, which the paper investigates are the following:

RQ1: How is the structure of a Fab Lab? Are there significant differences among laboratories developed in different economic context? In detail, the paper wants to investigate who are their main customers, with which sector they operate more, which digital technologies they use most, what kind of services they deliver to their customers and what are their main skills.

RQ2: What are the differences and similarities among Italian Fab Labs and the main European and the American realities of Fab Labs?

The paper is divided as follows: section two defines the theoretical framework, section three presents the research methodology used. Subsequently section four describes the results of the empirical research and discusses them. Finally section five draws the conclusions of the work, explaining the main theoretical and managerial implications and the limitations of it.

2.4.1 Methodology

2.4.1.1 Sampling and data collection

Data from European and American Fab Labs were collected using a questionnaire survey performed in total on a sample of n= 493 Fabrication Laboratories, Table 2.1 shows for each country the number of Fab Labs present in the same, the number of Fab Labs for which a contact was found and those that participated to the survey with the corresponding response rate for each country. The list and contacts needed to contact Fab Labs have been found in the official website of the Fab Foundation (http://fabfoundation.org/), an organization formed in 2009 to facilitate and support the growth of the international Fab Lab network. The survey began September 18th, 2017 and answers were accepted until November 8th, 2017. The administration of the survey took place by e-mail; 73 Fab Labs participated to the survey reaching a total response rate of 14.81% (Table 2.1). A structured questionnaire was distributed via Computer Assisted Web Interviewing (CAWI) consisting of three sections, following the structure of Menichelli and Ranellucci (2015) and Aliazzo (2014). The first section investigates the sample profile of the respondent Fab Labs, considering the location, the number of workers, the size of the structure, the annual revenue, the average number of users and their investments for machinery and technology. The second section depicts Fab Labs' skills and competences; in detail it has been investigated which are their main customers, which kind of products they realize and for which sector, which kind of new digital machines they use most, their main skills and the services they deliver most to their customers.

Finally section three takes into consideration the use of digital technologies and their impact on the environment. In this section we tried to investigate which percentage of Fab Labs' production is reserved to the creation of eco-sustainable products and if they think that the use of digital technologies, such as 3D printers, can affect the environment, in detail the air quality of the work environment. At the end of the section it has been asked if they think that 3D printers and other digital technologies can represent the turning point that will allow industries to enter a new industrial revolution.

Table 2.1. List of Fab Labs present in each Nation and contacted

	Italy	*France*	*Germany*	*The Netherlands*	*Spain*	*USA*	*Total*
Fab Labs present in the Nation	134	151	46	32	46	158	567
Fab Labs Contacted	112	142	41	29	42	127	493
Fab Labs which answered the survey	27	16	5	3	8	14	73
Response rate (%)	24,11	11,27	12,20	10,34	19,05	11,02	14,81

2.4.1.2 Process analysis

The aim of the research was to develop an exploratory analysis (Malhotra and Grover, 1998) using an inductive research approach Eisenhardt (1989).

Descriptive analysis was performed to describe the sample profile of respondent Fab Labs. A five-point Likert scale was used to evaluate Fab Labs' skills, competences and services delivered to their customers.

Subsequently, a Principal Component Analysis (PCA) followed by Oblimin rotation (Jennrich and Sampson, 1966) was applied to Italian Fab Labs to understand the kind of customers they have, the type of products realized, the services delivered, the skills owned and the product features they can exalt, and realizing products with new digital machines inside their laboratories. Variables with factor loadings less than 0.6 were excluded from further analysis, as they were not considered statistically significant. Joreskog (1999) provides an explanation for higher coefficients among the factor loadings of the PCA.

Moreover, to verify the reliability of the PCA, Cronbach's alpha values were computed, taking into account only alpha values greater than 0.60 as suggested by Nunnally and Bernstein (1994). As for sample size of 50 or less in the development of the PCA analysis, the study follows the line of Jung and Lee (2011).

Furthermore, the Analysis of Variance (ANOVA) was performed using F-tests to statistically test the equality of means (Markowski and Markowski, 1990) and analyze the differences and similarities of features in Italian, European and American realities of Fab Labs, followed by Bonferroni's post-hoc comparisons tests, to test the equality of means for more than two groups, (Armstrong, 2014). In data processing, the SPSS 23.0 program (Statistical Package for Social Science) was used.

2.4.1.3 Non-Response Bias

Non-response bias was assessed by verifying that early and late respondents were not significantly different (Armstrong and Overton, 1977). A set of tests compared respondents who answered to the questionnaire during the first administration and those who answered when the survey was submitted for the second time. All possible t-test comparisons between the means of the two groups showed insignificant differences ($p<0.1$ level).

2.4.2 Results: the Italian reality

In this first section only the results of the Italian economic reality have been considered, in order to describe in detail what are the features of Italian Fab Labs, and then comparing this economic reality with the European and American ones. Depicting the profile of respondent Italian Fab Labs (Table 2.2) it can be seen that volunteer workers are usual, and in the 73.3% of cases there are among 1 and 10 volunteers working on these laboratories, while more than 1 Fab Lab in 2 (55.6%) does not have paid staff. The size of these Italian laboratories is in majority between 25 and 74 square meters (33.3%) and between 75 and 200 square meters (44.4%). As for the number of associated or registered users, this is very varied, with some laboratories (probably of recent birth) that do not have registered users (14.8%), while others that have more than 100 users registered (22.2%).

In average the annual income of Italian Fab Labs is about 31,875.00 € and therefore their relative investments for machinery and technology are relatively slow, with 51.9% of them investing less than 10,000 € per year and a 25.9% arriving at most not more than 50,000 € per year. There are two singular cases of big laboratories which invest between 100,001 and 300,000 € and between 300,001 and 500,000 € per year, but these are exceptions in the Italian reality. Finally considering the acquisition of State of European incentives 11 out of 27 laboratories (40.7%) claimed to have received this kind of economic help.

Table 2.2 Profile of respondent Fab Labs

	Italy (27)	
	n	*%*
Volunteers workers		
0 volunteers	5	18.5%
1-5 volunteers	14	51.1%
6-10 volunteers	6	22.2%
11-20 volunteers	2	7.4%
more than 20 volunteers	0	0.0%
Paid staff		
0 employees	15	55.6%
1-5 employees	10	37.0%
6-10 employees	1	3.7%
11-20 employees	1	3.7%
more than 20 employees	0	0.0%
Size of Fab Lab		
5-24 SQM	1	3.7%
25-74 SQM	9	33.3%
75-200 SQM	12	44.4%
>200 SQM	5	18.5%
Associated or registered users		
0 users	4	14.8%
1-20 users	6	22.2%
21-50 users	6	22.2%
51-100 users	5	18.5%
More than 100 users	6	22.2%
Annual Income in avarage	31,875.00 €	
Investments for machinery and technology		
< 10,000 €	14	51.9%
10,001-50,000 €	7	25.9%
50,001-100,000 €	4	14.8%
100,001-300,000 €	1	3.7%
300,001-500,000 €	1	3.7%
500,001-1,000,000 €	0	0.0%
> 1,000,000 €	0	0.0%
Received State or European incentives		
Yes	11	40.7%
No	16	59.3%

As for the Italian regions in which the respondent Fab Labs are located (Table 2.3), it can be seen that the majority (5) are located in Piemonte, followed by 4 in Emilia Romagna and 4 in Lombardia. As for the center regions of Italy, Fab Labs answered from Marche (2) and Umbria (2) and finally the southern regions which participated to the survey are Basilicata (1) Campania (1) and Sardegna (1).

Table 2.3. Region of location in Italy

	n	*%*
Basilicata	1	3.7
Campania	1	3.7
Emilia Romagna	4	14.8
Friuli Venezia Giulia	1	3.7
Lazio	2	7.4
Liguria	2	7.4
Lombardia	4	14.8
Marche	2	7.4
Piemonte	5	18.5
Sardegna	1	3.7
Umbria	2	7.4
Veneto	2	7.4

Analyzing which are the main customers of Italian Fab Labs (Table 2.4), it can be seen that individual customers (3.85) are the main subjects for which these laboratories work, followed by Practitioners (3.00) and Designers (3.00). On the contrary universities seem to be the institutions with which they work less.

Table 2.4. Italian Fab Labs' main customers (α = 0.834)

	N	*Minimum*	*Maximum*	*Mean*	*Std. Deviation*
Manufacturing companies	27	1.0	5.0	2.56	1.050
Individual customers	27	2.0	5.0	3.85	0.864
Practitioners	27	1.0	5.0	3.00	0.920
Institutions/schools	27	1.0	5.0	2.78	1.050
University	27	1.0	5.0	2.30	1.031
Artists	27	1.0	5.0	2.59	0.971
Designers	27	1.0	5.0	3.00	1.000

Developing a Principal Component Analysis (PCA) on Fab Labs' main customers (Table 2.5) the first component in terms of importance (cumulative variance 76.94%) is named *Private* and it shows that individual customers are the main customers of Italian Fab Labs to whom they turn to make their own ideas concrete and realize objects tailored to their needs. It seems that customers are becoming "co-designers", because they are able to get access to the design process, (concept design and product development), and express the requirements or even co-designing the product with the configuration toolkit (Tseng and

Piller 2003). Therefore Fab Labs can help the market to change the design and production processes from "made-to-stock" to "made-to-order" (Tseng and Hu, 2014).

This first variable shows that the figure of the maker, that is, a person who is engaged in the creative production of artifacts in their daily lives and who find physical and digital forums to share their processes and products with others, is also developing in the Italian panorama (Halverson and Sheridan, 2014). Makers might be called the new craftsmen of the digital era. Many of them are hobbyists and amateurs (Manzo and Ramella, 2015).

The second component in term of importance is called *Business* and shows with a cumulative variance of 65.43% that manufacturing companies and practitioners represent together the second type of Fab Lab's customers. The most innovative companies, with smaller dimensions and relative more limited investment capacity, could decide to collaborate with these laboratories to develop product or process innovation strategies, taking advantage of the opportunities that new digital technologies (such as 3D printers, 3D scanners, laser cutters etc.) can bring to them (Murmura and Bravi, 2017). Additive Manufacturing (AM), commonly known as 3D printing, and other digital technologies as direct manufacturing processes, are leading companies to rethink where and how they conduct their manufacturing activities (Ford and Despeisse, 2016). Finally component 3, that is *Research and Ideas* (50.92%) shows that also universities and artists collaborate with Italian Fab Labs, the first to develop researches and studies, design and experiment on new products, and the second to use digital technologies in order to make their ideas concrete. The Italian economic reality seems to be different from what Troxler (2013) says in literature, that is to say, that two out of three Fab Labs are affiliated to institutions such as community colleges and universities.

Table 2.5. PCA on Italian Fab Labs' main customers (α = 0.834)

	Component		
	Research and Ideas	***Business***	***Private***
Manufacturing companies	-	.923	-
Individual customers	-	-	.960
Practitioners	-	.657	-
Institutions/schools	-	-	-
University	.835	-	-
Artists	.874	-	-
Designers	-	-	-
KMO		0.741	
Cumulative Variance	*50.92*	*65.43*	*76.94*

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.
a. Rotation converged in 9 iterations.

Subsequently it has been asked to the respondent to indicate to which industry the products that they realize most within their Fab Labs belong. From Table 2.6, it can be seen that in majority they realize product for the Technology industry, in detail for the Electronic industry (3.48) and the Internet of Things (IoT) one (3.19). In addition to this, it seems that also products for the furniture industry are produced with a certain frequency.

Table 2.6. Sectors with which Italian Fab Labs operate (α = 0.538)

	N	*Minimum*	*Maximum*	*Mean*	*Std. Deviation*
Fashion	27	1.0	5.0	2.11	1.086
Furniture industry / furniture components	27	1.0	5.0	3.07	1.141
Mechanics	27	2.0	5.0	2.93	0.829
Automotive	27	1.0	4.0	1.74	0.764
Food	27	1.0	4.0	1.89	0.892
Technology - Electronic	27	1.0	5.0	3.48	1.087
Technology – IoT	27	1.0	5.0	3.19	1.111
Technology – Software	27	1.0	5.0	2.63	1.115

Considering the type of product they realize most (Table 2.7), it can be seen that they generally produce any kind of prototypes, and as underlined before, they work more with single customers than with companies.

Table 2.7. Type of realized products (α = 0.844)

	N	*Minimum*	*Maximum*	*Mean*	*Std. Deviation*
Products to be marketed	27	1.0	5.0	2.00	1.000
Finished products for a single customer	27	1.0	5.0	3.00	1.074
Prototypes for companies	27	1.0	5.0	2.63	1.006
Prototypes for a single customer	27	1.0	5.0	3.26	0.859

In a later phase the study been tried to understand Italian Fab Labs skills and competences starting from the kind of advanced technologies most used inside their laboratory. As it can be seen from Table 2.8, laser cutters (4.33) and 3D printers (4.30) are used almost daily. These two tools are followed by the use of controls cards, such as Arduino (3.44) and CNC milling machines (3.41).

Table 2.8. Use of these machines in the Fab Lab (α = 0.721)

	N	*Minimum*	*Maximum*	*Mean*	*Std. Deviation*
3D printer	27	2.0	5.0	4.30	.823
3D scanner	27	1.0	4.0	2.63	1.043
Laser cutter	27	1.0	5.0	4.33	1.144
CNC milling machines	27	1.0	5.0	3.41	1.152
Vinyl cutter	27	1.0	5.0	2.59	1.083
Lathe	27	1.0	4.0	1.56	.801
Control Cards (Arduino or similar)	27	1.0	5.0	3.44	1.281
Precision punches for printed circuits	27	1.0	5.0	2.33	1.330

As for the major services delivered to their customers (Table 2.9), Italian Fab Labs offer a wide range of courses and training (3.85); in this regard the work of Mostert Van der Sar et al. (2013), showed that Fab Labs play an important role in design education. Moreover they offer with a certain frequency support in the creation of prototypes (3.70), they directly print products with 3D printing (3.56) and give support to design new products. Therefore these results show that Fab Labs are not only a practical place for creating objects, but also a place for sharing skills and competences, a pool of knowledge and technical-practical skills that are exchanged and shared between the staff and their registered users. These results show that Italian Fab Labs are near to the definition of Fab Lab given by their founders (Mikhak et al., 2002) that is to say a laboratory that is equipped with an initial selection of design and modelling, prototyping and fabrication, testing and monitoring and documentation tools.

Table 2.9. Services delivered to customers (α = 0.837)

	N	*Minimum*	*Maximum*	*Mean*	*Std. Deviation*
Printing of products	27	1.0	5.0	3.56	1.311
Support to the creation of prototypes	27	2.0	5.0	3.70	.823
Support to the design of new products	27	1.0	5.0	3.30	1.068
Support for finding the most suitable 3D printer	27	1.0	5.0	2.89	1.188
Support to the redefinition of the production process	27	1.0	5.0	2.89	1.013
Consultancy on materials	27	1.0	5.0	3.19	1.178
Provision of materials	27	1.0	5.0	2.37	1.391
Courses and training	27	2.0	5.0	3.85	1.064

Developing a PCA on the main services delivered to customers (Table 2.10) it can be seen that all variables can be grouped in two main features, that is *Support and Training* and *Product Realization*. The first component in terms of importance with a cumulative variance of 63.02% is Product Realization, and it shows that the major services delivered to customers are the ones linked to product realization and therefore material choices and provisions. Anyway there is a second component (Support and training, cumulative variance 49.31%), that shows the importance of the role of Fab Labs as incubators of knowing that is shared.

Table 2.10. PCA on services delivered to customers (α = 0.837)

	Component	
	Support and Training	**Product Realization**
Printing of products	-	.865
Support to the creation of prototypes	.737	-
Support to the design of new products	.800	-
Support for finding the most suitable 3D printer	.734	-
Support to the redefinition of the production process	.765	-
Consultancy on materials	-	.608
Provision of materials	-	.856
Courses and training	.604	-
KMO	0.707	
Cumulative Variance	*49.31*	*63.02*

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.
a. Rotation converged in 5 iterations.

Afterwards it has been asked to the respondent Fab Labs to indicate which are their main skills. As shown in Table 2.11, the main skills owned by these Italian laboratories are digital manufacturing skills (4.52), skills in using design softwares (4.26) and skills on materials (4.00). As for the skills less possessed, it seems that they have not so much knowledge on the Internet of Things (IoT) issue and on company products, and this second result is in line with the fact that Italian Fab Labs work more with single customers than with businesses and practitioners.

Table 2.11. Italian Fab Labs' skills (α = 0.848)

	N	*Minimum*	*Maximum*	*Mean*	*Std. Deviation*
Arduino Programming skills	27	1.0	5.0	3.41	1.448
Skills on materials	27	2.0	5.0	4.00	0.961
Hardware skills	27	2.0	5.0	3.81	1.001
Skills on business processes	27	1.0	5.0	3.63	1.115
Software programming skills	27	1.0	5.0	3.37	1.275
Skills in using design softwares	27	2.0	5.0	4.26	0.944
Skills on company products	27	1.0	5.0	3.33	1.109
Skills on Internet of Things	27	2.0	5.0	3.26	1.059

(IoT)					
Digital Manufacturing Skills	27	2.0	5.0	4.52	0.802

Performing a PCA on Fab Labs' skills, three main variables emerged (Table 2.12). The first in terms of relevance (83.11% of cumulative variance) is the one related to the possession of skills on materials; the second is named *Software & Hardware Skills* (74.53%) and defines Fab Labs' skills on hardware and software components, while finally component three is called *Business & Design Skills* (49.46%) and is linked to those competences that Fab Labs can use to cooperate with businesses.

Table 2.12. PCA on Italian Fab Labs' skills (α = 0.848)

	Component		
	Business & Design Skills	**Software & Hardware Skills**	**Material Skills**
Arduino Programming skills	-	.950	-
Skills on materials	-	-	-.850
Hardware skills	-	.665	-
Skills on business processes	.746	-	-
Software programming skills	-	.794	-
Skills in using design softwares	1.004	-	-
Skills on company products	.752	-	-
Skills on Internet of Things (IoT)	-	.826	-
Digital Manufacturing Skills	.757	-	-
KMO		0.724	
Cumulative Variance	*49.46*	*74.53*	*83.11*

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.
a. Rotation converged in 24 iterations.

But what are the differences between products realized in a company and products made in a Fab Lab? (see Table 2.13) Which kind of product features can be exalted realizing a product in this type of laboratories? Fab Labs answered that first of all the territoriality of product is exalted (3.93), that is the fact that the product is a handicraft product, of a handicraft that has become digital, but which allows the same to enhance the locality of the product and its realization ad hoc for the customer. The second element that distinguishes Fab Lab products from companies'ones is the Design: no more schemes to follow or molds to use; design freedom is the keyword of these laboratories (Hopkinson et al., 2006).

Table 2.13. Features exalted by Fab Lab's products (α = 0.870)

	N	*Minimum*	*Maximum*	*Mean*	*Std. Deviation*
Design	27	1.0	5.0	3.89	1.155
Product Quality	27	1.0	5.0	3.74	1.130
Ergonomics	27	1.0	5.0	3.74	1.095
Territoriality	27	1.0	5.0	3.93	1.072
Security	27	1.0	5.0	3.19	0.962

Later, the propensity of Italian Fab Labs to the creation of eco-sustainable products have been investigated. The 51.9% of respondents declared to realize products paying attention to the use of materials that therefore that respect the environment. There have been found differences when they were asked how many eco-sustainable products were made within their Fab Labs. While some claim to achieve a few tens of products with such characteristics, others say to realize at least 40% of the total, while others still say that all the products produced have such characteristics and exclusively sustainable materials are used to produce them. Among the sustainable products made within the Italian Fab Labs there are recycled wood furniture, candles, cases for electronic cigarettes, custom furnishing items in hemp bioplastic filament, wooden bat house, smart hive, sensors for improving energy efficiency, control units for environmental monitoring, paperweight in recyclable plastic, sustainable packaging, wooden signs, tablewear and shells in recycled PLA.

When asking them why they realize sustainable products (Table 2.14) it can be seen that mainly these are produced by request of individual customers (41.2%), also territorial requirements is an important motivation with the 29.4% and finally these are produced for the community of Fab Labs (23.5%). Only one respondent i the entire sample declared to produce these kind of products for teaching and education reasons, therefore again this underline the poor connections between Italian Fab Labs and educational institutions such as schools and universities.

Table 2.14. Motivation for developing eco-sustainable products/prototypes

	Italy	
	n	***%***
Community	4	23.5%
Teaching and education	1	5.9%
External customers	7	41.2%
Territorial requirements	5	29.4%
Total	17	100.0%

Finally it has been asked to the respondent if they thought that technologies could have an impact on the working environment, and if this impact could be positive or negative. The motivation was to understand the general thought of those who work daily with these digital tools in order to understand if they perceive only positive sensations, or if they are also aware of possible dangers related to them such as for example the novice emission of Volatile Organic Compounds (VOC) from 3D printers when they are printing objects. This problem has been highlighted recently in the literature by the works of Contos et al., (1995), Stephens et al., (2013) Azimi et al., (2016). Interviewing Italian Fab Labs showed that except for 14.8% of them who have no opinion about this, the 81.5% thinks that digital technologies could have a positive impact on the working environment, while only 3.7% thinks they could have negative aspects. In detail, when asking them how much they think that 3D printers emission could be harmful for human health of workers, the mean value of the 5-point Likert scale obtained was low and below the threshold value of 3 (mean value of the scale: 2.48) . Therefore it seems that the problem of VOC emissions of 3D printers is not considered relevant in the Italian Fab Labs panorama.

Finally when asking them if they think that 3D printers and other digital technologies could represent the turning point that will allow the industry to enter a new industrial revolution, using always a 5-point Likert scale, the value obtained is 3.85. This result underlines that there is a fairly high awareness that these technologies can make noticeable changes in the global economic landscape.

In order to investigate why there is this belief, it has been asked why they think these tools could revolutionize the global economic environment. For some of them the real revolution that 3D printing will have is that of being able to decide the shape and quantity of objects to be made, without the need to have a mold; design and industrialization processes are simplified and speeded up. Others think that the spread of 3D printing can also allow smaller industries and laboratories to prototype their ideas and see them grow faster. This having available, on the territory, laboratories such as Fab Labs that can take care, in a team, of the customization of design ideas and of their realization. Finally, others think it can have an impact not in terms of turnover but in terms of social impact, in responding to the needs of targets that cannot be satisfied by mass production.

2.4.3 Results: Italy compared to the rest of Europe and America

The aim of this second part of the research is to compare the Italian economic reality of Fab Labs to that of other European realities such as the French, German, Dutch and Spanish ones and to the American one, in order to consider similarities and differences among them. Table 2.15 describes the profile of respondent Fab Labs in Europe and America. The results show that French and German Fab Labs seem to be the ones with more volunteer workers even if in general volunteer workers are present in about all realities, while paid staff is not present in relevant percentages in France, Germany and Spain. As for the size of Fab Labs, most of the European Fab Labs have a size between 75 and 200 square meters, while American ones seem to be more heterogeneous, with some of very small dimensions while others that exceed 200 square meters of dimension. Considering Fab Lab’s users, America, Germany and the Netherlands are the ones with more registered users, while Spain seems to have Fab Labs with the lower number of associated users. Also in terms of turnover and investments American Fab Labs are more important realities than European ones, with an annual average income of 154,285.71 $ and investments that in some cases go over 1,000,000 $ like large multinational industries. Finally as for the reception of State incentives, it can be seen that in all the situations, the majority of respondents said they did not receive them; however America and Germany seem to be the realities most reached by this type of economic aids.

Table 2.15. Profile of respondent Fab Labs in Europe and America

	France *34.8% (16)*		**Germany** *10.9% (5)*		**The Netherlands** *6.5% (3)*		**Spain** *17.4% (8)*		**USA** *30.4% (14)*	
	n	***%***	***n***	***%***	***n***	***%***	***n***	***%***	***n***	***%***
Volunteers workers										
0 volunteers	2	12.5%	0	0.0%	0	0.0%	3	37.5%	4	28.6%
1-5 volunteers	6	37.5%	3	60.0%	1	33.3%	4	50.0%	5	35.7%
6-10 volunteers	3	18.8%	0	0.0%	1	33.3%	1	12.5%	2	14.3%
11-20 volunteers	0	0.0%	0	0.0%	1	33.3%	0	0.0%	1	7.1%
more than 20 volunteers	5	31.3%	2	40.0%	0	0.0%	0	0.0%	2	14.3%
Paid staff										
0 employee	6	37.5%	2	40.0%	0	0.0%	3	37.5%	0	0.0%
1-5 employees	10	62.5%	2	40.0%	3	100.0%	4	50.0%	10	71.4%
6-10 employees	0	0.0%	1	20.0%	0	0.0%	1	12.5%	2	14.3%
11-20 employees	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
more than 20 employees	0	0.0%	0	0.0%	0	0.0%	0	0.0%	2	14.3%
Size of Fab Lab										
5-24 SQM	1	6.3%	0	0.0%	0	0.0%	1	12.5%	3	21.4%
25-74 SQM	8	50.0%	2	40.0%	0	0.0%	1	12.5%	2	14.3%

75-200 SQM	5	31.3%	2	40.0%	3	100.0%	5	62.5%	4	28.6%
>200 SQM	2	12.5%	1	20.0%	0	0.0%	1	12.5%	5	35.7%
Associated or registered users										
0 users	0	0.0%	1	20.0%	0	0.0%	2	25.0%	0	0.0%
1-20 users	1	6.3%	0	0.0%	1	33.3%	2	25.0%	2	14.3%
21-50 users	6	37.5%	1	20.0%	0	0.0%	2	25.0%	3	21.4%
51-100 users	5	31.3%	0	0.0%	0	0.0%	0	0.0%	1	7.1%
More than 100 users	4	25.0%	3	60.0%	2	66.7%	2	25.0%	8	57.1%
Annual Income in avarage	34,346.15 €		10,500 €		35,500 €		15,333 €		154,285.71 $	
Investments for machinery and technology										
< 10.000 €/$	9	56.3%	1	20.0%	2	66.7%	4	50.0%	0	0.0%
10.001-50.000 €/$	5	31.3%	2	40.0%	1	33.3%	3	37.5%	3	21.4%
50.001-100.000 €/$	2	12.5%	1	20.0%	0	0.0%	0	0.0%	5	35.7%
100.001-300.000 €/$	0	0.0%	0	0.0%	0	0.0%	1	12.5%	2	14.3%
300.001-500.000 €/$	0	0.0%	0	0.0%	0	0.0%	0	0.0%	1	7.1%
500.001-1.000.000 €/$	0	0.0%	1	20.0%	0	0.0%	0	0.0%	1	7.1%
> 1.000.000 €/$	0	0.0%	0	0.0%	0	0.0%	0	0.0%	2	14.3%
Received State or European incentives										
Yes	6	37.5%	2	40.0%	1	33.3%	1	12.5%	6	42.9%
No	10	62.5%	3	60.0%	2	66.7%	7	87.5%	8	57.1%

Table 2.16 shows how Fab Labs believe State or Economic incentives important and the results underline that the Fab Labs of some the nations that receive a higher percentage of incentives are also those that consider them most important (Germany (4.40); Italy (4.15)). Also Dutch Fab Labs think that incentives are really important (4.00) for the development of laboratories, while even if American Fab Labs have received incentives for their activities, these are not considered so relevant (2.86). Therefore it can be said that incentives can be considered as a useful tool for developing and supporting the emergence of such realities, more in the European context than in the American one.

Table 2.16. Importance of State or European incentives

Nation	*N*	*Mean*	*Std. Deviation*
France	16	2.63	1.310
The Netherlands	3	4.00	1.000
Germany	5	4.40	0.548
Spain	8	3.75	1.832
USA	14	2.86	1.562
Italy	27	4.15	1.262
Total	73	3.63	1.252

Considering which type of consumer International Fab Labs have (Table 2.17), it can be seen that except for Germany and Spain where such laboratories seem to work in the majority with universities and educational institutions, in other cases the European and American realities follow the Italian one and indicate individual customers as their main customer. What is more from the Analysis of Variance (ANOVA) it can be seen that Italian Fab Labs works more with manufacturing companies than other realities, and less with Schools and Universities than the others. Therefore it seems that Italian Fab Labs are more oriented towards the labor market than to that of training and research, while Germany, Spain and USA more to the second one.

Table 2.17. Fab Labs' main customers: ANOVA between Nations (α = 0.782)

	Italy		**France** *34.8% (16)*		**Germany** *10.9% (5)*		**The Netherlands** *6.5% (3)*		**Spain** *17.4% (8)*		**USA** *30.4% (14)*		**ANOVA**	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***F***	***Sig.***
Manufacturing companies	**2.56a**	1.050	**1.75b**	0.931	2.00	1.414	1.33	0.577	1.75	0.707	1.78	0.949	**2.271**	0.057
Individual customers	**3.85a**	0.864	**3.88a**	0.719	4.00	0.707	3.33	1.155	**2.50b**	1.195	**3.63a**	1.385	**2.852**	0.021
Practitioners	3.00	0.920	2.56	1.459	3.40	0.894	2.33	1.155	2.50	1.069	2.83	1.528	0.950	0.455
Institutions/schools	2.78	1.050	**2.56a**	1.094	4.00	1.225	3.33	0.577	3.00	0.756	**3.20b**	0.995	**3.200**	0.012
University	**2.30a**	1.031	2.50	1.414	**4.20b**	1.304	2.67	1.528	3.25	1.488	2.89	1.326	**2.327**	0.052
Artists	**2.59a**	0.971	**2.56a**	0.964	3.00	0.707	3.33	1.155	2.74	0.916	**2.96b**	1.336	**2.686**	0.028
Designers	3.00	1.000	**2.56a**	0.957	3.40	1.140	3.33	1.155	2.50	0.926	**3.07b**	1.326	**2.173**	0.067

Score within the same statement followed by different letters are significantly different (i.e. "a" is different from "b" but not from "ab"). Bonferroni Post Hoc Test was applied.

Subsequently investigating the sectors with which International Fab Labs operate (Table 2.18) it can be seen that both European and American laboratories work more within the Technology industry, in detail the Electronic, followed by the IoT one. However in Italy the Furniture industry seem to have a good relevance in the cooperation with these laboratories, since it is one of the solid pillars of Made in Italy, and is known and appreciated in all international markets, with more than 40 industrial districts. Available data on this sector show that two of the three major European furniture producing regions are Italian (Veneto and Lombardy), and among the top 15, there are other three Italian regions, that is Marche, Friuli Venezia Giulia and Tuscany. Globally, this sector is second only to China for trade surplus, and owing to its manufacturing skills it generates an added value of 4.9 billion Euro. This is far greater than the many countries naturally rich in woody raw materials, such as France, Spain and Sweden (GreenItaly, 2016). It is important to underline that also German Fab Labs seem to work in different sectors compared to that of Technology, that is the Fashion, Mechanics and Food ones. This is in line with the literature that shows that AM is suitable to be applied within the textiles industry even if until today, the penetration of the market within the textiles industry is still limited to experimental purposes (Gausemeier et al., 2011). Also the Food industry has a relevant role with projects of AM and food printing carried out by Barilla, the Cornell University in collaboration with the French Culinary Institute in New York and by the company Natural Machines (Pricewaterhouse and Confartigianato imprese varese, 2015). Fab Labs are the perfect places to realize experiments of such types.

Table 2.18. Sectors with which Fab Labs' operate: ANOVA between Nations (α = 0.707)

	Italy		**France** *34.8% (16)*		**Germany** *10.9% (5)*		**The Netherlands** *6.5% (3)*		**Spain** *17.4% (8)*		**USA** *30.4% (14)*		**ANOVA**	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***F***	***Sig.***
Fashion	2.11	1.086	**1.56a**	0.629	**3.20b**	1.304	**1.33a**	0.577	**1.25a**	0.707	2.36	0.745	**4.452**	0.001
Furniture industry / furniture components	3.07	1.141	2.44	1.153	3.40	0.548	2.33	1.528	2.38	1.303	2.86	1.351	1.135	0.350
Mechanics	2.93	0.829	2.94	1.237	**4.00a**	1.000	2.67	0.577	**2.13b**	1.126	3.21	1.251	**2.187**	0.066
Automotive	1.74	0.764	2.00	1.155	2.60	1.517	1.67	1.155	1.38	0.744	1.86	0.864	1.190	0.323
Food	1.89	0.892	**1.31a**	0.602	**2.80b**	1.643	**1.00a**	0.000	**1.13a**	0.354	**1.43a**	0.646	**4.358**	0.002
Technology - Electronic	3.48	1.087	3.63	0.957	4.60	0.548	4.00	1.000	3.13	1.246	3.36	1.393	1.328	0.263
Technology - IoT	3.19	1.111	3.56	0.892	4.00	0.707	3.67	0.577	2.88	1.458	2.86	1.460	1.245	0.298
Technology – Software	2.63	1.115	3.00	1.265	2.80	0.447	2.67	1.528	2.75	1.581	2.79	1.311	0.187	0.966

Score within the same statement followed by different letters are significantly different (i.e. "a" is different from "b" but not from "ab"). Bonferroni Post Hoc Test was applied.

Considering the type of products realized inside Fabrication Laboratories (Table 2.19), it can be clearly seen that while in Europe mostly prototypes for individual customers are produced, in America, Fab Labs produce more finished products for individual customers. This allows to highlight how the overseas Fab Labs are more oriented towards the creation of finished products for the market than European ones.

Table 2.19. Type of realized products: ANOVA between Nations (α = 0.707)

	Italy		**France** *34.8% (16)*		**Germany** *10.9% (5)*		**The Netherlands** *6.5% (3)*		**Spain** *17.4% (8)*		**USA** *30.4% (14)*		**ANOVA**	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***F***	***Sig.***

Products to be marketed	2.00	1.000	1.81	0.750	1.60	0.548	2.33	0.577	2.25	1.282	2.71	1.326	1.605	0.171
Finished products for a single customer	3.00	1.074	2.86	1.258	2.20	1.304	3.00	1.000	2.13	1.246	3.50	1.286	1.776	0.130
Prototypes for companies	2.63	1.006	2.19	0.981	1.80	1.304	2.00	1.000	2.13	0.641	2.36	1.277	0.876	0.502
Prototypes for a single customer	3.26	0.859	3.06	1.124	2.60	1.517	3.00	1.000	3.00	1.309	3.14	0.866	0.394	0.852

Score within the same statement followed by different letters are significantly different (i.e. “a” is different from “b” but not from “ab”). Bonferroni Post Hoc Test was applied.

As for the kind of digital tools used in Fab Labs, Table 2.20 shows that 3D printers and laser cutters are the two most used, both in Europe and in America. These are followed by control cards such as Arduino mainly in Europe, while in America these are followed by vynil cutter. This underline that tools such as Arduino, that have been realized in Europe, in detail in Italy, have not reached such a high degree of overseas use.

Table 2.20. Use of digital machines in Fab Labs: ANOVA between Nations (α = 0.690)

	Italy		**France** *34.8% (16)*		**Germany** *10.9% (5)*		**The Netherlands** *6.5% (3)*		**Spain** *17.4% (8)*		**USA** *30.4% (14)*		**ANOVA**	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***F***	***Sig.***
3D printer	4.30	0.823	4.19	0.655	4.60	0.548	4.67	0.577	4.38	0.916	4.29	1.069	0.312	0.904
3D scanner	2.63	1.043	2.13	0.957	2.40	1.342	2.33	0.577	2.25	1.282	2.50	1.557	0.422	0.832
Laser cutter	4.33	1.144	4.25	1.000	3.80	1.643	5.00	0.000	3.25	1.982	4.64	0.633	1.890	0.108
CNC milling machines	3.41	1.152	2.81	1.109	3.40	0.894	2.00	1.000	3.25	1.389	3.43	1.505	1.171	0.333
Vinyl cutter	**2.59a**	1.083	**2.31a**	1.196	2.40	1.673	2.33	1.155	2.88	1.642	**3.93b**	1.269	**3.082**	0.015
Lathe	1.56	0.801	1.88	1.088	2.40	1.140	1.33	0.577	1.63	1.408	1.57	1.284	0.739	0.597
Control Cards (Arduino or similar)	3.44	1.281	3.75	0.931	3.80	1.414	3.00	1.732	3.50	1.414	2.79	1.369	1.128	0.354
Precision punches for printed circuits	2.33	1.330	1.88	0.885	2.40	0.894	1.33	0.577	2.25	1.488	1.71	1.437	0.861	0.512

Score within the same statement followed by different letters are significantly different (i.e. “a” is different from “b” but not from “ab”). Bonferroni Post Hoc Test was applied.

Analyzing the services Fab Labs deliver to customers (Table 2.21), courses and training are the most offered ones, even if the ANOVA test shows that these are offered with greater intensity in Spain and USA. Also the provision of material is a service that is offered more from German (4.00) and American (3.64) Fab Labs than by the others. Germany also give an important support to its customer to find the most suitable 3D printer (4.00). Another service that is spread among all the realities analyzed is the support for the creation of prototypes. Therefore it can be said that Fab Labs are not only places of practical practice, but also places where technical knowledge can be shared and learned.

Table 2.21. Services delivered to customers: ANOVA between Nations (α = 0.851)

	Italy		**France** *34.8% (16)*		**Germany** *10.9% (5)*		**The Netherlands** *6.5% (3)*		**Spain** *17.4% (8)*		**USA** *30.4% (14)*		**ANOVA**	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***F***	***Sig.***
Printing of products	3.56	1.311	3.50	1.095	2.60	1.517	3.67	1.155	3.75	1.035	3.79	1.311	0.731	0.603
Support to the creation of prototypes	3.70	0.823	3.94	1.124	4.00	1.732	3.00	1.000	3.75	0.886	4.00	0.961	0.639	0.670
Support to the design of new products	3.30	1.068	3.13	1.088	4.00	1.732	3.00	1.000	3.50	1.069	3.93	0.997	1.248	0.297
Support for finding the most suitable 3D printer	2.89	1.188	**2.06a**	0.998	**4.00b**	1.732	2.33	1.528	2.50	1.604	2.93	1.385	**2.087**	0.078
Support to the redefinition of the production process	2.89	1.013	2.63	1.310	3.40	1.517	2.67	1.528	2.50	1.414	3.07	0.917	0.607	0.695
Consultancy on materials	3.19	1.178	2.56	1.315	4.00	1.225	3.00	2.000	2.88	1.553	3.50	1.092	1.422	0.228
Provision of materials	**2.37a**	1.391	**1.94a**	0.854	**4.00b**	1.225	3.00	0.000	3.00	1.512	**3.64b**	1.336	**4.289**	0.002
Courses and training	3.85	1.064	**3.56a**	0.892	4.60	0.894	4.00	1.000	**4.75b**	0.463	**4.57b**	0.756	**3.390**	0.009

Score within the same statement followed by different letters are significantly different (i.e. “a” is different from “b” but not from “ab”). Bonferroni Post Hoc Test was applied.

If Fab Labs skills are taken into consideration, Table 2.22 shows that almost all Fab Labs have high skills in using design softwares, while Italy and the other European countries have more digital manufacturing skills and Arduino programming skills than the USA, which declare on the contrary to have relevant hardware and also material skills. Italy and America seem to have also quite relevant skills on company products if compared to the other realities. Therefore this underlines that these two realities are the most linked ones to businesses and to the market.

Table 2.22. Fab Lab skills: ANOVA between Nations (α = 0.766)

	Italy		**France** *34.8% (16)*		**Germany** *10.9% (5)*		**The Netherlands** *6.5% (3)*		**Spain** *17.4% (8)*		**USA** *30.4% (14)*		**ANOVA**	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***F***	***Sig.***
Arduino Programming skills	3.41	1.448	3.81	1.109	3.40	1.517	4.67	0.577	3.88	1.356	2.86	1.562	1.350	0.254
Skills on materials	4.00	0.961	**3.31a**	0.947	**4.60b**	0.894	4.33	0.577	3.38	1.061	4.14	0.864	**2.670**	0.029
Hardware skills	3.81	1.001	4.13	0.719	4.60	0.894	4.00	1.000	4.13	0.641	4.00	0.785	0.829	0.534
Skills on business processes	**3.63a**	1.115	**2.50b**	0.817	**4.00a**	1.247	3.00	1.000	2.63	1.188	3.50	0.941	**3.719**	0.005
Software programming skills	3.37	1.275	3.69	1.138	3.80	1.304	3.33	0.577	3.63	1.598	2.86	1.351	0.809	0.547
Skills in using design softwares	4.26	0.944	3.81	0.911	4.40	0.894	4.00	1.000	4.38	0.744	4.21	1.051	0.674	0.644
Skills on company products	**3.33a**	1.109	**2.38b**	1.148	3.20	1.304	2.67	1.155	2.38	1.188	3.50	1.225	**2.425**	0.044

Skills on Internet of Things (IoT)	3.26	1.059	3.44	1.153	3.40	1.140	3.00	1.000	3.50	1.195	2.79	1.528	0.604	0.697
Digital Manufacturing Skills	**4.52a**	0.802	3.75	1.126	4.40	0.894	4.33	1.155	4.38	0.744	**3.57b**	1.343	**2.279**	0.056

Score within the same statement followed by different letters are significantly different (i.e. “a” is different from “b” but not from “ab”). Bonferroni Post Hoc Test was applied.

As for product features that can be exalted realizing products in Fab Labs (Table 2.23), Italian laboratories stress more than others the importance of the territoriality of products, that is probably linked to the “Made in Italy”. Despite this, almost all agree to state that design and product quality are the features most exalted by Fab Labs’ products.

Table 2.23. Features exalted by Fab Lab's products: ANOVA between Nations (α = 0.837)

	Italy		**France** *34.8% (16)*		**Germany** *10.9% (5)*		**The Netherlands** *6.5% (3)*		**Spain** *17.4% (8)*		**USA** *30.4% (14)*		**ANOVA**	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***F***	***Sig.***
Design	**3.89a**	1.155	**3.00b**	0.817	3.60	1.140	3.67	0.577	3.75	0.886	**4.21a**	0.579	**2.789**	0.024
Product Quality	3.74	1.130	2.75	1.126	3.60	1.140	3.33	0.577	3.25	0.886	3.64	0.929	1.984	0.092
Ergonomics	3.74	1.095	2.88	1.025	3.40	1.140	2.67	0.577	3.00	1.414	3.21	1.051	1.686	0.150
Territoriality	**3.93a**	1.072	3.06	1.237	3.20	1.304	2.67	0.577	3.38	1.303	**2.79b**	1.122	**2.461**	0.042
Security	3.19	0.962	2.75	0.931	3.40	1.140	2.33	0.577	2.88	1.458	2.50	1.011	1.318	0.267

Score within the same statement followed by different letters are significantly different (i.e. “a” is different from “b” but not from “ab”). Bonferroni Post Hoc Test was applied.

Afterwards when asking to the respondents if they realize eco-sustainable products or prototypes, Table 2.24 show that this trend is not spread everywhere, and that The Netherlands, followed by Italy and America are the three countries in which this kind of products are produced most. Among the sustainable products cited in the survey there are aquaponic systems, models for innovative and eco friendly architecture, plant based (PLA) toys, prototypes for agro sensoring parameters, recycled fabric garments and accessories, solar powered air-pump stations, bike driven mixers, bike trailers, upcycling crafts of all types, wind turbines and solar panels.

Table 2.24. Production of eco-sustainable products

	France *34.8% (16)*		**Germany** *10.9% (5)*		**The Netherlands** *6.5% (3)*		**Spain** *17.4% (8)*		**USA** *30.4% (14)*		**Italy** *(27)*	
	n	***%***	***n***	***%***	***n***	***%***	***n***	***%***	***n***	***%***	***n***	***%***
No	10	62.5%	2	66.7%	1	20.0%	6	75.0%	7	50.0%	13	48.1%

Yes	6	37.5%	1	33.3%	4	80.0%	2	25.0%	7	50.0%	14	51.9%
Total	16	100.0%	3	100.0%	5	100.0%	8	100.0%	14	100.0%	27	100.0%

In the final section of the survey it has been investigated, in the same way it has been done for Italian Fab Labs, if they thought that technologies could have an impact on the working environment, and if this impact could be positive or negative, in order to understand the general thought of those who work daily with these digital tools and if they are aware of possible dangers related to the harmful emission of Volatile Organic Compounds (VOCs) from 3D printers (Table 2.25). Almost the entire sample of the respondent Fab Labs believe that there is an impact of technologies on the work environment and that this impact is positive. Only one interviewee out of 73 believes that this impact can be negative, while in some cases the respondents do not express an opinion about it.

Table 2.25. Perception of the impact of technologies on working environment

	France		***The Netherlands***		***Germany***		***Spain***		***USA***		***Italy***	
	n	***%***	***n***	***%***	***n***	***%***	***n***	***%***	***n***	***%***	***n***	***%***
No	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
I don't know	4	25.0%	1	33.3%	1	20.0%	0	0.0%	0	0.0%	4	14.8%
Yes, positive	12	75.0%	2	66.7%	4	80.0%	8	100.0%	14	100.0%	22	81.5%
Yes, negative	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	1	3.7%
Total	*16*	*100%*	*3*	*100%*	*5*	*100%*	*8*	*100%*	*14*	*100%*	*27*	*100%*

When asking them in a more direct way how much they believe that 3D printers emissions could be harmful for their health (Table 2.26), the majority of Fab Labs answered not to show much concern about it, except for Spanish Fab Labs that stressed a bit more this eventuality (3.50) and in a less way German Fab Labs too (3.00).

Table 2.26. 3D printers emissions: are they harmful?

Nation	***N***	***Mean***	***Std. Deviation***
France	16	2.86	.719
The Netherlands	3	2.33	2.309
Germany	5	3.00	1.414
Spain	8	3.50	.756
USA	14	2.71	1.326
Italy	27	2.48	1.189
Total	46	2.91	1.132

Finally it has been asked to international Fab Labs how much they think that digital technologies (Table 2.27), will be the turning point that will allow the industry to enter a new revolution. Italian Fab Labs (3.85), followed by Spanish (3.75), American (3.64) and German (3.60) ones are those most convinced that these technologies can be revolutionary.

Among the main motivations expressed there is the fact that decentralized production will affect transport/shipping, mass customisation will become a new niche for consumer products and a smaller time to market will result in smaller production runs with reduced fixed costs and hence more agility when it comes to innovation. Digital production allows for greater automation in the design phase with parametric generative design. The extent of how revolutionary it will be will largely be determined by copyright legislation/enforceability and cultural shifts in attitudes to creative commons and other "open" licences when it comes to software tools for digital production. For someone else it is the future, because it puts the tools and power back in the hands of the community; it is not the industry but the individuals, through the use and appropriation of these technologies in places like Fab Labs, makerspaces and hackerspaces that will revolutionize the economic panorama. The industry should adapt to this turning point and start opening up its processes, sharing its blueprints with customers so that people can repair and build for themselves. The next revolution will not be one of consumption but of upcycling and recycling. Others say that more people can design and make things, generating bottom up demand for and support of grassroots, local manufacturing. Thanks to these technologies there is increased control of output; lower barriers to entry for competent use of such technology, allowing more types of ideas to be expressed through digital fabrication.

While, in the ancient industrial revolutions, it would need a lot of resources (human, technological, financial) to introduce some product/service to a particular market; today, there is a digital and material democratization thanks to the open source notion. This democratization process is going from a centralized towards a distributed model.

Table 2.27. Are new digital technologies the turning point that will allow the industry to enter a new industrial revolution?

Nation	*N*	*Mean*	*Std. Deviation*
France	16	3.06	.854
The Netherlands	3	2.33	1.528
Germany	5	3.60	1.140
Spain	8	3.75	1.581
USA	14	3.64	1.151
Italy	27	3.85	0.989
Total	46	3.37	1.181

2.4.4 Conclusions and implications

Fab Labs are an example of maker communities and they can be described as “places to make (almost) anything” (Gershenfeld, 2008) where everybody can design, fabricate, test and debug innovations (Mikhak et al. 2002). Fab Labs offer open access to a range of low-cost fabricators and they are based on a commons-based peer production approach (Troxler 2010; Troxler and Wolf 2010). The aim of this research was to compare the Italian economic reality of Fab Labs with the major European (French, German, Dutch and Spanish) and American ones.

The results show for the Italian reality, that, while some laboratories are still in an embryonic phase, with no or very few registered users, others are in full activity reaching over 100 users. In any case, the growth of Italian Fab Labs can be defined exponential, if one think that the first Fab Lab in Italy was born in Turin in 2012 and now, six years later, there are 134 laboratories recognized by the global Fab Lab network (http://fabfoundation.org/). Italian laboratories are characterized by ample space available, but limited capacity for investment in machinery and technology. European Fab Labs are similar to those Italian (with a medium surface between 75 and 200 square meters), while American ones are more heterogeneous in size. However a fact that emerges clearly is how American Fab Labs are more important realities than European ones in terms of turnover and investments. They are more similar to businesses with an independent financial support.

What is more, as for customers and cooperation networks, the results show that Italian laboratories, compared to those of Germany, Spain and America, seem to have less contacts and relationships with schools and universities. However the function of Fab Labs in education is quite broad, reaching from basic science, technology, engineering, and mathematics (STEM) education in general and early encounters with design to the use of the labs as ideation and prototyping spaces in higher design education. Next to that they stimulate critical debate on material use and conceptual design issues (Mostert-Van Der Sar et al. 2013). Fab Labs have the ambition to share digital fabrication blueprints as well as operating instructions for using the machines in the worldwide community. They hold altruistic values of open and reciprocal knowledge sharing and implicitly understanding knowledge as a public asset, as a commons (Hess and Ostrom 2007; Verschraegen and

Schiltz 2007). The term knowledge refers in this context to “all types of understanding gained through experience or study” (Hess and Ostrom 2007). Fab Labs strive to achieve more equal participation and inclusion of citizens in knowledge transformation processes for a future society by establishing integrative public spaces where citizens are provided with open access to information and knowledge, and are supposed to share new information and knowledge back into the commons; receive training on the usage and further development of digital technologies; gain affordable or free access to the technologies and/or methodologies for the production of the commons (Wolf et al., 2014).

The commitment of the Fab Lab community to participate in processes of commons-based knowledge production thus also includes global knowledge sharing. However extant literature suggests that there might be further motivational, social, technological and legal barriers to the participation of the Fab Labs into global processes of commons-based knowledge production. As for motivational barriers, individuals have to be willing to share experiences and insights openly in a virtual environment (Spaeth et al. 2008; Rangachari 2009). What is more, for sharing efficiently, users have to complete the usually difficult, task of documenting what they have done. This is particularly relevant for maker communities where knowledge is transformed in the interaction with the material, in processes of fabrication, and with the physical world of hardware (Troxler and Zijp 2013). As for the social barriers, Mostert-Van Der Sar, et al., (2013) stated that firstly socialization is difficult to be effectively achieved by the means of online communication as they require some degree of externalisation. Hence, there is a trade-off between the usefulness of local versus global collaboration. Secondly, the willingness to share information, ideas and knowledge is usually possible in networks of mutual acquaintance, (i.e. friendships or memberships of a university class), while among strangers in groups this motivation decreases (Nahapiet and Ghostal, 1998). Besides motivational and social barriers, there are also technological barriers to communication, documentation and sharing to overcome. The technology of a virtual community platform has to be designed in a way that ensures compatibility of programs and infrastructure, as well as accessibility to information (Gibson and Cohen, 2003). When working in global virtual communities, in addition to time and geographical differences, disparities in national, cultural and linguistic attributes have to be dealt with by technology (Zakaria, Amelinckx and Wilemon, 2004). Finally, even if Fab Labs were created on the basis of open design (Määttä and Troxler, 2010) to generate new knowledge on making or (personal) manufacturing, and to share it throughout the making, there are always legal issues related to sharing knowledge openly through the Internet, as some forms of knowledge receive preferred legal protection from copying (i.e. intellectual property legislation, patenting, licensing, and lack of preservation of the public domain) (Mostert-Van Der Sar et al., 2013).

Going beyond the barriers to sharing knowledge and skills and considering the type of Fab Labs skills, the results of the PCA showed that these can be divided into three main groups: business and design, software and hardware and materials skills. Observing these skills in detail, it can be seen that digital manufacturing skills and Arduino ones are more developed in European Fab Labs that in the American ones. Moreover the research shows that 3D printers are in every investigated reality the most used digital tool. Therefore what are the practical implications of applying these skills and using digital tools in Fab Labs? What is the role of these digital craft laboratories? According to Stacey (2014) Fab Labs can be used to give entrepreneurs a low-cost space for designing and building prototypes. They should assist smaller firms in their process of digitalization in the Industry 4.0 era making available of their digital manufacturing tools to those companies that do not have the possibility to make huge investments in this type of digital machineries, creating collaborative networks with them. It is also essential that Fab Labs help smaller firms dealing with this industrial re-volution making their knowledge available to them, and organizing training courses to develop workers with the necessary skills to face these changes in the industrial landscape. Making available their tools and skills Fab Labs would facilitate the process of industry 4.0 transition for smaller firms. However, as the study shows, only in the Italian economic reality manufacturing companies and practitioners represent together the second type of Fab Lab’s customers. It would be important that this trend could develop also in the other European and American countries, where innovative companies, with smaller dimensions and relative more limited investment capacity, could decide to collaborate with Fab Labs to develop product or process innovation strategies, with more limited use of economic resources (Murmura and Bravi, 2017). The state could enter this phase, helping with incentives the development on one side of these new digital realities and their collaboration in the form of networks with companies, in such a way that a synergy between the subjects could be created. Therefore, it would be necessary that the government incentives in the form of collaborative projects should be developed more assiduously in Italy to continue developing the collaboration with businesses and also in the other European and American realities.

Moreover, Fab Labs can be spaces where students engage in design and technology education. And they can be centers of community-driven innovation, where problems that governments and corporations have not addressed can be solved using local materials, and those solutions can later be shared with similar communities around the world. One application for Fab Labs is providing the tools for entrepreneurs (in both developed and developing nations) to prototype their ideas at radically reduced costs. While the Fab Lab facilities cannot produce at the scale that might eventually be optimal to satisfy demand, the advantage for entrepreneurs is in nimble adaptability and simplicity; while creators can retain rights to the inventions, as much of the process as possible is shared so that others can build on and learn from the work. They provide tools also for common people, and particularly students, to get their hands “dirty” with digital manufacturing. It demonstrates how the gap between product design and electronics can be bridged in an easy and attractive manner (Mostert-Van Der Sar et al., 2013)..

In many cases the problems that Fab Labs focus on are in fact highly localized and address needs that governments or markets have overlooked. Once developed, however, they are often adaptable to markets and communities around the globe. By sharing information across the network, tinkerers and users around the world can adapt these innovations to their own local circumstances (Stacey, 2014).

2.4.5 Limitations and future research directions

As for the limitation of the research the narrowness of the sample analyzed is the most important one. It is however true that there are few numbers of respondent Fab Labs for each country, but it is important to consider that the total number of Fab Labs present in each country is very limited and that the response rate in every case does not fall below the 10% threshold, and for Italy it reaches the threshold of 24%. This limit will be overcome in future research by carrying out deeper qualitative analysis on Italian, European and American Fab Labs, always with the aim of highlighting and comparing their potential strength and weaknesses. Moreover, for future research it would be important also to consider the side of businesses, trying to understand if they are primarily aware of Fab Labs and if they have already developed collaborations with them or would have an interest in developing such collaborations; and the side of private consumers, in order to evaluate their involvement with these laboratories.

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3. AM PERCEPTION IN THE ITALIAN MARKET: CONSUMERS AND BUSINESSES

ABSTRACT

This chapter takes into consideration the analysis of the perception and development of Additive Manufacturing techniques in the Italian market. To do this, the results of three research works are presented. The first tries to investigate the knowledge and perception that Italian consumers have of 3D printers, and their propensity to use these manufacturing technologies in order to evaluate how much Italian consumers are near to the definition of the new consumer called "Prosumer" given by Alvin Toffler (1980). Subsequently the role of businesses in investing in this new manufacturing technology has been investigated. The research focus was the Italian wood-furniture industry, solid pillar of the Made in Italy, where design is the first element of importance. The aim was to understand if companies in this sector were investing in digital technologies and in particular in AM techniques, to remain competitive in their reference markets. The research also attempted to investigate the potential sustainable benefits and barriers to the implementation of AM in this specific sector, trying to identify the gaps in perception between "traditional companies", which have never implemented AM techniques and those "innovative", which have implemented these technologies yet.

3.1. Attitudes and Behaviours of Italian 3D Prosumer in the Era of Additive Manufacturing

Abstract

The Additive Manufacturing technology can move the method of customisation away from the conventional means; this technology can serve consumers as individuals in the same way craft customisation can, but employing different forms of communication and interaction. Therefore the traditional consumer is changing his role, becoming at the same time producer and consumer of what he needs. This research tries to investigate how much this new trend in consumer attitudes is influencing Italian consumers, analyzing consumer knowledge and perception of 3D printing and its propensity to use these manufacturing technologies. The results show that not all Italian consumers are aware of these manufacturing technologies yet, and those who know them, are still divided into four different categories: passive consumers, 3D prosumers, not influenced consumers and unfashionable ones. A third of the total sample is made by consumers open to change and to the purchase of innovative products made with AM techniques, that believe that they are better products in terms of quality, sustainability, design and especially they could meet their taste and needs. Finally there are still hesitant and traditional consumers that remain anchored to traditional production methods and do not trust completely these technologies. Therefore in the Italian context although these technologies are known and appreciate from a third of the population, there is still ample room for growth in the use of Additive Manufacturing as innovative production tool of collaboration between companies and consumers.

Keywords: 3d Printing, Additive Manufacturing, Consumer Behaviour, Quality,
Prosumer.

3.1.1 Introduction

In recent decades the production paradigm has changed and many industries have shifted from production-driven and market-driven approaches to consumer-driven approaches (Labreque et al., 2013; Tseng and Hu, 2014). This latter approach connects consumers' choices with the capabilities of the company and extends the philosophy of concurrent engineering to sales, marketing and end users. Thereby, it brings the voice of customers into design and manufacturing (Tseng and Du, 1998; Tseng and Piller, 2003). In the pre-industrial era, craft customisation existed. People created products in a customised way despite the limitations of technology at the very beginning of market trade. Products were initially made one-by-one according to each individual's needs. This procedure was typically carried out by individuals or home industries. The desire to reduce production costs and time created strong influences in the increased use of Mass Production (MP) (Fralix, 2001). Good quality and a cheap price became very popular drivers. MP provided a low cost option that led to uniformity (Ariadi et al. 2012). At some point, simplification of product variants was criticised, and consumers required industries to listen to their expectations of styles, sizes, needs or even schedules. This drives production away from pure MP towards the need to accommodate versions and options. It starts the era of Mass Customization (MC), that is a production system that enables customisation and personalisation or individualisation of products as well as services at a price comparable to MP (Davis, 1987; Bae and May-Plumlee, 2005; Hu, 2013).

The term Mass Customization was first coined by Stan Davis in Future Perfect (Davis, 1987) and later developed by Pine (1993), which embarks a paradigm shift for the enterprise that offers products and services best fitting to individual customer's needs while still keeping near-mass production efficiency (Tseng and Jiao 2001). The key feature of mass customization is the capability to integrate the product varieties derived from the individual customer's needs and desire and the efficiency of mass production, so that the product is affordable due to low product cost achieved by the production scale of economy (Tseng and Hu, 2014).

The essence of mass customization is to transform a customer to "co-designer", in which the customer is able to get access to the design process, such as concept design and product development, by expressing the requirements or even co-designing the product with the configuration toolkit (Tseng and Piller 2003). Mass Customization changes the design and production from "made-to-stock" to "made-to-order" (Tseng and Hu, 2014).

The Additive Manufacturing (AM) technology can move the method of customisation away from the conventional means, such as product modularity, towards bespoke production (Berman, 2012). AM capabilities can serve consumers as individuals in the same way craft customisation can, but employing different forms of communication and interaction. In some ways, this shows similarity to the manufacturing conditions of the pre-industrialisation era (Ariadi et al., 2012; Berman, 2012).

According to Davis (1987), similar events to those in the past will happen in the future regardless of how or what form they will take. Hence, as suggested by Ariadi et al., (2012), the use of AM could be portrayed as a means of completing the circular pattern of production technologies, from craft customization, fragmented production, Mass Production to Mass Customization, Additive Manufacturing could close the circle that leads again to the new digital craft customization.

Increasingly today, individuals and micro-organizations are afforded digital tools, either through affordable 3D printing hardware or streamlined outsourcing, to engage with the act of making directly, out of self-motivation (Kuznetsov and Paulos, 2010). Furthermore, this engagement does not typically occur in isolation; rather, digital media also provides the means for sharing the experience of making with others, through both receipt and dissemination of resources. Current uses of 3D printing seem to empower people in several distinct ways, including: fashioning custom tools to accomplish specific tasks; extending or connecting disparate forms, systems or structures; visualizing problems that are difficult to picture virtually; expressing their aesthetic taste, individualism, community affiliation or "brand" and of course, having fun by making their own toys (Ree, 2011).

Considering that, this research tries to investigate the attitudes of Italian consumers in relation to these new forms of consumer behaviour, their knowledge of AM, 3D printing technologies and Fabrication Laboratories (FabLabs), their perceptions about products made using 3D printers, and their propensity to use these technologies. Therefore the research questions are: do Italian consumers have the propensity to become prosumers in the new era of digital craft customization? Do Italian consumers will be able to act as a driving force for the development of the Additive Manufacturing technology in Italy?

This study aims to start a line of research still almost completely undeveloped, combining the analysis of the behavior of the figure of the modern consumer with the analysis of Additive Manufacturing techniques, to see if the market demand side (consumer) can push the development of such digital production techniques in Italy.

3.1.2 Consumer behaviour in the digital era

In the contemporary digital economy, consumers increasingly seek out individualized experiences and expect products to be tailored to their specific needs, wants, contexts and tastes.

Analyzing the manufacturing shift toward individualized consumerism in terms of the gaps that occur when users' needs for a technology or product, Von Hippel (2005) states that these ones are far more heterogeneous than can be adequately satisfied through Mass Production. There are multiple ways in which producers can fill this gap. One is, of course, the "bespoke" mode of customization, now reserved for highly specialized and often elitist items. Alternatively, the manufacturer may allow consumers to select from various options late in the production phase, which is common for such features as car colour or a condominium's interior finishes (Ree, 2011). While the above forms of customization are consumer-oriented but producer-driven, emerging modes of customization are decidedly consumer-driven (Mowatt, 2005).

In the mass customization manufacturing environment, the customer becomes a co-designer, using the firm's capability to create an individualized unique solution (Bae and May-Plumlee, 2005). The literature calls this new consumer as "prosumer". The term prosumer is generally attributed to Alvin Toffler (1980) who devoted considerable attention to it in The Third Wave (Ritzer and Jungerson, 2010). Toffler argued that resumption was predominant in pre-industrial societies; what he called the “first wave”. It was followed by a “second wave” of marketization that drove “a wedge into society, that separated these two functions, thereby giving birth to what we now call producers and consumers” (Toffler, 1980, p. 266). Thus, the primordial economic form is neither production nor consumption, but rather it is resumption. However, in Toffler’s view, contemporary society is moving away from the aberrant separation of production and consumption and towards a “third wave” that, in part, signals their reintegration in “the rise of the prosumer” (Toffler, 1980, p. 265). In fact as stated by Ritzer and Jungerson (2010), in late 2007 both consumption and production declined as a result of the global “great recession”. While the increasing pre-eminence of resumption, and the growing attention to it, were not caused by the recession, the decline of both production and consumption, arguably, made space for greater scholarly interest in and concern with resumption. There are signs that consumer (and producer) society is beginning to be challenged in importance by what might be called “prosumer society” (Prahalad and Ramaswamy, 2004; Tapscott and Williams, 2006). Gerzema and D’Antonio (2010) in *Spend Shift: How the Post-Crisis Values Revolution Is Changing the Way We Buy, Sell, and Live* describe the manner in which consumer and entrepreneurial behaviour has been transformed in (North) America following the recent economic downturn, and continues to the present recovery. They observe that in general, people are questioning and repositioning their relationships to consumption and to material things; there is a move from an acquisitive to an inquisitive society and they see that Making, and Do It Yourself (DIY) are on the rise, because hard times have reinforced the virtues of practical skills, doing it by themselves, and mending and repairing in order to make things last (Kuznetsov and Paulos, 2010). As Professor Mizik noted, this move toward more values – based spending reflects an adaptation to a life event that has been shared across society. When a great number of people experience a crisis of this magnitude, needs replace wants and consumerism become not just thrifty but strategic. The values described in Gerzema and D’Antonio (2010), that were emerging even before the official start of the recession could be grouped in five categories:

- *Indestructible spirit:* optimistic and resilient people are leveraging hardship into opportunity;
- *Retooling:* fiercely self – reliant people retain their faith in core traditions and actively seek to better their communities and themselves.
- *Liquid life:* people are adopting a more nimble, adaptable, and thrifty approach to life.

- *Cooperative consumerism:* crisis has prompted people to collaborate to solve problems and create new options.
- *From materialism to the material:* old status symbols no longer appeal as purpose, character, authenticity, and creativity become pathways to the new good life.

In this context the availability of 3D printing technology is a new step in the emergence of what has been called the 'prosumer' – the consumer who achieves *complete customization* by manufacturing one-of-a- kind products (Troxler and van Woensel, 2015). This form of manufacturing is thus able to introduce elements of bespoke tailoring to products normally associated with mass production, but at mitigated price points due to economies of scale. "Co-creation" platforms, are also variants of mass customization that afford prosumers the opportunity to interactively personalize products in such a way that encourages users to feel more like 'designers' of objects rather than passive recipients.

3.1.3 Methodology

The research was carried out through a questionnaire proposed to 1203 individuals in paper or through the use of e-mail and Computer Assisted Web Interviewing (CAWI). Data have been collected from the 1st September to 15th November 2016. The questionnaire has been divided in 3 sections: the first section investigates socio-demographic features of the sample, the factors of importance in product choice and respondents life style. The second section provides information about consumer knowledge, perception and interest in 3D printing, trying to understand their propensity to become prosumers and evaluating if they believe that AM could represent the breakthrough that will allow the advent of a new Industrial Revolution. Finally section 3 investigates consumer knowledge and relationships with FabLabs. Data were elaborated using SPSS 23.0 program, Statistical Package for Social Science. Descriptive analysis was performed to describe the sample profile of respondent companies, and the Analysis of Variance (ANOVA) was performed using F-tests to statistically test the equality of means (Markowski, 1990). Moreover Cronbach's alpha values were computed, taking into account only values greater than 0.60 as suggested by Nunnally and Bernstein (1994). A Principal Component Analysis (PCA) followed by oblimin rotation (Jennrich and Sampson, 1966) was applied to factors influencing consumer purchase behaviour and perception of 3D printing. In the estimation data process, the variables with factor loadings less than 0.6 were dropped from further analysis, because these are not considered statistically significant. Finally a cluster analysis was performed using the k-mean algorithm (Johnson and Wichern, 2007).

3.1.4 Results and discussion

1.4.1 Sample profile

In the first part of the research the socio-demographic characteristics of the sample have been analyzed (Table 3.1). The majority of respondents are female (60.3%), aged between 18 and 24 years, even if a relevant percentage of consumers are present in the bands between 25 and 34 and 35 and 44 years old; moreover 46.9% of respondents in the sample have a diploma, followed by a bachelor (24.2%) or master degree (17.2%) and they live in the central regions of Italy (56.1%).

Table 3.1. Consumer Profile

		n	*%*
Gender	Male	477	39.7
	Female	726	60.3
Age	18-24	474	39.4
	25-34	378	31.4
	35-44	162	13.5
	45-54	117	9.7
	> 55	72	6.0
Level of education	Primary School Diploma	6	0.5
	Middle School Diploma	54	4.5
	Diploma	564	46.9
	Bachelor Degree	291	24.2
	Master Degree	207	17.2
	Ph.D.	81	6.7
Region	North	291	24.2
	Center	675	56.1
	South and Islands	237	19.7

3.1.4.2 Consumer Choices and Life Style

In this section the factors which affect consumers’ choices and their purchase and consumption behaviour have been analyzed. It was asked to the respondents to evaluate the importance of each element present in Table 3.2 using a Likert scale from 1 (not important) to 5 (very important), when considering the purchase of a product, and the results showed that Quality of Materials (4.40) and Price (4.30) are the main relevant factor of choice; these are followed by Technology Innovation (3.90) and by Design (3.83) considered as peculiarity, beauty and modernity of the product. Brand (2.97) is the element less considered in the choice of purchasing.

Subsequently the sample has been divided in two main groups, the one of *Young Consumers* and that of *Mature Consumers*, in order to evaluate if there is a different perception between them. The first group is made up of consumer up to 34 years, while the other group includes consumer with more than 34 years.

Factors such has Technology Innovation (4.04), Made in Italy (4.06), Sustainability (3.94) and Customization (3.91) are considered more important, in a statistically significant way by Mature Consumers as well as Corporate Image and Brand, even if in a less relevant way.

Table 3.2. Factors of Importance in Product Choice (Five point Likert scale; α = 0.687)

	Total Sample *n=1203*		***Young Consumers*** *(70,8%) n= 852*		***Mature Consumers*** *(29,2%) n=351*			
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*F Test*	*Sig.*
Design (peculiarity, beauty and modernity of the product)	3.83	0.851	3.82	0.819	3.84	0.928	.034	.854
Quality of Materials	4.40	0.728	4.38	0.716	4.44	0.759	.483	.487
Sustainability (lower waste of resources and the possibility to be recycled)	3.63	1.157	3.50	1.145	3.94	1.132	**12.527**	.000
Made In Italy	3.55	1.214	3.35	1.210	4.06	1.069	**30.892**	.000
Price	4.30	0.772	4.32	0.704	4.24	0.916	.997	.319
Customization	3.59	1.083	3.45	1.064	3.91	1.063	**15.755**	.000
Technology Innovation	3.90	0.887	3.84	0.906	4.04	0.824	**4.450**	.036
Brand	2.97	1.026	2.86	1.008	3.24	1.023	**11.469**	.001
Corporate Image	3.68	0.942	3.63	0.917	3.81	0.991	**3.100**	.079

After that, Consumer willingness to pay more for certain relevant factors in the purchase of a product was investigated. It was asked to the respondents to answer, using a Likert scale from 1 (totally disagree) to 5 (totally agree) how much they agreed with the statements found in Table 3.3. In general it seems that consumers would pay more for Quality Products (4,40), moreover it seems that there is a statistically different perception for all the product features cited in text; that is to say Mature Consumers seem to be willing to pay more not only for Quality, but also for Made in Italy (3.74), Sustainable Products (3.68) and Customized Products (3.64). This result may arise because older consumers have certainly greater monetary autonomy than younger ones.

Table 3.3. Consumer Willingness to Pay for Product Features (Five point Likert scale; α = 0.610)

	Total Sample *n=1203*		***Young Consumers*** *(70,8%) n= 852*		***Mature Consumers*** *(29,2%) n=351*			
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*F Test*	*Sig.*
I'm willing to pay more for customized products	3.44	1.033	3.35	1.034	3.64	1.004	**6.575**	.011
I'm willing to pay more for sustainable products	3.44	1.137	3.35	1.116	3.68	1.157	**7.473**	.007
I'm willing to pay more for Made in Italy products	3.40	1.123	3.26	1.106	3.74	1.092	**16.153**	.000
I'm willing to pay more for Quality Products	4.40	0.613	4.35	0.630	4.53	0.550	**7.363**	.395

Afterwards, following the studies of Gerzema and D’Antonio (2010) which described the changes in consumer and entrepreneurial behaviour in (North) America after the recent economic downturn, the research wants to investigate if this move from an acquisitive to an inquisitive society where Making and Do It Yourself (DIY) are on the rise, is also found in the Italian society. For this reason the same items used by Gerzema and D’Antonio (2010) have been restated in the research in addition to further variables. In general the results (Table 3.4) show that the two most cited behaviours in terms of importance are the interest in learning new skills, in order to do more alone and be independent from the others (4.60), that has been cited more from Young Consumers than from Mature ones, followed by the attempt to transform the difficulties in new opportunities (3.87) and the will to maintain faith and traditions trying to improve the world around them (3.78). Among the items less mentioned there is the belief that the crisis didn’t push so much people to work together to solve problems and create new opportunities (3.13). Making a comparison between the two groups of consumers, Mature ones seem to be more near to the type of post-crisis consumer described in literature, they first of all are proud to maintain their faith and traditions (4.13), they want to learn new skills (4.05) and want to transform difficulties in new opportunities for work and life (4.02), moreover they try to adopt a more simpler approach to life (3.67) (Table 4).

Table 3.4. Consumer Life Style (Five point Likert scale; α = 0,684)

	Total Sample *n=1203*		***Young Consumers*** *(70,8%) n= 852*		***Mature Consumers*** *(29,2%) n=351*			
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*F Test*	*Sig.*
I'm interested to learn new skills, in order to do more alone and rely less on others	4.60	0.939	4.06	0.907	4.05	1.016	.014	.907

I'm willing to repair items (shoes, bags, home appliances...) in order to not have to replace them	3.76	1.086	3.73	1.061	3.84	1.144	.886	.347
I try to transform the difficulties in new opportunities for work and social life (Indestructible spirit)	3.87	0.970	3.81	0.953	4.02	1.000	**3.678**	.056
I maintain my faith and my traditions and actively try to improve my community and myself (Retooling).	3.78	1.008	3.64	1.053	4.13	0.876	**20.601**	.000
I'm adopting an approach to life simpler and parsimonious (Liquid life)	3.52	1.020	3.46	1.020	3.67	1.009	**3.381**	.067
I believe that the crisis push people to work together to solve problems and create new opportunities (Cooperative consumerism)	3.13	1.223	3.04	1.172	3.34	1.321	**5.142**	.024
I think that the old status symbols have no value, but character, authenticity, and creativity become the new life paths (From materialism to the material).	3.56	1.036	3.50	1.014	3.70	1.077	**3.245**	.072

In order to evaluate Consumer Choices and Life Style a PCA was performed. As for the factors of importance in product choice, two main component were found (Table 3.5). The first one in terms of importance (49.1%) is called *Beauty and Innovation* and it is linked to the design of product, the image of the company and its features of innovation, while the second component, with a cumulative variance of 33.9% is called *Traditions and Quality* and it is linked to the traditions of Italian products which are made with quality materials, they represent the Made in Italy and are sustainable.

Table 3.5. PCA on Factor of Importance in Product Choice

Pattern Matrix[a]

	Tradition & Quality	***Beauty & Innovation***
Design (peculiarity, beauty and modernity of the product)	-	.639
Quality of Materials	.605	-
Sustainability (least possible waste of resources and possibility to recycle)	.888	-
Made In Italy	.681	-
Customization	-	-
Technology Innovation	-	-
Brand	-	.899
Corporate Image	-	.674
Cumulative Variance	*33.9*	*49.1*
KMO	0.73	

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.
a. Rotation converged in 11 iterations.

As for Consumer Life Style the PCA showed the presence of three different types of consumers (Table 3.6): the first component in terms of cumulative variance (64.6) is called *Self Made Consumer* and is composed of consumers who are interested in learning new skills so that they can be real producers of everything they need to have. The second component in terms of cumulative variance (52.0) is called *Post-Crisis Consumer* and it consists of consumers who believe the crisis has led to radical changes in the way of living and thinking of people; while there is also a minor percentage of consumers (35.3%) called *Bound to Traditions Consumer* that are still bound to traditions even if the crisis has led them to have a simpler life style.

Table 3.6. PCA on Consumer Life Style

Pattern Matrix[a]

	Bound to Traditions Consumer	***Post-Crisis Consumer***	***Selfmade Consumer***
I'm interested to learn new skills, in order to do more alone and rely less on others	-	-	.777
I'm willing to repair items (shoes, bags, home appliances...) in order to not have to replace them	-	-	.819
I try to transform the difficulties in new opportunities for work and social life (Indestructible spirit)	-	-	-
I maintain my faith and my traditions and actively try to improve my community and myself (Retooling).	.836	-	-
I'm adopting an approach to life simpler and parsimonious (Liquid life)	.688	-	-
I believe that the crisis push people to work together to solve problems and create new opportunities (Cooperative consumerism)	-	.724	-
I think that the old status symbols have no value, but character, authenticity, and creativity become the new life paths (From materialism to the material).	-	.880	-
Cumulative Variance	*35.3*	*52.0*	*64.6*
KMO		0.736	

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.
a. Rotation converged in 8 iterations.

3.1.4.3 Consumer knowledge and interest in 3D printing

This section investigates how much Italian consumers know 3D printers and if they are interested in purchasing products made with them or purchase desktop 3D printers to make alone the products they need. The 68.3% of the entire sample claim to know what a 3D printer is, 23.7% of respondents have heard only vaguely about 3D printing and 8% of them said not to know this technological manufacturing tool. Among the main means of knowledge of 3D printing there is the Internet (32.9%), followed by Tv (22.4%), Family and Friends (15.5%), Magazine and Newspapers (10.2%) and the Work Environment (9.7%).

When asking consumers what is their perception of 3D printers and what can be done using the same (Table 3.7), they believe most that this tool permits the creation of customized products (4.21) and of modern, special and trendy products (3.91). On the contrary they are not sure about the fact that 3D printers could allow the creation of products with the features of Made in Italy (3.22) and about the fact that the materials used are of quality and can last long (3.17). Moreover the perception that 3D printers allow the realization of products with the minimum use of resources and as to be recycled is more present among Mature Consumers than Young ones.

Table 3.7. Consumer Perception about 3D Printing (Five point Likert scale; α = 0.780)

	Total Sample *n=1203*		***Young Consumers*** *(70,8%) n= 852*		***Mature Consumers*** *(29,2%) n=351*			
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*F Test*	*Sig.*
3D printers allow the realization of products with a minimum use of resources and such as to be recycled	3.65	0.913	3.58	0.900	3.81	0.928	**5.361**	.021
3D printers allow the creation of products with high quality materials that last long	3.17	0.935	3.13	0.896	3.27	1.022	1.933	.165
3D printers allow the creation of customized products, completely customized to tastes and needs	4.21	0.919	4.21	0.896	4.20	0.976	.021	.885
3D printers allow the creation of products with the features of Made in Italy (eg. the quality of materials and design)	3.22	1.147	3.17	1.112	3.33	1.225	1.704	.193
3D printers allow the creation of modern, special and trendy products	3.91	0.981	3.87	0.955	4.01	1.038	1.663	.198

After having analyzed the respondents knowledge about 3D printers, it has been asked if they were interested in buying some types of products made with 3D printers (Table 3.8). In general consumers' interest does not exceed much the indifference threshold (value 3 of Likert scale), emphasizing their not excessive confidence in buying products made using Additive Manufacturing techniques. However among the most cited items there is the interest in buying products that are tailored and customized according to consumer tastes and needs (3.57) and in buying products with quality of materials and design (3.45); in this second case Mature Consumers are more interested in quality and design features of products than Young ones.

Table 3.8. Consumer Interest in Buying 3D Products (Five point Likert scale; α = 0.853)

	Total Sample *n=1203*		***Young Consumers*** *(70,8%) n= 852*		***Mature Consumers*** *(29,2%) n=351*			
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*F Test*	*Sig.*
I am interested in purchasing products made with 3D printers trying to use the least amount of resources and likely to be recycled	3.28	1.140	3.26	1.120	3.33	1.189	.305	.581
I am interested in purchasing products made with 3D printers tailored and customized according to my tastes and my needs	3.57	1.134	3.52	1.113	3.68	1.179	1.707	.192
I am interested in buying Italian products made with 3D printers that have quality of materials and design	3.45	1.083	3.39	1.053	3.61	1.144	**3.313**	.069
I am interested in purchasing products made with 3D printers that are modern and trendy	3.20	1.103	3.17	1.041	3.27	1.243	.694	.041

Table 3.9 shows the main types of products in which consumers are interested in: in the first place there are Accessories (3.82), followed by Furnitures, also intended as furnishing complements (3.79) and Toys (3.45). There is a lot of mistrust in the purchase of Food and Beverage (2.04), and Fashion (2.80) made with 3D printers, maybe also due to the fact that consumers do not know printers are able to realize such products.

Table 3.9. Type of 3D Products Consumer are Interested in (Five point Likert scale; α= 0.495)

	Mean	**SD**
Food and Beverage	2.04	1.145
Electronics	3.36	1.173
Furnitures	3.79	1.064
Fashion	2.80	1.258
Toys	3.45	1.262
Accessories	3.82	1.123

Subsequently a PCA has been done also on consumer perception and interest in 3D printing products (Table 3.10). The first component is called *Customized Products* (cumulative variance 35.6%) and it represents the part of the sample which believes that 3D printing permits the realization of customized, trendy and modern products, while the second component (35.0% of cumulative variance) is called *Quality and Sustainable Products* and it is made up of consumers who believe that 3D printers permit the realization of products with a minimum use of materials and these ones are of high quality and last long.

Table 3.10. PCA on Consumer Perception about 3D Printing

Pattern Matrix[a]

	Customized Products	*Quality and Sustainable Products*
3D printers allow the realization of products with a minimum use of resources and such as to be recycled	-	.785
3D printers allow the creation of products with high quality materials that last long	-	.874
3D printers allow the creation of customized products, completely customized to my tastes and my needs	.861	-
3D printers allow the creation of products with the features of Made in Italy (eg. the quality of materials and design)	-	-
3D printers allow the creation of modern, special and trendy products	.848	-
Cumulative Variance	*35.6*	*35.0*
KMO	0.763	

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.
a. Rotation converged in 3 iterations.

As for consumer interest in 3D printing two main components arose (Table 3.11): the first component in terms of importance (83.1%) is called *Sustainable Consumer* and it represents those consumer interested in buying products made with 3D printers in order to use the least amount of resources possible, and developing a product that can be recycled; this underlines the attention of the majority of the sample to the life cycle of the products and to their impact on the environment. The second component is made up of *Aesthetics and Quality Consumers* (69.5% of cumulative variance), that would approach to the purchase of products made using Additive Manufacturing in order to buy products of high design and quality.

Table 3.11. PCA on Consumer Interest in Buying 3D Products (KMO = 0.807)

Pattern Matrix[a]

	Aesthetics and Quality Features	*Sustainable Features*
I am interested in purchasing products made with 3D printers trying to use the least amount of resources and likely to be recycled	-	.980
I am interested in purchasing products made with 3D printers tailored and customized according to my tastes and my needs	-	-
I am interested in buying Italian products made with 3D printers that have quality of materials and design	.897	-
I am interested in purchasing products made with	.941	-

3D printers that are modern and trendy		
Cumulative Variance	*69.5*	*83.1*
KMO	0.807	

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.
a. Rotation converged in 5 iterations.

3.1.4.4 3D Prosumer or Consumer?

Finally it has been tried to figure out how much the Italian consumer is close to the prosumer described in literature (Prahalad and Ramaswamy, 2004; Tapscott and Williams, 2006). The 40.9% of respondents say they would be interested in buying a 3D printer, 26.2% are not interested in this manufacturing tool, while 32.9% of them haven't an opinion about it. When asking them, what kind of product they would like to create, it was found that about 3 out of 4 (72.8%) are willing to create different types of accessories, and more than one in two (61.1%) would like to create furnitures and furnishing complements with 3D printers (Table 3.12). Consumers seem not interested in creating their own Food and Beverage, in fact only 6.2% said they would use a 3D printer to realize this kind of products, first of all because maybe they are unaware of the existence of printers that produce these items and since they do not know their mechanism, they are hesitant in using them. In fact, in recent decades, it is developing a growing trend in the demand of healthy, nutritious, convenient and safe food, that has gradually improved among Young and Mature consumers (Jennifer, Gillian and Heather, 2003; Vermeir and Verbeke, 2006; Rezai *et al.*, 2012; Savelli et al., 2016).

Table 3.12. Products that Prosumers Want to Wealize with 3D Printing

	n	**%**
Food and Beverage	25	6.2
Electronics	134	33.4
Furniture	245	61.1
Fashion	105	26.2
Toys	114	28.4
Accessories	292	72.8

In addition to the desire to buy a 3D printer, consumer knowledge of digital fabrication laboratories has been investigated. Only an Italian consumer in 5 (20.7%) knows what a FabLab is, the 8.0% knows it only vaguely but the majority (71.3%) doesn't know what it is. As shown in Table 3.13, Internet is the most used channel of knowledge in fact 26.0% of respondents claimed to have heard about FabLabs through it, followed by the Work environment (18.1%), the word of Family and Friends (17.25) and Tv (12.6%). Among the respondents that claimed to know what a FabLab is, only 5% said they had realized something in it, including shop signs, custom shirts, home furnishings, school supplies, jewellery, home accessories, but also very challenging prototypes such as a 3D human model heart scale 1:1 modelled from Computed Tomography (CT) images. In any case the perception of what a FabLab is and the ability to exploit its full potential is not well understood by the sample, in fact, when it was asked them if they would like to realize an idea or a project asking to a Fablab, the sample was divided in a half: 50.4% say they are interested in creating something in it, while the remaining part declared not to be interested. Between those who would like to achieve their idea or their project within a FabLab, most of it is oriented to the creation of various objects for home or personal use, there are those who say they want to create innovative products ever sold on market, those that want to realize electronic items of advanced technology and others who even would like to create dental implants.

Table 3.13. FabLabs Means of Knowledge

	n	*%*
Magazines and newspapers	20	9.3
Tv	27	12.6
Radio	2	0.9
Internet	56	26.0
Conferences	15	7.0
Training courses (school/University)	19	8.8
Family/Friends	37	17.2
Work environment	39	18.1

The last part of the research investigates consumer perception of potential advantages and dangers of this manufacturing technique. As for dangers, a small part of the literature (Contos et al., 1995; Stephens et al., 2013; Azimi et al., 2016) is focusing on the possible consequences arising from the emission of Volatile Organic Compounds (VOCs) during the operation of a 3D printer. The results are still contrasting, showing that different types of materials such as plastics (ABS and PLA) have different types of VOCs emissions, although not indicative of a serious risk in this regard. However these emissions need to be controlled and further researches have to be carried out to assess their dangerousness. Analyzing consumer perception of this issue, the research reveals that the respondents consider really important the air quality of the environment in which they spend most of their time (4.66) but they don't believe that 3D printers can be a danger in terms of polluting the air of the environment in which it operates (2.83) (Table 3.14).

Moreover there is the perception among consumers that this Additive Manufacturing technique along with the other digital technologies can represent the breakthrough that will allow the advent of a new Industrial Revolution (3.72), even if Young consumer more than Mature ones believe that Italian companies are not taking full advantage of the opportunities offered by 3D printers and other digital technologies for the development of national economy and that something more could be done (3.57). Consumers are a bit less certain that 3D printers in the future will be daily used by each individual, as it is common now using 2D printers (3.49).

Table 3.14. Is 3D Printing the Beginning of a New Revolution? (Five point Likert scale; α = 0.456)

	Total Sample *n=1203*		***Young Consumers*** *(70,8%) n= 852*		***Mature Consumers*** *(29,2%) n=351*			
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*F Test*	*Sig.*
I think it is important the air quality of the environment where I spend most of my time	4.66	0.665	4.67	0.659	4.63	0.682	.308	.580
I believe that 3D printers can pollute the air of the environment in which it operates because of the melting of the materials it uses more strongly than the current production techniques	2.83	0.978	2.84	0.948	2.80	1.049	.147	.702
I believe that 3D printers and other digital technologies can represent the breakthrough that will allow the advent of a new Industrial Revolution	3.72	1.016	3.75	1.025	3.68	1.000	.416	.519
I believe that Italian companies are not taking full advantage of the opportunities offered by 3D printers and other digital technologies for the development of national economy	3.57	0.937	3.61	0.926	3.48	0.961	**1.436**	.231
I believe that 3D printers in the future will be daily used by each individual (as it is common now using 2D printers)	3.49	1.077	3.50	1.084	3.47	1.066	.041	.840

3.1.4.5 A market segmentation

Evidences from this study, as well as recent researches (Prahalad and Ramaswamy, 2004; Tapscott and Williams, 2006; Ritzer and Jurgenson, 2010), suggest that in the current environment, in which both consumption and production declined as a result of the global recession, the contemporary society is moving towards a “third wave” that would define the rise of a new figure called prosumer, a new consumer which actively participates in the implementation of products (Toffler, 1980; Ritzer and Jungerson, 2010). Thus, it could be very useful to develop a market segmentation to investigate the individuals’ consumer behaviour. To this end, a K-means clustering was performed, based on the results of the above PCA. The clustering procedure strongly suggested the presence of four clusters and profile was depicted by using a variety of demographic and behavioural characteristics of the respondents (Table 3.15). Only variables explaining relevant differences among clusters were considered to describe the characteristics of each cluster. The first cluster called *Passive Consumers*, is the smallest one with 15% of respondents in the total sample. It’s members are driven by no particular values in consumptions; they do not consider as relevant factors in product choice Traditions and Quality factors such as the presence of quality of materials, the feature of recyclability of products; they even don’t believe important the customization of products. In their life style they era not Bound to Traditions and they seem not to be Self Made consumers. They act as passive consumers, they are not active buyers but seem to be driven by inertia in their purchases: this type of consumer is not interested in buying 3D printed products, because they do not perceive any possible advantage from the purchase of such products. This cluster is characterized by high presence of female respondents, mainly of very young age, and mostly with the possession of a Bachelor, Master or Phd Degree.

The second cluster called *3D Prosumers* makes up 29.9% of the sample. Its members are among the closest to the definition of prosumer in literature, they are interested in Traditions and Quality features of products, but also in Innovations features and customization of products. The members of this cluster maintain their own traditions trying to be proactive member of the society. They are open to change and to the purchase of innovative products made with AM techniques so that they may be better in terms of quality, sustainability, design and especially they could meet their taste and needs. This cluster has an high presence of female Mature consumers, with Diploma, Bachelor or Master Degree. The third cluster, representing 30.2% of the sample, is called *Not Influenced Consumers* since it represents the segment of consumers that are not particularly attached to any of the factors resulting from the principal component analysis. The signs of the values in this cluster, even if they era not significant because less than 0.6, permit to state that this cluster is similar to *Passive Consumers* as for the non importance given to Quality of materials and sustainability in products choice, and also for consumer

Life Style, but they are similar to 3D Prosumers as for the need to customized products and for the propensity to buy 3D products. In this cluster there is a relevant percentage of male consumers and 86.8% have less than 44 years old. Finally the fourth cluster represents 24.9% of the total sample and is called *Unfashionable Consumers*, since they do not care to Brands and Corporate Image, but they care about price and sustainability of products. They seem to have a proactive Life style as *3D Prosumers* but they are not interested in buying 3D products, with quality of materials and that are modern and trendy. Regarding the socio-demographic characteristics of this cluster, there is a relevant percentage of male consumers, they are mostly young and almost no one has a very low level of education. Therefore cluster analysis results are used to detect the presence of four clusters of consumers, very heterogeneous between them, representing Italian consumers of the post crisis period.

Table 3.15. Cluster Analysis on 3D Consumers/Prosumers

	Cluster 1: Passive Consumers ***n= 180 (15.0%)***	***Cluster 2: 3D Prosumers*** ***n= 360 (29.9%)***	***Cluster 3: Not Influenced Consumers*** ***n=363 (30.2%)***	***Cluster 4: Unfashionable Consumers*** ***n=300 (24.9%)***
Factors of Importance in Product Choice				
Design (peculiarity, beauty and modernity of the product)	-0.245	0.401	0.030	-0.371
Quality of Materials	**-0.682**	**0.600**	-0.057	-0.242
Sustainability (least possible waste of resources and possibility to recycle)	**-0.829**	**0.755**	-0.355	0.021
Made In Italy	-0.374	**0.663**	-0.225	-0.300
Price	-0.215	0.141	-0.109	0.092
Customization	**-0.695**	**0.675**	0.085	-0.495
Technology Innovation	-0.486	**0.632**	0.162	**-0.663**
Brand	0.124	0.246	0.269	**-0.695**
Corporate Image	-0.195	0.504	0.012	-0.503
Consumer Life Style				
I'm interested to learn new skills, in order to do more alone and rely less on others	-1.147	0.345	0.068	0.192
I'm willing to repair items (shoes, bags, home appliances...) in order not to have to replace them	**-0.975**	0.307	-0.242	0.508
I try to transform the difficulties in new opportunities for work and social life (Indestructible spirit)	**-0.848**	**0.638**	-0.423	0.255
I maintain my faith and my traditions and actively try to improve my community and myself (Retooling).	**-0.691**	**0.664**	-0.381	0.079
I'm adopting an approach to life simpler and parsimonious (Liquid life)	-0.397	0.559	-0.519	0.195

I believe that the crisis push people to work together to solve problems and create new opportunities (Cooperative consumerism)	-0.417	0.577	-0.442	0.092
I think that the old status symbols have no value, but character, authenticity, and creativity become the new life paths (From materialism to the material).	-0.296	0.485	-0.385	0.062
Consumer interest in buying 3D products				
I am interested in purchasing products made with 3D printers trying to use the least amount of resources and likely to be recycled	**-1.024**	**0.621**	0.099	-0.249
I am interested in purchasing products made with 3D printers tailored and customized according to my tastes and my needs	**-1.119**	**0.623**	0.366	-0.519
I am interested in buying Italian products made with 3D printers that have quality of materials and design	**-0.788**	**0.643**	0.275	**-0.631**
I am interested in purchasing products made with 3D printers that are modern and trendy	**-0.652**	**0.610**	0.289	**-0.691**
***Gender* (%)**				
Male	38.3	36.7	42.1	41.0
Female	61.7	63.3	57.9	59.0
***Age* (%)**				
18-24	43.3	31.7	39.7	46.0
25-34	30.0	27.5	34.7	33.0
35-44	10.0	16.7	12.4	13.0
45-54	11.7	11.7	9.1	7.0
55 and more	5.0	12.5	4.1	1.0
Graduation				
Primary School Diploma	1.7	0.8	0.0	0.0
Middle School Diploma	5.0	5.0	5.8	2.0
Diploma	40.0	47.5	47.1	50.0
Bachelor Degree	16.7	20.0	28.1	29.0
Master Degree	26.7	20.0	14.0	12.0
Ph.D.	10.0	6.7	5.0	7.0

3.1.5 Conclusions

This research investigates how much Italian consumers are near to the definition of the prosumer described in literature in this new era of digital craft customization, trying to understand their knowledge and willingness to use Additive Manufacturing and 3D printing technologies.

From the analysis of the factors of importance in the purchasing decision for a product, the research shows that the most important aspect is quality, followed by price. This means that although quality is the most important element of choice, consumers cannot fail to give importance to the price, for this, products are attractive if they have a good value for money. In any case Mature consumers are able to spend more for the guarantee of a product better suited to their needs. Furthermore always Mature consumers seem to be more close to the kind of post-crisis consumer described by Gerzema and D'Antonio (2010), while Young consumers seem to be less tied to tradition and it seems that the crisis has not affected their purchasing behaviour. From PCA it can be seen that in Italy there are two main categories of consumers: those who pay attention to typical Italian products that bear the quality mark of the Made in Italy, and that are made with the attention and the typical Italian care, and those consumers seeking beauty and technology in products. Furthermore the majority of the sample appears to have a Self Made Life Style; they are willing to learn new skills to be independent and create for themselves what they need. For this reason, through the use of AM techniques, innovation is starting to be democratized (Von Ippel, 2005), in facts users of products and services, both firms and individual consumers, are increasingly able to innovate for themselves, and as shown in the research they have also the willingness to create and innovate. User-centered innovation processes offer great advantages over the manufacturer-centric innovation development systems that have been the mainstay of commerce for hundreds of years. Users that innovate can develop exactly what they want, rather than relying on manufacturers to act as their (often very imperfect) agents. Moreover, individual users do not have to develop everything they need on their own: they can benefit from innovations developed and freely shared by others. Consumers have the will and the digital technologies necessary to become real Prosumers.

These consumers have the awareness that 3D printers allow the realization of design customized products, and are willing to purchase 3D products that promise sustainable features intended as saving of resources and recyclability. The research shows that the tendency of Do it Yourself is developing also in Italy, in fact, 40.9% of the sample is interested in buying a 3D printer for the personal creation of objects. Moreover the *3D Prosumers* cluster, which represents a third of the sample in the research, is assumed growing, since *Not Influenced Consumers* have very similar behavioral aspects to the latter and could become the next Prosumers. For this, one can conclude that looking at 3D printing this way, its future is more than just technology for a market of one producing one-of-a-kind products; it is more than *"personal expression in technology"* (Gershfeld 2006). It is not only consuming personal fabrication as a commodity provided by a new branch of the entertainment industry in the form of e.g. Maker Faires. The impact is broader than that: the main impact of making will be a social one. Consumer 3D printing would develop into social fabrication. The constituents of social fabrication here are participation, collaboration and sharing, made possible by the networked society. Its goals are: self-realisation in a “cosy” social context that is built on interdependence, preserving one’s cultural identity in a multicultural world. Social fabrication is cosmopolitan. This is why 3D printing as a social phenomenon is a truly international development, connecting communities and transgressing borders (Troxler and van Woensel. 2015).

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3.2. Additive Manufacturing in the Wood-Furniture Sector

Abstract

In the world economy there is the emergence of advanced manufacturing technologies that are enabling more cost and resource-efficient small-scale production. In combination with other prominent trends such as servitisation, personalisation and prosumption, the emergence of Additive Manufacturing, commonly known as 3D printing, as a direct manufacturing process, is leading companies to rethink where and how they conduct their manufacturing activities. The aim of the research is to focus in detail in the Italian wood-furniture industry to understand if the companies in this sector are investing in digital technologies and in particular in AM techniques, to remain competitive in their reference markets. The research also attempts to investigate the potential sustainable benefits and barriers to the implementation of AM in this specific sector, trying to identify the gaps in perception of these aspects between "traditional companies" and those "innovative", which have implemented these technologies yet. Data were collected using a structured questionnaire survey performed on a sample of 234 Italian companies in this sector. The research has highlighted how Italian 3D companies have a specific profile; they are companies aimed at innovating through the search for new products and product features, putting design and Made in Italy in the first place. They pay high attention to the image they communicate to the market and are highly oriented to the final customer, and to the satisfaction of its needs. On the contrary the major reason of traditional companies for non implementing 3D printing is the belief that this technology is not suited for this sector. In conclusion the results of the research seem to confirm that 3D printing is a strong growing phenomenon, already quite widespread in Italy, and with further potential of development.

Keywords: Additive Manufacturing; Wood-Furniture Sector; Drivers; Industry 4.0; Innovation

3.2.1 Introduction

Currently the world economy is going through a period of transition and change in the manufacturing landscape. Jeremy Rifkin believes that the phase of digitization, the third, has just begun and has yet to fully show all its implications and its potential (Rifkin, 2011).

On the contrary Klaus Schwab, a German engineer and economist, best known as the founder and executive chairman of the World Economic Forum, in his book "The Fourth Industrial Revolution", argues that the first three revolutions are the transport and mechanical production revolution of the late 18th century; the mass production revolution of the late 19th century, and the computer revolution of the 1960s. He accepts that some people might consider the fourth revolution just an extension of the third but argues that the scale, speed and impact of the latest technologies deserve a revolution of their own (Schwab, 2016).

Whether the revolution in act today is the Third or the Fourth, one of the most significant drivers of this change is the emergence of advanced manufacturing technologies that are enabling more cost- and resource-efficient small-scale production. In combination with other prominent trends such as servitisation (Neely, 2008), personalisation (Zhou et al., 2013) and prosumption (Fox and Li, 2012), the emergence of Additive Manufacturing (AM), commonly known as 3D printing, as a direct manufacturing process, is leading companies to rethink where and how they conduct their manufacturing activities (Ford and Despeisse, 2016).

AM is defined as "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" (ASTM, 2010). The 3D printing process works as follows. Once the user has selected an electronic design blueprint and loaded up the raw materials into the 3D printer, the machine begins its work. In a process that can take several hours to days, the 3D print head deposits layer upon layer of tiny droplets of raw material to form the object. Depending on the complexity of the design, the machine is able to switch between different print heads to work with multiple materials and form shapes with a number of colours and diverse textures. Eventually, after countless back-and-forth sweeps, a three-dimensional object forms out of raw material (Lipson and Kurman, 2010).

This technology evolved during the mid-1980s when computing and control systems progressed (Hopkinson et al., 2006); in its early years AM was mostly applied for the fabrication of conceptual and functional prototypes, also known as Rapid Prototyping (RP) (Mellor et al., 2014). These prototypes were most commonly used as communication and inspection tools, producing several physical models in short time directly from computer solid models helped to shorten the production development steps (Santos et al., 2006).

Only recently 3D Printing has gained much attention, as the process has proven to be compatible with industrial manufacturing beyond prototyping (Berman, 2012; Gershenfeld, 2012; Reeves, 2008). Therefore the concept of Rapid Manufacturing (RM), the production of end-use parts from Additive Manufacturing systems (Hague et al., 2004), emerged in the last decade; though its economic impact has remained modest (Levy et al., 2003).

The most commonly applied processes are Stereolithography (SLA), Selective Laser Sintering (SLS), Digital Light Processing (DLP), Fused Deposition Modelling (FDM), Selective Laser Melting (SLM) and Electron Beam Melting (EBM) (Petrovic et al., 2011). Since the development of many of these technologies has occurred simultaneously, there are various similarities as well as distinct differences between each one (Kulkarni et al., 2006). Reviews of the numerous AM technologies have been performed in previous works (Gibson, 2010; Hopkinson et al., 2006; Groover, 2007). Polymers, alloys of aluminium, steel and titanium, as well as ceramic composites are printable at a minimum layer thicknesses of 20–100 μm, depending on the process and the physical state of the material (Hopkinson etal.,2006). Therefore, 3D Printing can be applied to various manufacturing markets. The decision to invest in Additive Manufacturing technologies must be linked to the market and product characteristics. High utilization underpins any technology investment (Hill, 2000), if the process will not be highly utilized on one product it must meet the manufacturing and business needs of other products. Generally, the product characteristics are: products with a degree of customisation; products with increased functionality through design optimisation and those of low volume (Mellor et al., 2014).

Considering that the aim of the research is to focus in detail in the Italian wood-furniture industry to understand if the companies in this sector are investing in digital technologies and in particular in AM techniques, to remain competitive in their reference markets. The research also attempts to investigate the potential sustainable benefits and barriers to the implementation of AM in this specific sector, trying to identify the gaps in perception of these aspects between "traditional companies" and those "innovative", which have implemented these technologies yet. Therefore the research questions, which the paper investigates are the following:

RQ1: what is the extent to which Additive Manufacturing is adopted in the Italian wood-furniture industry and how much these companies are investing in it to remain competitive in their reference market?

RQ2: which are the sustainability benefits perceived by those companies that adopt AM technologies?

RQ3: which are the main limitations perceived by those companies that adopt AM technologies?

RQ4: which are the differences in AM perception among "innovative" companies which have already implemented those technologies and the "traditional" ones?

RQ5: which are the main factors that lead companies to the adoption of AM technologies?

Since there are no previous studies that consider the development of AM technologies in the wood-furniture industry, the paper aims to cover this gap. The main contribution to the field is given by the attempt to understand which are the main applications of Additive Manufacturing technologies in the wood-furniture industry, which are the advantages of using an additive production instead of subtractive techniques and which are the main barriers to the implementation of it. The analysis of the Italian context, could be taken as a reference for those companies which operate in the same industry in other developed countries.

The novelty resides in the experimental techniques used, that is a quantitative analysis. Many qualitative case studies have been developed analyzing AM, but no previous quantitative analysis have been developed on a large sample of companies and, no previous studies focused on the furniture industry to understand the diffusion and use of such technologies in this sector.

The paper is divided as follows: section two investigates the literature panorama on Additive Manufacturing, section three defines the methodology developed for both empirical researches, that is the first on the "Sustainability of the Technology, Diffusion and Drivers of Adoption" and the second on "Differences of Perception among Innovative and Traditional Companies". Section four presents the results of the researches and then a final conclusion section is defined.

3.2.2 Literature panorama on Additive Manufacturing

3.2.2.1 AM production techniques and their classification

The need for reduced development time together with the growing demand for more customer-oriented product variants have led to the next generation of Information Technology (IT) systems in manufacturing (Chryssolouris et al., 2009). The possibility of controlling through a computer the equipment for the Manufacturing production was a reality as early as the 80s, when the first numerical control equipment for milling, turning, drilling, etc. were introduced, according to the logic of "subtraction from full ", typical of traditional manufacturing (Beltrametti and Gasparre, 2015). Another example of the introduction of IT, in the manufacturing world, is the concept of Computer Integrated Manufacturing (CIM). This concept was introduced in the late 1980s, favouring the enhancement of performance, efficiency, operational flexibility, product quality, responsive behaviour to market differentiations, and time to market (Cagliano and Spina, 2003). Almost simultaneously the first 3D printer, which were used to realize plastic prototypes, developed. Unlike numerical control machines, for a few decades this technology had important applications in the process of development of new products but its diffusion was relatively limited and it started to be used into the final production only about ten years later. As in the case of numeric control machines and robot, 3D printers manufacturing can be called "digital" since the designer must be able to use a software - the CAD- which gives a virtual representation of the object that has to be produced starting from its geometric parameters that are transmitted from a computer to a machine that realizes it (Beltrametti and Gasparre, 2015). The CAD systems have become indispensable to today's manufacturing firms, because of their strong integration with advanced manufacturing techniques such as 3D printing. CAD models are often considered sufficient for the production of the parts, since they can be used for generating the code required to drive the machines for the production of the part (Chryssolouris et al., 2009). CAD technologies are available for assisting in the design of large buildings and of nano-scale microprocessors. CAD technology holds within it the knowledge associated with a particular type of product, including geometric, electrical, thermal, dynamic, and static behavior. AM technology primarily makes use of the output from mechanical engineering, 3D Solid Modeling CAD software. It is important to understand that this is only a branch of a much larger set of CAD systems and, therefore, not all CAD systems will produce output suitable for layer-based AM. AM technology focuses on reproducing geometric forms; and so the better CAD systems to use are those that produce such forms in the most precise and effective way (Gibson et al., 2010).

As for the classification of AM technologies, there are numerous ways to classify these technologies. A popular approach is to classify according to baseline technology, like whether the process uses lasers, printer technology, extrusion technology, etc. (Kruth et l., 1998; Burns, 1993). Another approach is to collect processes together according to the type of raw material input (Chua and Leong, 1998). The problem with these classification methods is that some processes get lumped together in what seems to be odd combinations (like Selective Laser Sintering being grouped together with 3D Printing) or that some processes that may appear to produce similar results end up being separated. It is probably inappropriate, therefore, to use a single classification approach (Gibson et al., 2010).

The use of a technology rather than another is a choice to be made according to a number of very varied parameters: speed of production and the final cost of the piece, investment required for the printer (in case it is decided to buy it), mechanical resistance and finish surface desired.

Classifing these technologies for 3D printing based on the materials used in the process and the way they are treated, in general they can be divided into three categories, based on the characteristics of consistency of the raw material: powder, liquid or solid (Advanced Manufacturing Office, 2012):

- the category of *powder* printers belong to those based on sintering or melting of powders (Selective Laser Sintering - SLS, Selective Laser Melting - SLM, Direct Metal Laser Sintering - DMLS, Electron Beam Melting - EBM) or deposition of chemically bonded on a homogeneous powder bed (3D Printing or binder jetting - 3DP);
- on the front of the *liquid* material technologies there are those which are based on curing by UV lamps (Stereolithography - SLA, Digital Light Processing - DLP) and secondly those who print with a jet (Ink Jet Modeling - IJM, Multi Jet Modeling - MJM);
- finally, the machines for 3D printing employing starting materials in the *solid* state (considering also filament and paste) are divided in models employing a stratified based on sizing technique of sheets (Laminated Object Manufacturing - LOM), or extrusion of a solid material or semi solid (Fused Deposition Modeling - FDM).

Another classification is given by the American Society for Testing Materials (ASTM), in particular the International Committee F42 on AM Technologies, which divides the AM technologies in seven families of processes (www.astm.org; Wong and Hernandez 2012; Munoz et al. 2013):

- *Vat Photopolymerization*, an AM process in which a photopolymer sensitive to UV light, localized inside a tub, is solidified by a ultraviolet light source, layer by layer;
- *Material Jetting*, the principle of operation takes advantage of a print head similar to those of the two-dimensional Inkjet printers. The only substantial difference lies in the material with which the head is fed: instead of ink, wax acrylic resins or photopolymers are released;
- *Binder Jetting*, even in this case it is provided the use of a print head, with a difference, that is to say it is not released material of construction but a chemical

binder capable of combining in a progressive manner the individual grains of a homogeneous bed of powder;

- *Powder Bed Fusion,* it is an AM process which uses thermal energy to melt and solidify a region of a powder bed, layer by layer;
- *Material Extrusion,* the operating principle exploited by this technology is the extrusion. A malleable material in a semi-solid state is deposited, through the nozzle of an extruder, on a layer of underlying material deposited previously and already solidified;
- *Sheet Lamination,* it is a process by which the material sheets are properly cut, stacked and united. It is a technique among the least popular. The sheets of material can be of various types: paper, plastic, cellulose, metals and reinforced composite materials.
- *Direct Energy Deposition,* a typical Direct Energy Deposition (DED) machine consists of a nozzle mounted on a multi axis arm, which deposits melted material onto the specified surface, where it solidifies.

3.2.2.2 Economic environmental and organizational implications

The adoption of AM and other advanced manufacturing technologies appears to herald a future in which value chains are shorter, smaller, more localised, more collaborative, and offer significant sustainability benefits (Gebler et al., 2014).

As stated by Ford and Despeisse (2016), among the many potential sustainability benefits of this technology, three stand out: improved resource efficiency, extended product life and reconfigured value chain.

As for the economic and environmental implications this technology may significantly reduce the need for large inventory, which is a significant cost in manufacturing. In 2011, there was an average of $208 billion or the equivalent of 14% of annual revenue held in inventory for medium- and high-tech manufacturing with an estimated cost of $52 billion or 3% of revenue. Reducing inventory frees up capital and reduces expenses (Douglas and Stanley, 2014).

Life cycle analyses have shown that the adoption of AM could have significant savings in the production of goods. Savings are estimated at $113-370 billion by 2025, with these arising from reductions in material inputs and handling (Gebler et al., 2014). 3D printing lowers manufacturing-related resource inputs as it solely requires the amount of material which ends up in the printed good without too many losses. Support materials can usually be reused (Reeves, 2008; Huang et al., 2013). Also energy consumptions is an important factor of sustainability in considering AM compared to other methods of manufacturing, especially in terms of examining the costs from cradle to grave. Energy studies on AM, however, tend to focus only on the energy used in material refining and by the AM system itself (Hopkinson and Dickens, 2003; Baumers et al., 2011; Morrow et al., 2007; Telenko and Seepersad, 2012)

Moreover 3D printing generates shifts in labour patterns, as the process is highly automated and only requires human workforce in pre- and post- processing (Lindemann et al., 2012; Petrovic et al., 2011). Labour related implications show different patterns in developed and developing countries. The high degree of automation could be economically beneficial for developed countries with ageing societies, but destabilize developing countries if the production and thereby the production volumes re-shift to consumer countries (Campbell et al., 2011). Open source-based applications of 3D printing could contribute to a sustainable development in rural areas with low economic profiles, as 3D printing bridges the spatial gap to the next market of spare parts, consumer products or tools (Pearce et al.,2010).

Hopkinson et al. (2006) suggest that an important impact could be on company culture and how it has to change to accommodate. Using AM processes as a manufacturing technology requires designers and engineers to re-think design for manufacturing (DFM). DFM is any aspect of the design process in which the issues involved in manufacturing the designed objects are considered explicitly with a view to influencing the design. AM requires users to match product with process and to understand new technology process capabilities. Therefore the workforce experience and skill is also proposed to be a key factor in AM implementation.

Moreover the design freedoms offered by AM allow product and component redesign. Using additive techniques, several parts made of various materials can be replaced by one integrated assembly, which will reduce or eliminate cost, time and quality problems resulting from assembling operations (Ford and Despeisse, 2016).

Furthermore with geometric freedom, AM allows products to be produced using less material while maintaining the necessary performance. Products can be produced at the level of performance needed rather than significantly exceeding the necessary performance level because of limitations in traditional manufacturing. Materials used for AM are not necessarily greener than materials used in traditional manufacturing. The one exception may be the bio-polymer polylactic acid (PLA) (Faludi et al., 2015). As for materials, metal and plastic are the primary used for this technology. The cost of material for AM can be quite high when compared to traditional manufacturing. Atzeni and Salmi (2011) showed that the material costs for a selected metal part made from aluminium alloys was €2.59 per part for traditional manufacturing and €25.81 per part for AM using selective laser sintering; thus, the AM material was nearly ten times more expensive. The material costs of AM are significant; however, technologies can often be complementary, where two technologies are adopted alongside each other and the benefits are greater than if they were adopted individually. One example is computer aided design and computer aided manufacturing, as both are needed to be utilized for the other to be valuable (Reevese, 2008, Douglas and Stanley, 2014). Therefore machines and materials for AM are still expensive but the cost of these will decrease as AM becomes a more commonly used production technique. Furthermore, AM is expected to become more cost effective as larger production volumes become more economically feasible than at present (Ford and Despeisse, 2016).

AM can also bring some changes in the supply chain of a company: the supply chain includes purchasing, operations, distribution, and integration. Purchasing involves sourcing product suppliers. Reducing the need for these activities can result in a reduction in costs (Reeves, 2008).

Furthermore, supply chains shift from physical goods to digital ideas/designs (Campbell et al., 2011). This shift increases supply chain dynamics by reducing the “time-to-market” (Petrovicet al., 2011) and by inducing furthermore a relative decline in imports/exports (Campbell etal., 2011). Exports are projected to shift back to consumer countries as 3D Printing reduces the labour cost-related comparative advantage of countries such as China and the technological advantage of countries like Germany or Japan (Campbell et al., 2011). Global supply chains are furthermore expected to relatively shift from final products to raw materials as goods manufacturing becomes more localized while material raw production is spatially bound to its reserves (Campbell et al., 2011). Lastly, supply chains are expected to become less transport intensive (Birtchnell et al., 2013). In fact AM allows for the production of multiple parts simultaneously in the same build, making it possible to produce an entire product. Traditional manufacturing often includes production of parts at multiple locations, where an inventory of each part might be stored. Douglas and Stanley (2014) summarize three different alternatives for AM, defining a fourth one. The first is where a significant proportion of consumers purchase AM systems or 3D printers and produce products themselves (Reeves, 2008). The second is a copy shop scenario, where individuals submit their designs to a service provider that produces goods (Neef et al., 2005). The third scenario involves AM being adopted by the commercial manufacturing industry, changing the technology of design and production. They consider a fourth scenario: since AM can produce a final product in one build, there is limited exposure to hazardous conditions, and there is little hazardous waste (Huang et al., 2013). For this reason there is the potential to bring production closer to the consumer for some products (Holstrom et al., 2013).

However, analyzing organizational implications of this new manufacturing technology, for the adopting organisation to gain competitive advantage from the implementation of AM its ability to link the technology benefits to the business strategy has to be emphasised (Mellor et al., 2014). The size of an organization has been identified to be critical to the understanding of the process of implementation of new manufacturing technologies. A number of scholars have suggested small business cannot be considered scaled-down larger ones, and the theories proved in large enterprises might not be suitable for small business (Federici, 2009; Schubert et al., 2007). Therefore, the approach to implementation for a SME is likely to be different to that in a large multinational company. Linked to size, previous study into new manufacturing technology implementation suggests that the structure of an organization is the key factor to successfully implement manufacturing technology (Abdul et al., 2002; Saberi et al., 2010), and that companies that adopt without first re-designing organizational structures and processes encounter high difficulties (Saberi et al, 2010). Therefore, it is proposed for successful implementation of AM technologies that the decision to adopt is accompanied by a change in jobs and tasks, and thus a change in work practices and structure.

3.2.3 Methodology

3.2.3.1. Sampling and data collection

Data were collected using a questionnaire survey performed on a sample of n= 2035 Italian companies which operate in the wood-furniture industry, using simple random sampling. The survey began January 26th, 2017 and answers were accepted until February 28th, 2017. The administration of the survey took place by e-mail, following a two-step administration. In fact, two weeks after the first submission of the questionnaire, the same was sent again, asking those who did not have time to fill it out, the possibility to do this. This double administration allowed to obtain 234 companies who participated to the survey, in detail 113 answered during the first submission of the survey and 121 after the second.

The questionnaire was divided in four sections. The first section investigates the sample profile of the respondent companies, the factors in which they pay attention to the development of their products, whether or not they produce prototypes in their company and their knowledge and use of 3D printers. Section 2 was reserved to those companies that know and use 3D printings in their production process, and it was asked them to give an assessment to the perceived benefits of this technology, and evaluating the possible barriers to the implementation of it. Section 3 was reserved to those companies which know 3D printing but have never used this technology (neither internally nor externally), and the reasons why they have never approached o this technology were evaluated. Finally section 4, is a conclusive section that evaluate the level of adoption of this technology in the company supply chain, if companies perceive some dangerous related to this additive technology such as emissions in the air and the importance that they give in investing in digital technologies.

3.2.3.2. Process analysis

Descriptive analysis was performed to describe the sample profile of respondent companies. A five-point Likert scale was used to evaluate companies' attitudes and behaviours and perceived benefits and barriers of the implementation of AM technologies. To verify the reliability of the Likert analysis, Cronbach's alpha values were computed, taking into account only alpha values greater than 0.60 as suggested by Nunnally and Bernstein (1994).

Subsequently, in paper 1 a Principal Component Analysis (PCA) followed by oblimin rotation (Jennrich and Sampson, 1966) was applied to the items related to benefits and limitations of adopting AM technologies and to factors related to what kind of products companies are willing to realize with AM. The PCA, an optimal dimensionality reduction technique in terms of capturing the variance of the data (Russel et al., 2000), facilitated the summarization of group companies' main perceived benefits and limitations to the implementation of AM in this sector and also understanding their orientation in productive terms through the use of AM technologies.

In paper 2, the Analysis of Variance (ANOVA) was performed using F-tests to statistically test the equality of means (Markowski, 1990) and analyze the different perception of benefits and barriers of Additive Manufacturing between those companies that use it and those that do not use it. To test the reliability of the results Cronbach’s alpha values were computed, taking into account only values greater than 0.60 as suggested by Nunnally and Bernstein (1994).

Finally, a binary regression model (Bowen and Wiersema, 2004; Hoetker, 2007) was used to assess whether companies attitudes and behaviours and the perceived benefits contribute to determine the investment on AM technologies by firms. The binary regression model equation is estimated as follows.

$$Pr\,(AM=yes) = logit\,(\beta_0 + \beta_1\, PRICERANGE + \beta_2\, AT\_CUSTOMIZ + \beta_3\, AT\_DESIGN + \beta_4\, AT\_QUAL\_MADEIN + \beta_5\, AT\_ECOSUST + \beta_6\, AT\_QUALMATERIALS + \beta_7\, AT\_BRAND + \beta_8\, AT\_IMAGINE + \beta_9\, BTIMESPEC + \beta_{10}\, BTIMEPROTOT + \beta_{11}\, BTIMEPROD + \beta_{12}\, BTIMETOMARKET + \beta_{13}\, BCOSTMATERIAL + \beta_{14}\, BCOSTMAGAZ + \beta_{15}\, BCOSTTRANS + \beta_{16}\, BCOSTMANODOPERA + \beta_{17}\, BRISPENERG + \beta_{18}\, BGEOMEQUAL + \beta_{19}\, BMODBUSINESS + \beta_{20}\, BINTERNAZIONALIZZ + \beta_{21}\, BPUNTIVENDITA + \beta_{22}\, BPERSONALIZZ + \beta_{23}\, BECODESIGN + \beta_{24}\, BIMPAMBIENTALE + \beta_{25}\, BNICCHIE + \mathcal{E}) \qquad (1)$$

Where:

- AM (Additive Manufacturing) is 1 if the company has used both internally or externally AM techniques.
- PRICERANGE is the range of products realized by the company assessed by a the scale “low”, “medium-low”, “medium”, “medium-high”, “high”.
- AT_CUSTOMIZ is the attention paid to the creation of customized products assessed by a Likert scale from 1 to 5.
- AT_DESIGN is the attention paid to the creation of modern and innovative products with high design assessed by a Likert scale from 1 to 5.
- AT_QUAL_MADEIN is the attention paid to the creation of quality products that meet the standards of the "Made in Italy" assessed by a Likert scale from 1 to 5.
- AT_ECOSUST is the attention paid to the creation of sustainable products assessed by a Likert scale from 1 to 5.
- AT_QUALMATERIALS is the attention paid to the quality of the materials used for the creation of products assessed by a Likert scale from 1 to 5.
- AT_BRAND is the attention paid to the enhancement of the brand to be competitive on the market assessed by a Likert scale from 1 to 5.
- AT_IMAGINE is the attention paid to the image of the company communicated to customers assessed by a Likert scale from 1 to 5.
- BTIMESPEC is the perceived benefit of reduction in time to define technical specifications of products assessed by a Likert scale from 1 to 5.
- BTIMEPROTOT is the perceived benefit of reduction in prototyping time assessed by a Likert scale from 1 to 5.
- BTIMEPROD is the perceived benefit of reduction in production time assessed by a Likert scale from 1 to 5.
- BTIMETOMARKET is the perceived benefit of reduction in time to market assessed by a Likert scale from 1 to 5.
- BCOSTMATERIAL is the perceived benefit of reduction in costs of materials assessed by a Likert scale from 1 to 5.
- BCOSTMAGAZ is the perceived benefit of reduction of inventory and unsold costs assessed by a Likert scale from 1 to 5.
- BCOSTTRANS is the perceived benefit of reduction in transport costs assessed by a Likert scale from 1 to 5.
- BCOSTMANODOPERA is the perceived benefit of reduction of labor costs assessed by a Likert scale from 1 to 5.

- BRISPENERG is the perceived benefit of energy saving assessed by a Likert scale from 1 to 5.
- BGEOMEQUAL is the perceived benefit of the creation of new products with complex geometries, increased performance and quality assessed by a Likert scale from 1 to 5.
- BMODBUSINESS is the perceived benefit of the creation of a new business model assessed by a Likert scale from 1 to 5.
- BINTERNAZIONALIZZ is the perceived benefit of a greater chance of internationalization assessed by a Likert scale from 1 to 5.
- BPUNTIVENDITA is the perceived benefit of the shift of production to retail outlets assessed by a Likert scale from 1 to 5.
- BPERSONALIZZ is the perceived benefit of product customization assessed by a Likert scale from 1 to 5.
- BECODESIGN is the perceived benefit of co-design with the customer assessed by a Likert scale from 1 to 5.
- BIMPAMBIENTALE is the perceived benefit of reduction in environmental impact assessed by a Likert scale from 1 to 5.
- BNICCHIE is the perceived benefit of having the ability to serve niche markets assessed by a Likert scale from 1 to 5.

3.2.3.2 Non-Response Bias

Non-response bias was assessed by verifying that early and late respondents were not significantly different (Armstrong and Overton, 1977). A set of tests compared respondents who answered to the questionnaire during the first administration and those who answered when the survey was submitted for the second time. All possible t-test comparisons between the means of the two groups showed insignificant differences ($p<0.1$ level). What is more, in order to have the right figure to answer the questionnaire in the company, the individuals that received the e-mail were requested to pass on the questionnaire to their colleague in the technical / production department, or to the figure who is more knowledgeable with respect to Additive Manufacturing, prototyping and internal production techniques.

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3.2.4. Results and discussion

3.2.4.1 Sample profile

Among the whole sample of respondent companies (n=234), the paper will focus on analyzing the behaviour of those which are using internally or externally 3D printing technologies, called "3D companies". In detail 19.2% of respondents declared to use internally these technologies and 13.2% to use them externally, in total 76 companies were taken as reference sample.

Defining the profile of 3D companies (Table 3.16), the majority of companies are of small (30.3%) and medium (43.4%) size, with a turnover between 2 and 50 million of Euro. They are mainly located in the northern and central regions of Italy, that are the most economically developed and 89.5% of them have as reference markets the international ones. As for the type of products they sell, the respondent companies declared to realize products in the upper-middle (65.8%) or even high (21.1%) range.

Table 3.16. Sample Profile of the Respondent Companies

		All sample		***3D companies***	
		n=234		***n=76 (32.5%)***	
		n	***%***	***n***	***%***
Dimension	Micro	25	10.7	4	5.3
	Small	101	43.2	23	30.3
	Medium	79	33.8	33	43.4
	Large	29	12.4	16	21.1
Turnover (€)	Less than 2 Mln	41	17.5	4	5.3
	2-10 Mln	84	35.9	21	27.6
	11-50 Mln	77	32.9	34	44.7
	More than 50 Mln	32	13.7	17	22.4
Regions	North	124	53.0	43	56.6
	Center	106	45.3	31	40.8
	South and Islands	4	1.7	2	2.6
Reference markets	Italy	14	6.0	3	3.9
	Italy and Europe	30	12.8	5	6.6
	International markets	190	81.2	68	89.5
Price range	Low	0	0.0	0	0.0
	Lower-middle	10	4.3	1	1.3
	Medium	48	20.5	9	11.8
	Upper-middle	141	60.3	50	65.8
	High	35	15.0	16	21.1

Table 3.17 shows the areas of specialization of companies that participated in the survey within the wood-furniture industry. In the whole sample the majority of respondents work in the accessorize sector (13.7%), followed by those producing office furnishing (12.0%), kitchen furnishing (11.1%) and bathroom ones (9.4%). 3D printing technologies are used mainly by those realizing accessorizes (18.4%) and those producing bathroom (13.2%) and office (13.2%) furnishing. On the contrary among the sector in which AM techniques are not considered at all there are outdoor furnishing, mattresses, school furnishing and semi finished products. Therefore there seems to be a high degree of heterogeneity in the use of these technologies within the same reference industry, depending on the great heterogeneity of manufactured products.

Table 3.17. Wood-furniture Sectors of Respondent Companies

	All sample n=234		*3D companies n=76 (32.5%)*	
	n	***%***	***n***	***%***
Accessories	32	13.7	14	18.4
Furnishing for bars and shops	15	6.4	6	7.9
Classic furnishing	13	5.6	3	3.9
Outdoor furnishing	4	1.7	0	0.0
Bathroom furnishing	22	9.4	10	13.2
Bedroom furnishing	11	4.7	6	7.9
Collectivity	15	6.4	5	6.6
Kitchen furnishing	26	11.1	6	7.9
Domestic multiproducts	16	6.8	6	7.9
Upholstered furnishing	14	6.0	5	6.6
Mattresses	1	0.4	0	0.0
Panels	5	2.1	1	1.3
School furnishing	3	1.3	0	0.0
Semi finished products	18	7.7	0	0.0
Living room furnishing	7	3.0	2	2.6
Office furnishing	28	12.0	10	13.2
Other	4	1.7	2	2.6

3.2.4.2 Wood-furniture Companies' attitudes and behaviours

Firstly is has been asked to 3D companies, what percentage of their total production (including prototyping) is made in 3D. The 72.4% of respondents declared to have started using it in a small scale, in only 10% of their total production; the 15.8% make from 11 to 50% of their total production with 3D printings and only 11.8% of them realize more that 50% of their production using AM techniques.

Secondly, analyzing 3D companies attitudes and behaviours, it can be seen that they give really high importance to all the aspects defined in Table 3.18, even if in particular to the creation of modern and innovative products with high design (4.79), which meet the standards of “Made in Italy” (4.70) and they pay high attention to the image they communicate to customers (4.79). Furthermore it is considered as very important the enhancement of the brand as a source of competitiveness on the market (4.61) and the use of materials of quality for the realization of their products (4.61).

Table 3.18. Companies Attention Paid to these Business Practices

	3D companies n=76 (32.5%)	
	Mean	***SD***
Creation of customized products	4.50	0.721
Creation of modern and innovative products with high design	4.79	0.442

Creation of quality products that meet the standards of the "Made in Italy"	4.70	0.542
Creation of sustainable products	4.18	0.725
The quality of the materials used for the creation of products	4.68	0.518
The enhancement of the brand to be competitive on the market	4.68	0.571
The image of the company communicated to customers	4.79	0.442
Cronbach's Alpha 0.748		

3.2.4.3 Benefits and barriers of Additive Manufacturing implementation

Subsequently the main benefits and barriers of using AM techniques have been investigated.

As for the main advantages (Table 3.19) experienced from companies in the wood-furniture industry, it can be seen that the reduction in time for prototyping is the most perceived one in terms of importance (4.53), followed by the reduction in time to define technical specifications of products (4.09) in line with the studies of Petrovicet et al. (2011) and Ford and Despeisse (2016). 3D companies have also strengthened the ability of AM techniques to create products with complex geometries, increased performance and quality (4.05), as underlined from Hopkinson et al. (2006) and Ford and Despeisse (2016), which say that freedom of design of AM Techniques allow to redesign the whole product and its components, eliminating assembling problems related to cost, time and quality.

Two further important elements perceived are the reduction in time to market (3.82) and in production time (3.42). This is confirmed by the work of Petrovicet et al. (2011), which says that AM will increase supply chain dynamics, and therefore at the same time will also create a relative decline in imports/exports (Campbell et al., 2011).

On the contrary among the less important benefits considered there is the shift of production to retail outlets (1.93), followed by the reduction in transport costs (2.16) and in inventory and unsold costs (2.21). This is in contrast with what is found by Birtchnell et al. (2013) who said that supply chains are expected to become less transport intensive and Douglas and Stanley (2014) that found that AM reduces the need for large inventory.

Table 3.19. Perceived Benefits from 3D Printing Use

	3D companies n=76 (32.5%)	
	Mean	***SD***

Reduction in time to define technical specifications of products	4.09	0.786
Reduction in prototyping time	4.53	0.642
Reduction in production time	3.42	1.074
Reduction in time to market	3.82	0.795
Reduction in costs of materials	2.99	1.149
Reduction of inventory and unsold costs	2.21	1.123
Reduction in transport costs	2.16	1.132
Reduction of labor costs	2.75	1.297
Energy saving	2.64	1.116
Creation of new products with complex geometries, increased performance and quality	4.05	1.082
Creation of a new business model: offer of a virtual model	2.67	1.331
Greater chance of internationalization	2.53	1.238
Shift of production to retail outlets	1.93	1.075
Product customization	3.34	1.302
Ability to co-design with the customer	2.83	1.360
Reduction in environmental impact	2.74	1.300
Ability to serve niche markets	2.92	1.374

Cronbach’s Alpha 0.928

As for the disadvantages in using 3D printings (Table 3.20), it can be seen that there are no relevant ones perceived, in fact the lack of staff training (3.04) and the investment considered excessively high slightly exceed the threshold of indifference (value 3) and are the two most relevant ones. As stated in literature (Abdul et al., 2002; Saberi et al., 2010), for the successful implementation of AM technologies, the decision to adopt them has to be accompanied by a change in jobs and tasks, and also in work practices and structure, however the investment needed is not considered a constraint to their implementation.

Moreover this technology seem not perceived as not suited for this specific industry, therefore wide spreading margins of AM techniques are possible.

Table 3.20. Perceived Barriers from 3D Printing Users

	3D companies n=76 (32.5%)	
	Mean	***SD***
Technology is not suited to the wood-furniture sector	2.61	1.287
Lack of interest in the market	2.59	1.180
Lack of knowledge of potential benefits and problems	2.83	1.182
Lack of staff training	3.04	1.194
Excessively high investment	3.03	1.107

Cronbach’s Alpha 0.683

When considering the type of use companies can have of 3D printings (Table 3.21), it can be seen that these technologies are clearly used almost completely for prototyping (Mellor et al., 2014; Santos et al., 2006), even if the standard deviation of the items “small finished product series” and “customized products” seem to define that some of them are also trying to create small product series and also products that are totally created on customer needs. Therefore companies which are using this technology are starting to understand that AM has the potential to bring production closer to the consumer (Holstrom et al., 2013). This result shows also that 3D printing could be easily used for furniture production, even if wood is still a critical material to be printed, but AM can be used for the realization of modern furniture that are not wooden made but made in others materials such as plastics, resin and metal and also for producing some components of wooden made furniture. Therefore the fact that AM is not frequently used for production purposes denotes the still little diffusion and knowledge of these technologies among Italian furniture companies and their willingness to remain anchored to traditional production methods, typical of Made in Italy.

Table 3.21. Willingness to Create with 3D Printing

	3D companies n=76 (32.5%)	
	Mean	***SD***
Prototypes	4.59	0.593
Small finished product series	2.50	1.456
Customized products	2.51	1.419
Eco-sustainable products	2.30	1.395
Cronbach’s Alpha 0.775		

After performing a Principal Component Analysis of variables which were positively influenced by the use of 3D printings, 3 main components emerged (Table 3.22). The first one in terms of importance with a cumulative variance of 67.24% is called *Design & Customization* and it includes benefits related to the possibility to create products with free forms and complex geometries with reduced time and high performance and the possibility to create products that completely satisfy customers needs (Hague et al., 2003; Hopkinson et al., 2006; Holstrom et al., 2013).

The second component named *Time & Material Reduction* explains 59.79% of cumulative variance, and refers to benefits related to time spare in the definition of technical specifications and prototyping but also in cost saving for materials used, since AM does not operate in a subtractive manner as in the traditional production system (Beltrametti and Gasparre, 2015). Finally the third component, named *Sustanability & Competitiveness* (47.57% of cumulative variance), concerns factors related to new market strategies, more internal efficiency and reductions in environmental impacts, supporting the theory of Gebler et al. (2014) that see, thanks to these new technologies, a future in which value chains are shorter, smaller, more localised, more collaborative, and offer significant sustainability benefits (Gebler et al., 2014).

Table 3.22. PCA on Perceived Benefits from 3D Companies

Pattern Matrix[a]

	Sustainability & Competitiveness	**Time & Material Reduction**	**Design & Customization**
Reduction in time to define technical specifications of products	-	.801	-
Reduction in prototyping time	-	.735	-
Reduction in production time	-	-	-
Reducton in time to market	-	-	-
Reduction in costs of materials	-	.661	-
Reduction of inventory and unsold costs	.922	-	-
Reduction in transport costs	.882	-	-
Reduction of labor costs	.608	-	-
Energy saving	.808	-	-
Creation of new products with complex geometries, increased performance and quality	-	-	.644
Creation of a new business model: offer of a virtual model	.799	-	-
Greater chance of internationalization	.728	-	-
Shift of production to retail outlets	.947	-	-
Product customization	-	-	.684
Ability to co-design with the customer	.644	-	-
Reduction in environmental impact	.666	-	-
Ability to serve niche markets	.604	-	-
Cumulative variance	*47.57*	*59.79*	*67.24*
KMO	0.879		

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization
a. Rotation converged in 4 iterations.

Subsequently, after performing the PCA on factors which could affect the use of AM technologies, three main component emerged (Table 3.23). The most relevant one (cumulative variance of 46.37%) is called *Unsuitability*, and it is related to the belief that the technology is not suited for the wood-furniture industry and that there is no interest in this market about it. The second component in terms of relevance, with a cumulative variance of 24.88%, is named *Knowledge and Training* and it explains that sometimes a relevant barrier for the development of this technology is the fact that in this industry there is a low knowledge of these new production techniques and a lack of staff training on these themes. Finally the third component, even if the less relevant one (16.32% of cumulative variance), refers to the excessive investment perceived by companies in the purchase of such production tools.

Table 3.23. PCA on Perceived Barriers from 3D Companies

Pattern Matrix[a]

	Unsuitability	**Knowledge & Training**	**Costs**
Technology is not suited to the wood-furniture sector	.917	-	-
Lack of interest in the market	.888	-	-
Lack of knowledge of potential benefits and problems	-	-.688	-
Lack of staff training	-	-.956	-
Excessively high investment	-	-	.944
Cumulative variance	*46.73*	*24.88*	*16.32*
KMO		0.567	

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.
a. Rotation converged in 8 iterations.

Finally, the PCA on the type of use companies have of 3D printings shows two main components (Table 3.24), that is the realization of prototypes and of series of products. The most relevant component (84.00% of cumulative variance) is called *Prototyping* and it explains that in majority AM technologies are used in the wood-furniture industry as a tool to create prototypes faster and more freely (Mellor et al., 2014). However, as shown by component two, called *Product Series*, there is a segment of companies that is also open to the use of these technologies for the realization of small series of finished products, totally customized in relation to customer needs and also products that are more environmentally-friendly (Hague et al., 2004; Berman, 2012; Gershenfeld, 2012; Reeves, 2008).

Table 3.24. PCA on Willingness to Create with 3D Printing

Pattern Matrix[a]

	Product Series	**Prototyping**

Prototypes	-	1,000
Small finished product series	.855	-
Customized products	.913	-
Eco-sustainable products	.891	-
Cumulative variance	*59.97*	*84,00*
KMO	0.722	

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.
a. Rotation converged in 3 iterations.

3.2.5 Conclusions

This paper has evaluated the main advantages and disadvantages that AM technologies can bring to companies, considering those which are implementing them in the specific industry of wood-furniture. The research has highlighted how Italian 3D companies have a specific profile; they are companies aimed at innovating through the search for new products and product features, putting design and Made in Italy in the first place. They pay high attention to the image they communicate to the market and are highly oriented to the final customer, and to the satisfaction of its needs.

Reduction in time to market of products and the freedom of design seem to be the two major advantages perceived by companies implementing AM technologies. Thanks to 3D printing these companies are free to explore their imagination, bringing in a short time on the market products with complex shapes and high quality.

As for the disadvantages in using 3D printings, these are grouped in three categories, the ones related to the *Unsuitability* of the technology, those linked to the necessity to have more knowledge and training on this issue and the economic one, concerning the investment needed to implement 3D printing. However these are not perceived as real limits to the use of AM technologies from those companies which have started to use them.

Considering the way in which companies have started using AM, it can be said that until now 3D printing was mainly used for prototyping (Mellor et al., 2014), but recently it has gained much attention, as the process has proven to be compatible with industrial manufacturing beyond prototyping (Berman, 2012; Gershenfeld, 2012; Reeves, 2008). The research confirms these results, in fact while the majority of respondents say to use it as a useful tool for prototyping, there is a segment of them that is also open to the use of these technologies for the realization of small series of finished products, oriented to satisfy customer needs.

3.2.5.1 Implications

Considering practical implications that can derive from this study, firstly it can be said that AM provides opportunity for organisations to create product innovation, beating competitors on time, thanks to less time spent in defining technical specifications of products and in prototyping, dramatically reducing the time to market of the same. Moreover 3D printing may allow to experiment with their business models. Because DDM eliminates tooling, a product can be manufactured on the same day that the design is completed. This enables companies to produce an instant prototype and react faster to the demands of the user (Singh, 2015). The application in the wood-furniture industry would lead to the direct realization of final end-user products completely customized according to customer needs. For example a chair manufacturer could make chairs of every size and shape at the request of the individual customer, as craftsmen did in the past.

The research shows that it is not the design of the wooden furniture, but it is mainly the design of the components, accessories and furniture complements to be influenced by the use of AM technologies in the wood-furniture-industry; and very often these elements are not made with woody materials, but increasingly using plastic and composite materials; anyhow these parameters could define the competitive design of the businesses in this sector since the consumer's attention lies in the details.Wood is in fact currently a challenging material for AM, but there are studies such as Henke and Treml’s (2013), which show progresses in using wood based bulk materials for creating products with 3D printing. The joint use of these materials and AM technologies would be a game-changer and an important element of innovation for this particular industry.

Moreover AM technologies can create opportunities for more sustainable productions and the development of competitive strategies in their own reference market, owing the creation of a more sustainable value chain that is shorter, smaller, more localised and more collaborative, with also the ability to serve unexplored niche markets. To implement sustainable manufacturing, an organization needs to focus on key enablers such as international and contemporary issues, innovative products, reconfigurable manufacturing systems, complexity analysis, lean production, agile manufacturing, performance measurement, and flexible organization (Garbie, 2014; Cagliano and Spina, 2003). As stated by Holmstrom et al. (2017) and confirmed by this study, AM can help to reach such sustainability objectives, whether it is used for prototyping or for the production of finished products, thanks to product performance improvements, reduced materials use, and reduced logistics and transportation. The value chain of companies adopting these technologies could become shorter, smaller, more localised and more collaborative (Gebler et al., 2014).

3.2.5.2 Limitations and future research

The first limitation of this research may derive from the fact that a specific industry (i.e. wood furniture) was investigated, therefore a future research line could be to investigate the main advantages and disadvantages of 3D printing in other different and important for Italian sectors such as for example the mechanical, textile or food industry in order to compare differences and similarities.

Another limitation could derive from the fact that the sample is composed only of Italian companies. Nevertheless it was the aim of this paper to directly examine the Italian reality in order to understand how these new technologies are perceived and developed in the Italian context. These limitations give rise to another suggestion for future research; it would be important to expand the analysis of the main benefits and limitations of AM to other countries outside Italy, within Europe such as Germany, Poland and France as they are among the top producing countries in the wood-furniture industry, to see if these results could be confirmed.

Moreover a third limitation may derive from the fact that this research is based on only empirical data, therefore for future research it could be important to supplement the survey findings with a few in-depth qualitative interviews in order to have more information on aspects that were not considered in the survey, for instance the order to delivery strategy of the firms and volume and variety of productions, and also to understand depth of the type of strategy these companies are developing owing to the investment in AM technologies.

Finally further studies could investigate deeply of the advantages and challenges of 3D printing, through deep-dive single case studies and comparative case studies of different sectors, organisations, products and components, along with models of AM-based production systems.

Paper 2: Differences of Perception among Innovative and Traditional Companies

3.2.6 Results and discussion

3.2.6.1 Sample profile

Among the whole sample of respondent companies in the wood-furniture industry (n=234), the paper will focus on considering differences of perception among those companies which are implementing internally or externally AM techniques, called *3D companies* (n=76) and those *Traditional* ones (n=158), which have never used 3D printings.

In detail in the whole sample, 19.3% of companies declared to use internally these technologies, 13.2% to use them externally, while Traditional companies which do not use them are 67.5%.

Defining the profile of companies (Table 3.25), the majority of them are of small (43.2%) and medium (33.8%) size, with a turnover between 2 and 50 million of Euro. Among these, 3D companies are in majority of a medium size (43.4%) with a higher turnover (between 11-50 Mln Euro), while Traditional ones are of a smaller size (49.4%) with a lower turnover. 3D and Traditional companies are mainly located in the north, they have International markets as reference markets and realize in majority products of an upper-middle range.

Table 3.25. Sample Profile of Respondent Companies

		All sample ***n=234***		***3D companies*** ***n=76 (32.5%)***		***Traditional companies*** ***n=158 (67.5%)***	
		n	***%***	***n***	***%***	***n***	***%***
Dimension	Micro	25	10.7	4	5.3	21	13.3
	Small	101	43.2	23	30.3	78	49.4
	Medium	79	33.8	33	43.4	46	29.1
	Large	29	12.4	16	21.1	13	8.2
Turnover (€)	Less than 2 Mln	41	17.5	4	5.3	37	23.4
	2-10 Mln	84	35.9	21	27.6	63	39.9
	11-50 Mln	77	32.9	34	44.7	43	27.2
	More than 50 Mln	32	13.7	17	22.4	15	9.5
Region	North	124	53.0	43	56.6	81	51.3
	Center	106	45.3	31	40.8	75	47.5
	South and Islands	4	1.7	2	2.6	2	1.3
Reference markets	Italy	14	6.0	3	3.9	11	7.0
	Italy and Europe	30	12.8	5	6.6	25	15.8
	International markets	190	81.2	68	89.5	122	77.2
Price range	Low	0	0.0	0	0.0	0	0.0
	Lower-middle	10	4.3	1	1.3	9	5.7
	Medium	48	20.5	9	11.8	39	24.7

Upper-middle	141	60.3	50	65.8	91	57.6
High	35	15.0	16	21.1	19	12.0

In the whole sample of companies that participated to the survey the majority of respondents work in the accessories sector (13.7%), followed by those producing office furnishing (12.0%), kitchen furnishing (11.1%) and bathroom ones (9.4%). 3D printing technologies are used mainly by those realizing accessories (18.4%) and those producing bathroom (13.2%) and office (13.2%) furnishings (Table 3.26).

Table 3.26. Wood-furniture Sectors of Respondent Companies

	All sample		***3D companies***		***Traditional companies***	
	n=234		***n=76 (32.5%)***		***n=158 (67.5%)***	
	n	***%***	***n***	***%***	***n***	***%***
Accessories	32	32.6	14	18.4	18	11.4
Furnishing for bars and shops	15	6.4	6	7.9	9	5.7
Classic furnishing	13	5.6	3	3.9	10	6.3
Outdoor furnishing	4	1.7	0	0.0	4	2.5
Bathroom furnishing	22	9.4	10	13.2	12	7.6
Bedroom furnishing	11	4.7	6	7.9	5	3.2
Collectivity	15	6.4	5	6.6	10	6.3
Kitchen furnishing	26	11.1	6	7.9	20	12.7
Domestic multiproducts	16	6.8	6	7.9	10	6.3
Upholstered furnishing	14	6.0	5	6.6	9	5.7
Mattresses	1	0.4	0	0.0	1	0.6
Panels	5	2.1	1	1.3	4	2.5
School furnishing	3	1.3	0	0.0	3	1.9
Semifinished products	18	7.7	0	0.0	18	11.4
Living room furnishing	7	3.0	2	2.6	5	3.2
Office furnishing	28	12.0	10	13.2	18	11.4
Other	4	1.7	2	2.6	2	1.3

3.2.6.2 Wood-furniture Companies' attitudes and behaviours

Firstly it has been asked to wood-furniture companies if they were usual to realize prototypes; only 5.1% said not to realize them, while 80.8% said to realize them internally and 14.1% externally.

Therefore it was asked them if they knew 3D printing techniques, and where did they know about it. The majority of respondents (44.9%) have heard about AM via Internet, followed by the relationships with customers and suppliers (39.7%), the working environment (31.2%) and magazines and newspapers (18.8%).

As for 3D companies, it has been asked what percentage of their total production (including prototyping) is made in 3D. The 72.4% of respondents declared to have started using it in only 10% of their total production; the 15.8% make from 11 to 50% of their total production with 3D printings and only 11.8% of them realize more that 50% of their production using AM techniques.

Analyzing companies attitudes and behaviours (Table 3.27), it can be seen that in general they give much importance to their image (4.62), to the brand of Made in Italy (4.61), to quality of materials (4.60) design (4.56) and customization (4.53). Considering the differences between 3D and Traditional companies, it can be seen that companies that have begun to use AM techniques, compared to traditional companies, give more importance to the creation of modern and innovative products with high design (4.79), which meet the standards of "Made in Italy" (4.70) and they pay high attention to the image they communicate to customers (4.79). Furthermore it is considered as very important the enhancement of the brand as a source of competitiveness on the market (4.68) and the creation of products that meet sustainability standards (4.18).

Table 3.27. Attention Paid to these Factors in Companies' Corporate Behaviour (α = 0.748)

	All sample ***n=234***		***3D companies*** ***n=76 (32.5%)***		***Traditional companies*** ***n=158 (67.5%)***			
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***F***	***Sig.***
Creation of customized products	4.53	0.759	4.50	0.721	4.55	0.778	0.228	0.634
Creation of modern and innovative products with high design	4.56	0.673	4.79	0.442	4.46	0.737	**13.287**	0.000
Creation of quality products that meet the standards of the "Made in Italy"	4.61	0.668	4.70	0.542	4.56	0.718	**2.080**	0.151
Creation of sustainable products	3.93	0.896	4.18	0.725	3.81	0.945	**9.270**	0.003
The quality of the materials used for the creation of products	4.60	0.532	4.61	0.518	4.60	0.541	0.003	0.957
The enhancement of the brand to be competitive on the market	4.51	0.707	4.68	0.571	4.42	0.751	**7.130**	0.008
The image of the company communicated to customers	4.62	0.597	4.79	0.442	4.54	0.645	**9.424**	0.002

3.2.6.3 3D printing: different perception of benefits and barriers

Subsequently the main benefits and barriers of using AM techniques have been investigated.

As for the main advantages (Table 3.28), it can be seen that the reduction in prototyping time (3.84), and the reduction in time to define technical specifications of products (3.50) are the most perceived ones by the whole sample. However there are big differences of perception among the two different categories of companies. In detail, 3D companies seem to perceive in a stronger way the advantages related to the reduction in time to define technical specifications of products, in time for prototyping, for production and in the time-to-market of products. Moreover it is strongly perceived the possibility to create products with complex geometries, high performance and quality, to co-design products with the customer and in the same time to reduce the costs of materials used to realize products. On the contrary it seems that, while Traditional companies think that 3D printing technologies allow the creation of a new business model, this is less perceived by those companies which have adopted it.

Table 3.28. Benefits from 3D Printing Use, Considering 3D and Traditional Companies (α=0.948)

	All sample		***3D companies***		***Traditional companies***			
	n=234		***n=76 (32.5%)***		***n=158 (67.5%)***			
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***F***	***Sig.***
Reduction in time to define technical specifications of products	3.50	1.237	4.09	0.786	3.22	1.313	**28.877**	0.000
Reduction in prototyping time	3.84	1.243	4.53	0.642	3.51	1.325	**40.419**	0.000
Reduction in production time	2.93	1.245	3.42	1.074	2.70	1.255	**18.731**	0.000
Reduction in time to market	3.27	1.136	3.82	0.795	3.01	1.184	**28.718**	0.000
Reduction in costs of materials	2.67	1.179	2.99	1.149	2.52	1.166	**8.341**	0.004
Reduction of inventory and unsold costs	2.29	1.134	2.21	1.123	3.22	1.141	0.501	0.48
Reduction in transport costs	2.12	1.103	2.16	1.132	2.11	1.092	0.106	0.745
Reduction of labor costs	2.60	1.250	2.75	1.297	2.53	1.224	1.662	0.199
Energy saving	2.55	1.135	2.64	1.116	2.50	1.144	0.834	0.362
Creation of new products with complex geometries, increased performance and quality	3.65	1.295	4.05	1.082	3.46	1.348	**11.132**	0.001
Creation of a new business model: offer of a virtual model	2.91	1.320	2.67	1.331	3.02	1.304	**3.606**	0.059
Greater chance of internationalization	2.61	1.211	2.53	1.238	2.65	1.199	0.551	0.459
Shift of production to retail outlets	2.05	1.091	1.93	1.075	2.11	1.098	1.297	0.256
Product customization	3.18	1.330	3.34	1.302	3.10	1.341	1.686	0.195
Ability to co-design with the customer	3.02	1.297	2.83	1.360	3.11	1.26	**2.383**	0.124
Reduction in environmental impact	2.71	1.177	2.74	1.300	2.69	1.117	0.081	0.776
Ability to serve niche markets	3.01	1.287	2.92	1.374	3.05	1.246	0.519	0.472

As for the disadvantages in using 3D printings (Table 3.29), it can be seen that there are no relevant ones perceived. The fact that the technology is not suited to the sector (3.15) and the investment considered excessively high slightly exceed the threshold of indifference (value 3) and are the two most relevant ones. However Traditional companies think in a stronger way that there is a lack of interest in 3D printing in the wood-furniture industry and that this technology is not suited for this sector. This could be the reasons why they have not approached yet to them.

Table 3.29. Barriers from 3D Printing Use, Considering 3D and Traditional Companies (α=0.688)

	All sample *n=234*		*3D companies* *n=76 (32.5%)*		*Traditional companies* *n=158 (67.5%)*			
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***F***	***Sig.***
Technology is not suited to the wood-furniture sector	3.15	1.405	2.61	1.287	3.41	1.388	**18.143**	0.000
Lack of interest in the market	2.97	1.267	2.59	1.180	3.16	1.270	**10.676**	0.001
Lack of knowledge of potential benefits and problems	2.92	1.281	2.83	1.182	2.97	1.328	0.606	0.437
Lack of staff training	2.92	1.309	3.04	1.194	2.86	1.361	0.956	0.329
Excessively high investment	3.05	1.237	3.03	1.107	3.06	1.298	0.031	0.86

When considering the type of use companies can have of 3D printings (Table 3.30), it can be seen that these technologies are mostly used for prototyping, and in a less way to create customized products.

Anyhow it seems that while 3D companies are actually using these technologies almost entirely for the production of prototypes (4.59), Traditional ones seem more interested also in starting using 3D printing to create customized products, to bring the production closer to the consumer.

Table 3.30. Willingness to Create with 3D Printing (α=0.825)

	All sample *n=234*		*3D companies* *n=76 (32.5%)*		*Traditional companies* *n=158 (67.5%)*			
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***F***	***Sig.***
Prototypes	3.82	1.324	4.59	0.593	3.44	1.420	**45.531**	0.000
Small finished product series	2.44	1.377	2.50	1.456	2.38	1.337	0.243	0.622
Customized products	2.71	1.448	2.51	1.419	2.78	1.452	2.078	0.151
Eco-sustainable products	2.42	1.319	2.30	1.395	2.46	1.277	0.939	0.334

3.2.6.4 Adoption of 3D printing along the supply chain

Subsequently the research has considered the level of adoption of AM techniques along the supply chain of the interviewed companies, considering supply chain partners, linked companies, competitors, suppliers and contractors. As it can be seen in Table 3.31, the level of perceived adoption of these technologies is really low, even if surely higher in the supply chains of 3D companies. This allows to say that the use of these technologies drives the actors present in the same supply chain to conform and innovate in turn.

Table 3.31. Degree of Adoption of 3D Printing by External and Internal Actors in the Supply Chain (α= 0.897)

	All sample ***n=234***		***3D companies*** ***n=76 (32.5%)***		***Traditional companies*** ***n=158 (67.5%)***			
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***F***	***Sig.***
Supply Chain Partners	2.24	1.096	2.71	1.129	2.01	1.006	**23.186**	0.000
Linked companies	2.22	1.084	2.79	1.135	1.94	0.946	**35.972**	0.000
Competitors	2.36	1.023	3.01	0.945	2.04	0.905	**57.111**	0.000
Suppliers	2.45	1.183	3.00	1.189	2.18	1.088	**27.209**	0.000
Contractors	2.16	1.071	2.50	1.137	1.99	1.000	**12.017**	0.001

Table 3.32 shows the sectors in which there is an higher level of adoption of AM technologies by internal and external actors in the supply chain. As it can be seen, the sector Domestic multiproducts, which represents those companies that make furniture both for the living and sleeping area, has the major number of 3D printing users along its supply chain (n=30), followed by those companies realizing accessories (n=28), office furnishing (n=23) and bathroom ones (n=21).

Table 3.32. High level of adoption (value 4 and 5 of the Likert scale) of 3D printing by external and internal actors in the supply chain

	Supply Chain Partners	***Linked companies***	***Competitors***	***Suppliers***	***Contractors***	***Total***
	n	*N*	*n*	*n*	*n*	
Accessories	6	7	7	5	3	28
Furnishing for bars and shops	5	2	2	6	3	18
Classic furnishing	1	0	0	2	1	4
Outdoor furnishing	1	0	1	1	1	4
Bathroom furnishing	3	5	3	7	3	21
Bedroom furnishing	2	3	2	3	0	10
Collectivity	2	3	1	2	1	9
Kitchen furnishing	4	2	2	7	3	18
Domestic multiproducts	5	4	5	8	8	30
Upholstered furnishing	2	2	4	3	1	12
Mattresses	0	0	0	0	0	0

Panels	1	1	1	1	1	5
School furnishing	1	0	0	1	1	3
Semifinished products	1	1	1	0	1	4
Living room furnishing	1	1	0	1	1	4
Office furnishing	4	4	4	8	3	23
Other	1	0	0	0	0	1

Finally, when asking companies if they consider important to continue to invest in digital technologies to remain competitive in their markets, the whole sample answered in a positive way, giving an importance of 4.08 in the 5-points Likert scale; even in this case there is a statistically different perception (F test = 7.001) among 3D and Traditional companies, which sees 3D ones more convinced that investments in digital technologies are strictly necessary to remain competitive (3D companies= 4.32; Traditional companies=3.97) and that 3D printers and other digital technologies can represent the breakthrough that will allow in industry the advent of a new Industrial Revolution (3D companies= 3.83; Traditional companies= 3.57; F test= 3.715).

3.2.6.5 Logistic regression

The logistic regression model tries to identify which are the main factors defining the probability of a company to use 3D printers (Table 3.33). The dependent variable is a binary variable that takes the value 1 if the company is using AM technologies, otherwise zero. The logistic model allows to predict 3D printing use with a probability equal to 79.1% considering among the factors, companies' price range, their corporate behaviour (see Table 3.27) and the main perceived benefits of 3D printing use (see Table 3.28).

Table 3.33. Estimation of Factors which Defined the Probability of 3D Printing Use

Observed			Predicted		
			Y_Possession of 3D Printing		**Percentage Correct**
			0.00	1.00	
Step 1	Y_Possession of 3D Printing	0.00	125	33	79.1
		1.00	16	60	78.9
	Overall Percentage				79.1
a. The cut value is .340					

Among the factors influencing the use of 3D printing in wood-furniture companies (Table 3.34), price range is the one with the higher level of significance, meaning that it is mainly the companies that produce more high-end products that approach the use of these new digital technologies. Considering companies' corporate behaviour, it seems that the willingness to create products modern and innovative with an high design has prompted companies to approach to these technologies, while the attention paid to the creation of products that are customized and meet the standards of Made in Italy would seem not to favour the use of 3D printings. Finally among the perceived benefits, the model has estimated the reduction in prototyping time as the main driving factor, while the ability to serve niche markets seem not to have a negative influence in the adoption of AM technologies.

Table 3.34. Factors Influencing the Adoption of 3D Printing

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Price Range	.887	.333	7.091	1	**.008**	2.428
	Creation of customized products	-.704	.308	5.209	1	**.022**	.495
	Creation of modern and innovative products with high design	1.095	.476	5.302	1	**.021**	2.990
	Creation of quality products that meets the standards of the "Made in Italy"	-.785	.383	4.205	1	**.040**	.456
	Creation of sustainable products	.414	.289	2.047	1	.153	1.512
	The quality of the materials used for the creation of products	-.608	.457	1.769	1	.183	.544
	The enhancement of the brand to be competitive on the market	-.474	.417	1.295	1	.255	.622
	The image of the company communicated to customers	.908	.502	3.274	1	.070	2.478
	Reduction in time to define technical specifications of products	.022	.280	.006	1	.936	1.023
	Reduction in prototyping time	.858	.338	6.441	1	**.011**	2.360
	Reduction in production time	.407	.249	2.682	1	.101	1.503
	Reducton in time to market	.198	.292	.457	1	.499	1.219
	Reduction in costs of materials	.041	.253	.026	1	.872	1.042
	Reduction of inventory and unsold costs	-.425	.303	1.965	1	.161	.654
	Reduction in transport costs	.167	.308	.293	1	.588	1.181
	Reduction of labor costs	-.095	.238	.160	1	.689	.909
	Energy saving	.169	.295	.327	1	.567	1.184
	Creation of new products with complex geometries. increased performance and	.397	.237	2.816	1	.093	1.487

quality						
Creation of a new business model: offer of a virtual model	-.452	.280	2.618	1	.106	.636
Greater chance of internationalization	-.010	.315	.001	1	.975	.990
Shift of production to retail outlets	.088	.290	.092	1	.762	1.092
Product customization	.185	.263	.494	1	.482	1.203
Ability to co-design with the customer	-.248	.226	1.200	1	.273	.780
Reduction in environmental impact	.248	.260	.909	1	.340	1.282
Ability to serve niche markets	-.560	.289	3.769	1	**.052**	.571
Constant	-7.803	2.556	9.319	1	.002	.000

Model summary: -2 Log Likelihood 188.307; Cox & Snell R Square 0.366; Nagelkerke R Square 0.511; Hosmer and Lemeshow Test: Chi-square=6.452; Sig. 0.597

3.2.7.Discussion and conclusions

The aim of this research was to understand the diffusion of 3D printing technologies in Italy, focusing in detail in the wood-furniture industry, one of the solid pillars of Made in Italy, known and appreciated in all international markets, thanks to the operations of over 40 industrial districts. Two of the three major European furniture producing regions are Italian (Veneto and Lombardy), and among the top 15, there are 5 (also Marche, Friuli Venezia Giulia, Tuscany). In the world, the sector is second only to China for trade surplus, and despite the structural deficit of raw materials, thanks to its manufacturing skills it generates an added value (€ 4.9 billion) far greater than that of many countries naturally rich in woody raw materials (such as France, 2.3, Spain, 1.8, Sweden, 900 million €). These results are due to the fact that its businesses have a great tradition and also have a strong ability to innovate, from an environmental and technological point of view (GreenItaly, 2016). Therefore the goal was to understand how much these companies are investing in digital technologies and in particular in AM techniques, to remain competitive in their reference markets, distinguishing among "traditional companies" and those "innovative", which have implemented these technologies yet. The results of the research seem to confirm what stated by Rusconi (2015), about the fact that 3D printing is a strong growing phenomenon, already quite widespread in Italy, with further potential of development, in fact about a third of wood-furniture companies have already approached internally or externally the use of this production technique in their production chain. In the Italian context they are mainly the most structured companies with a higher turnover to have started investing in these new technologies; this is supported by the literature which has identified the size of an organization as a critical factor to the understanding of the process of implementation of new manufacturing technologies (Federici, 2009; Schubert et al., 2007). Linked to size, previous studies into new manufacturing technology implementation suggest that the structure of an organization is the key factor to successfully implement manufacturing technology (Abdul et al., 2002; Saberi et al., 2010), and that companies that adopt without first re-designing organizational structures and processes encounter high difficulties (Saberi et al, 2010).

Profiling the companies which have started to use AM techniques, it seems that these ones give a relevant importance to aesthetic aspects of products they sell related to design and innovation and also to communicate a good image of themselves.

The results show that among the main advantages of using 3D printing, 3D companies perceive in a stronger way the ones related to the reduction in time to define technical specifications of products, in time for prototyping and for production as underlined in the studies of Petrovicet et al. (2011) and Ford and Despeisse (2016). Two further important elements perceived are the reduction in time to market and in production time; this is confirmed by the work of Petrovicet et al. (2011), which says that AM will increase supply chain dynamics, and therefore at the same time will also create a relative decline in imports/exports (Campbell etal.,2011). As for the disadvantages, the research shows that no relevant ones are perceived and that the major reason of traditional companies for non implementing 3D printing is the belief that this technology is not suited for this sector. It is true that the approach to the implementation for a SME is likely to be different to that in a large multinational company, and that for the successful implementation of AM technologies the decision to adopt them has to be accompanied by a change in jobs and tasks, and thus a change in work practices and structure (Saberi et al, 2010). However the successful adoption by many companies in the sector shows that in reality, made the necessary organizational changes, the technology can be implemented successfully in the field. Moreover evaluating through the binary regression, the main factors defining the probability of a company to use 3D printers in the wood-furniture industry it can be seen that it is the willingness to create products modern and innovative with an high design the has prompted companies to approach to these technologies. They have also been pushed to make the investment by the benefit of reducing the prototyping times in their production chains and consequently getting faster and easier to the final market with sophisticated and special products, gaining a competitive advantage over competitors. Flexible manufacturing systems, such as AM is, provide dynamic and structural flexibility to an organization. First, product flexibility enables an organization to adapt quickly to changing environment. With the passage of time, the product life cycle is reducing, and to sustain in an intense competitive environment, an organization needs to have enough product flexibility. Second, volume flexibility enables an organization to adapt their production strategy according to the market needs, without compromising with profitability of the organization. Third, the mix flexibility enables a firm to handle large product variants by using equipment having short setup times (Dubey and Gunasekaran, 2015).

As stated by Campbell et al., (2011) thanks to 3D printing supply chains shift from physical goods to digital ideas/designs increasing supply chain dynamics by reducing time-to market (Petrovicet al., 2011).

In conclusions it can be said that AM provides opportunities for organisations to create product innovation, beating competitors on time, thanks to less time spent in defining technical specifications of products and in prototyping, dramatically reducing the time to market of the same. Moreover AM technologies can create opportunities for more sustainable production and the development of competitive strategies in their own reference market, thanks to the creation of a more sustainable value chain that is shorter, smaller, more localised and more collaborative (Gebler et al., 2014).

As for the limitations of the research, the specific focus on the wood-furniture sector could be the first one. Therefore it would be important to understand if such technologies are developing in other Italian relevant industrial sectors, such as the textile, food and automotive ones, in order to compare these realities with the European ones.

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4. INDOOR AIR QUALITY: IS THERE A PROBLEM WITH ADDITIVE MANUFACTURING?

ABSTRACT

This chapter deals with Additive Manufacturing and the possible problem of Indoor Air Pollution due to the melting process of 3D printers, during which materials such as plastics emit gaseous substances, commonly called Volatile Organic Compounds (VOCs). Assessing that the quantity of substances emitted does not exceed threshold levels is important for the health and safety of those using such digital tools. The analysis starts defining the concept of Air Pollution, and distinguishing between Indoor and Outdoor Air Pollution. It continues describing what VOCs are and the guidelines for Indoor Air Quality defined at an European and Italian level. The chapter ends with the description of the results of my research, which performed air sampling of indoor air environments, while a 3D printer was under function, with different types of plastic materials (PLA, ABS, PET) in order to understand and assess the potential dangerousness to human health of this technological tool.

4.1 The concept of Air Pollution

Various chemicals are emitted into the air from both natural and man-made (anthropogenic) sources. The quantities may range from hundreds to millions of tonnes annually. Natural air pollution stems from various biotic and abiotic sources such as plants, radiological decomposition, forest fires, volcanoes and other geothermal sources, and emissions from land and water. This result in a natural background concentration that varies according to local sources or specific weather conditions. Anthropogenic air pollution has existed at least since people learned to use fire, but it has increased rapidly since industrialization began. The increase in air pollution resulting from the expanding use of fossil energy sources and the growth in the manufacture and use of chemicals has been accompanied by mounting public awareness and concern about its detrimental effects on health and the environment. Moreover, knowledge of the nature, quantity, physicochemical behaviour and effects of air pollutants has greatly increased in recent decades (World Health Organization, 2000).

Air pollutants may be either emitted into the atmosphere (*primary air pollutants*) or formed within the atmosphere itself (*secondary air pollutants*). Apart from the physical state of pollutants (such as gaseous or particulate matter) it is important to consider the geographical location and distribution of sources. The local, urban, regional and global scale of air pollution can be distinguished, depending primarily on the atmospheric lifetime of specific air components.

Primary air pollutants are those that are emitted into the atmosphere from a source such as a factory chimney or exhaust pipe, or through suspension of contaminated dusts by the wind. In principle, therefore, it is possible to measure the amounts emitted at the source itself. This is relatively straightforward in terms of the factory chimney or vehicle exhaust pipe; it becomes very much more difficult when considering diffuse sources such as wind-blown dusts. When such sources are added together they comprise an emission inventory of primary sources, as described below (Fenger, 2003; World Health Organization, 2006).

Secondary air pollutants are those formed within the atmosphere itself. They arise from chemical reactions of primary pollutants, possibly involving the natural components of the atmosphere, especially oxygen and water. The most familiar example is ozone, which arises almost entirely from chemical reactions that differ with altitude within the atmosphere. Because of this mode of formation, secondary pollutants cannot readily be included in emissions inventories, although it is possible to estimate formation rates per unit volume of atmosphere per unit time (Emission Inventory Guidebook, 2002; World Health Organization, 2000; World Health Organization, 2006).

For primary air pollutants, emission inventories are (often in combination with dispersion models) a powerful tool for predicting air quality. They can, for example, be used to model local, regional and global conditions and observe spatial and temporal trends in emissions. Receptor modelling is an alternative method that uses measurements of air quality, frequently in combination with simultaneously measured meteorological data, to recognize and quantify the contributions of specific characteristic source types to air pollutant concentrations. For secondary air pollutants, the mode of their formation makes it difficult to readily include them in emissions inventories or receptor modelling. Nevertheless, it is possible to estimate formation rates of secondary pollutants per unit volume of atmosphere per unit time.

Another important distinction must be made in relation to the physical state of a pollutant. *Gaseous air pollutants* are those present as gases or vapours, i.e. as individual small molecules capable of passing through filters provided they do not adsorb to or chemically react with the filter medium. Gaseous air pollutants are readily taken into the human respiratory system, although if water-soluble they may very quickly be deposited in the upper respiratory tract and not penetrate to the deep lung. Particulate air pollutants comprise material in solid or liquid phase suspended in the atmosphere. Such particles can be either primary or secondary and cover a wide range of sizes. Newly formed secondary particles can be as small as 1−2 nm in diameter (1 nm = 10−9 m), while coarse dust and sea salt particles can be as large as 100 μm (1 μm = 10−6 m) or 0.1 mm in diameter. However, the very large particles have a short atmospheric existence, tending to fall out rapidly through gravity and wind-driven impaction processes. Thus in practice there are few particles in the atmosphere exceeding 20 μm in diameter, except in areas very close to sources of emission (Fenger, 2003; Air Quality Expert Group, 2005; World Health Organization, 2006).

4.2 Indoor Air Quality

For indoor air it is meant the air present in non-industrial indoor environments (such as homes, offices, hospitals, schools, etc ...) and it is characterized by the presence of various types of substances that come from both inside the buildings (originated from the same human presence or of emissions from materials and activities) that from the outside, but which are not naturally present in the outside air of high quality ecological systems. The pollutants present in the indoor air can be generated from multiple sources, each of which is difficult to identify; indoor pollution is often modest and often assumes a diffuse character. Indoor Air Quality (IAQ) has seen over the years a gradual worsening, both in number and concentration of airborne pollutants with its negative consequences for the health effects. These changes can be attributed to two main reasons, political and structural ones:the political reason is due to the adoption of laws on energy saving which led to the adoption of limitation of heat exchanges towards the outside and also reducing air changes; the structural reason, has to be attributed to the use of new building materials and furnishings, and here the use of 3D printers can be included, and the increasingly frequent recourse to installations for the conditioning to recover a part of the thermal energy, adopting an air recirculation.

Beside these two main causes of changes in IAQ it is important to signal the greater permanence of people within these environments (in industrialized countries people spend inside buildings more than 80% of their time); they contribute to air pollution with breathing and discretionary habit of cigarette smoking (Nicolini et al., 2006). Table 4.1 sets out an indicative list of the main indoor pollutants.

Table 4.1 Main Indoor Air Quality Pollutants (Source: Nicolini et al., 2006)

POLLUTANTS	*SOURCES*
Asbestos and synthetic mineral fibbers	Building materials, insulation
Carbon dioxide (CO_2)	Occupants (breathing), combustions
Pesticides	Wood, outdoor air
Volatile Organic Compounds (VOC)	Furniture, smoke, cleaning products, insulating
Formaldehyde (HCHO)	Furnishings
Tobacco smoke (ETS)	Voluptuary smoking habits of the occupants
Nitric oxide (NO e $NO_{2)}$	Tobacco smoke, burner stoves with open chamber
Carbon monoxide (CO)	Heating and cooking systems, tobacco smoke
Ozone ($O_{3)}$	Outdoor air, external tools with high voltage
Unlovable particulate	Tobacco smoke, combustion sources, occupant activities
Microbiological pollutants	Occupants, pets, air conditioning equipment, outdoor air, plants
Radon	Soil, water, building materials

Indoor pollutants, that can act individually or in combination with other factors, determine a decrease in the environmental comfort and a health risk; these are chemical (organic and inorganic), physical (ionizing and non-ionizing) and biological (micro-organisms, molds, mites) agents (WHO, 2010). Over the past decades there has been a progressive deterioration of air quality in confined environments; numerous scientific studies have demonstrated the presence, in the air of the living environments, of contaminants at low concentration of difficult measurement that can determine effects on health is not yet fully known (Sarigiannis, 2011).

Considering that much of the population spends its time in confined rooms, exposure to indoor pollution is dominant than outdoor. It is necessary to add that the IAQ depends not only by the presence of internal sources, but also from the external air quality. The main internal sources are determined by man and his activities, from building materials, from furniture and air handling systems; among these one of the most important sources is definitely the tobacco smoke, in addition to the processes of combustion of fossil fuels. Other possible internal sources of pollution are products for cleaning and maintenance of the house, the pesticides, the use of glues, adhesives, solvents in addition to the use of working tools such as printers, plotters and copiers (Wolkoff, 1995).

For the purposes of classification of the factors that influence the microclimate of an indoor environment, it must consider that the indoor environment (confined) is a portion of space separated from the external via a control/boundary surface (walls/building envelope) which allows thermal exchanges, exchanges of air and water (or water vapor) with the external environment. The boundary surface (walls/building envelope), in fact, is schematically characterized by two essential parameters, the permeability (Santarsiero, 2013; UNI 10351:1994) which depends on the porosity of the materials (Blondeau et al., 2013; De Biase et al., 2014) and the thermal conductivity of materials which affect hygrothermal exchanges.

The indoor microclimate is conditioned by a series of factors such as (Santarsiero, 2009):

- the outdoor climate with its variations (temperature, humidity, solar radiation, wind, etc.) of short, medium and long term;
- the characteristics of the external environment which can influence the direct interactions between climate and microclimate parameters (wind barriers, canyon effects, shading, the surface water mirrors, etc.);
- the technological and structural characteristics of the environment in question (architecture, materials and products used, microclimate control systems, etc.);
- the use of the environment and lifestyle habits of the occupants;
- the thermal air and water exchanges, (steam, humidity) that occur with the outside;
- heat and water exchanges between the inside and the elements therein.

Under the thermo-hygrometric aspect, however, the variable parameters in the time and space, that influence the microclimate of an indoor environment are, for the various factors, the following (Santarsiero et al., 2015):

1. Humidity
    - Relative Humidity (RH)
    - Absolute Humidity (UA);
2. Temperature
    - Air Temperature (T_a),
    - Mean Radiant Temperature (T_{mr}),
    - Surface Temperature (T_s);
3. Ventilation
    - Air Speed (S_{air})
    - Replacement/Airflow.

Within a building these indoor climate components will display spatial and temporal variations both due to effects on the building arising from the outdoor ambient climate and as a result of occupant behaviour and requirements. To fulfil comfort requirements there are several options according to the needs: limitation of the lowest temperature (heating); limitation of the highest temperature (cooling); control of humidity; provision of clean and circulated air (ventilation). Several factors may simultaneously influence the indoor climate in particular heating, ventilation and air conditioning. The materials and methods used in the construction of the building as well as its operation, use and maintenance will also have considerable impact on the indoor climate. In the present context of IAQ most of the components of the indoor climate, either individually or in combination, may be important determining factors for the concentration of many indoor air pollutants.

Humidity

The humidity inlet sources in an environment can be of different origin (WHO, 2009):

- *natural*: rain, soil moisture, groundwater and aquifer veins, ice and snow melting, surfaces of water bodies;
- *artificial*: failures in water supply pipelines and wastewater disposal, nearby industrial processes, heating and cooling systems, air treatment.

Another origin of the water is due to the condensation of water vapor caused by the difference in temperature between ambient air (air/water vapor mixture) and the contact surfaces where the condensation takes place when these are found at temperature values below the dew point.

Among the origins of humidity mentioned the most persistent and frequent are:

- meteoric: due to rain water that wetting the outer wall penetrates in masonry also throughout its thickness;
- by condensation: it is formed by the difference in temperature between the internal environment and the "cold wall", as a result of different thermal conductivity and porosity of the materials. But you can also have condensation of concealed piping;
- by infiltration: it may depend on the presence of ground water or from unforeseen causes (breakage of pipes, drains, etc.);
- by rising (or ascending) originates from the soil and dates back in the walls by capillarity.

The first three are episodic, linked to seasonal and special events. Humidity from capillary rise is rather a phenomenon that occurs constantly throughout the year.

The indoor sources of humidity are mostly attributable to:

- presence: respiration/perspiration of people, animals and plants, tanks and siphons at a free surface of the water, swimming pools, fountains, wash;
- activity: cooking (both for combustion either by evaporation), washing and drying clothes and dishes, bathrooms and showers, cleaning of the environment, watering;
- moisture from building materials: water of construction, materials and thermal bridges (when the relative humidity of the interior is combined with a surface temperature of the building envelope that has the lowest value of the dew-point temperature).

The presence of people and their activity, as a function of the density of crowds of people, can affect the amount of indoor air humidity. For example, the supply of humidity, through the evaporation of sweat and the water vapor emitted by respiration significantly increase the relative humidity (even by 10% points, in the case of very high flocking density of people making high physical efforts, such as in indoors gyms).

Some examples of significant impact on the humidity, in the absence of air changes in an environment, are the following:

- in extreme conditions with the perspiration a single person may enter 500 g/h of water;
- a single pot from the kitchen of an household type (capacity of about 8 liters) per hour of boiling can enter approximately 30% of the contained liquid;
- a room of about 200 m_3, with an air temperature of about 20° C, RH 50%, with the presence of 10 persons doing a light activity for 2 hours, can achieve a RH of 100%; similar relative humidity value is reached if it is in the presence of a pot that is boiling for about 45 minutes.

Humidity influences the formation and proliferation of molds and other biological agents in the air and on surfaces and inside of these materials (furniture, furnishings and the elements constituting the buildings). With different kinetics and mechanisms from case to case, the water, airborne or condensed, replaces in some adsorbent or absorbent substrates substances already present in the materials favouring the dispersion in the indoor air. In other cases it reacts with the substances adsorbed, or constituting the materials, giving rise to substrates that support growth of biological agents, and constituting or promoting the formation of further chemical compounds (Bjurman et al., 1997; Nilsson et al., 2004) that may be dispersed in the form of gases, vapours or powders.

An epidemiological study on eye irritation showed that values both low (Litvak et al., 2000) and high (Miguel et al, 2004; Fromme et al, 2007) of relative humidity both seem to increase the deposition of the fine particles.

The concentration of formaldehyde increases with the relative humidity; formaldehyde from wood-based materials, at a given temperature is proportional to relative humidity (Salthammer et al, 1995). However, it was also concluded that the air exchange rate has a greater influence on the concentration of indoor pollutants (Fromme et al, 2007).

Nguyen et al. (2014) shows that the correlations between indoor/outdoor relative humidity and outdoor/indoor absolute humidity are linear:

- the correlation for indoor/outdoor relative humidity is modest (coefficient of Pearson correlation $r = 0.55$, $\beta = 0.39$);
- the absolute humidity has a stronger correlation, however, at warmer ambient temperatures.

The outdoor relative humidity is a weak indicator of indoor relative humidity.

The indoor absolute humidity has a strong correlation with the outdoor throughout the year.

Temperature

It is important first to make a distinction between indoor air temperature and temperature of the different elements (ie. Solid surfaces, leaving air, etc.) in the environment. In fact, the temperature of some surfaces can be different from that of air also of several tens of degrees.

The temperatures of the surfaces present in indoor environments are in general influenced by the following factors:

- directly and indirectly solar radiation;
- transmission of heat through the walls or generated by internal equipments and transmitted to air;
- outside air temperature, wind speed.

The solar radiation has the effect of transmitting the internal heat to the environment through the walls either opaque or transparent. The values of temperature of a wall subject to direct sunlight can easily reach values of temperature of 60° C and beyond. The thermal conduction through the opaque walls is lower than the heat transmitted through the glazed surfaces at the same surface area. When there is heat generation inside it must be taken into account.

Some examples of surfaces in the indoor environment, which can reach temperatures greatly different from those of the air are casings of stoves and ovens, non-insulated parts of chimneys, halogen lamps, internal combustion engines (generators), radiators and thermal distribution systems, boilers and water heaters to gas, iron, hairdryer and refrigerator. Lighting and other equipment are indoor heat sources that contribute to the variation of T_s, and T_a. The UNI EN 13970:2007 estimates between 20 and 200 W per person the values of caloric intake from devices in the office. The energy consumption (due to turning activities) and relative number of occupants can vary the air temperature of 10° C.

As regards the influence of outdoor air temperature in indoor air temperature, Nguyen et al. (2014) shows that the relationship between indoor and outdoor temperatures is generally non-linear:

- at high temperatures there is a strong correlation between indoor and outdoor temperatures (Pearson correlation coefficient, $r = 0.91$, $\beta = 0.41$);
- at lower (cooler) temperatures the correlation is weak ($r = 0.40$, $\beta = 0.04$).

Similar results have also been seen for the perceived temperature.

The temperature has generally influence on both the development of microbiological agents and VOC emissions. However, the range of air temperatures normally present in the environments of life is typical of moderate temperatures and does not vary in the course of the day in a decisive way. Therefore the influence of the air temperature against the emission of chemical and biological agents should be considered as part of the seasons or environments with particular temperature or even in uncontrolled environments thermally sensitive to the external climatic conditions (garages, cellars, attics, etc.). The influence of temperature on pollutants should be considered case by case and it is necessary to distinguish the air temperature from the surface temperature (furniture, walls etc.). The emissions of VOCs by some materials (Salthammer et al., 1995; Wolkoff, 1998) are affected by temperature (and relative humidity), but the dependence is related to the type of VOCs emitted. For many VOCs emitted, the effect of the temperatures is modest or negligible in the range 23-35 ° C, while high at the temperature of 60° C (Sollinger et al., 1994; Van der Wal, 1997). For the formaldehyde it was shown that the emission rate doubles with a increase of temperature of 7° C or an increase in relative humidity from 30 to 70% RH at the temperature of 22° C (Zhang et al., 2007).

Ventilation

Aeration/ventilation can take place in different ways (Guohui, 2000):

- natural, for the difference of pressure between the static pressure and the wind pressure, and/or temperature differences;

- artificial, using fans or other mechanical injection/extraction devices or with air recirculation systems after treatment.

In general, the external air introduced by mechanical systems acts in a "controlled" way, while air for infiltration through doors, windows, walls and others, has random behaviour and is determined by the pressure difference between inside and outside. The amount of infiltrated air depends on the size of the openings, the tortuosity of the paths, the cracks or discontinuities of perimeter. Factors that affect the flow of air are:

- location of the openings;
- opening area;
- type and open mode.

The openings for the passage of air are constituted by:

- opening windows;
- specific devices for ventilation, such as screens and vents;
- doors and gates;
- communicating passages with the outside or with other adjacent inner environments, open occasionally in a stable manner or in an alternating manner with more or less relevant frequency.

The ventilation has effects (Park et al., 2014; Smedje et al., 2011; Sundell et al., 2011) on the concentration and distribution of contaminants in the air and on surfaces, but also on humidity and temperature that in turn affect on pollutants of both chemical and biological origin. Therefore, the ventilation, should allow the removal (Dimitroulopoulou, 2012) and or dilution of the pollutants and moisture generated indoor. Aeration in terms of quality and quantity should be such as not to enter outdoor contaminants and remove or dilute indoor contaminants. However the lack of acceptable limits of concentration of all the indoor pollutants does not allow to determine the amount of aeration (Seppänen and Fisk, 2004). Air velocity, air flow that is localized or general, could cause the solid material lifting or detachment of both chemical and biological agents, from any surfaces on which they adhere; also excessive air currents can influence the release of pollutants from surfaces. It was found that the speed of emission of VOCs from the materials (Zhang Y. and Haghighat, 1997) is function of the air flow conditions at the surface of the material: as the air speed increases, the contaminants from the materials run out more quickly, moreover turbulent flows have a smaller effect on the emission rate.

4.2.1 Primary Air Pollutants: Volatile Organic Compounds

Volatile Organic Compounds (VOCs) comprise a very wide range of hydrocarbons, oxygenates, halogenates and other carbon compounds existing in the atmosphere in the vapour phase. The predominant source is typically through leakage from pressurized systems (e.g. natural gas, methane) or evaporation of a liquid fuel such as benzene from the fuel tank of a vehicle. However, combustion of fossil fuels and incineration processes also give rise to combustion emissions containing some unburned or partially burned fuel fragments that are emitted in the form of VOC. The exhaust pipe of a vehicle may therefore be as important as the fuel tank as a source of VOC emissions. Organic solvents, used for example in paints and adhesives, are designed to disperse in the atmosphere to allow the active ingredients to dry (Gurjar et al., 2004). In Western Europe people may be exposed to indoor air for more than 20 hours per day. The quality of indoor air has a non-negligible impact on human comfort and even health. These two facts explain the growing interest in making available simple yet effective ways for the characterisation of the air indoors. In the past, when human bioeffluents were considered to be the most important pollutants of indoor air, carbon dioxide (C_{02}) was generally accepted as an indicator for IAQ. C_{02} has lost this function partly because today many more sources than human beings emit pollutants into indoor air. In fact the widespread use of new products and materials in our days has resulted in increased concentrations of indoor pollutants, especially of VOCs, that pollute indoor air and maybe affect human health. As a result, the air of all kinds of indoor spaces is frequently analysed for VOCs (Brown et al., 1994). In many scientific publications dealing with VOCs a tendency can be observed not to report the concentrations of all analysed VOCs individually but rather to indicate the total concentration of VOCs under the term "Total Volatile Organic Compounds" (TVOC). One of the reasons is that the interpretation of one single parameter is simpler and faster than the interpretation of the concentrations of several dozens of VOCs typically detected indoors (ECA Report 19, 1997). Literature shows that there is a large variety of ways to calculate a TVOC value from the results of an analysis (De Bortoli et al., 1986; Gammage et al., 1986; Krause et al., 1987; Molhave, 1992; Rothweiler et al., 1992; Seifert, 1990; Wallace et al., 1991). In addition to the mere calculation procedure, differences may arise from the influence of the analytical system including the adsorbent used for sampling, the sampling rate and volume, and the separation and detection system. For all these reasons, published TVOC data are often not comparable and, consequently, there is a need for an agreement on what "TVOC" means from the standpoint of the analyst. Although there is not an agreed definition for TVOC, this entity is often used in the literature to describe indoor air exposures and to estimate health consequences and risks. The justification for this is mostly derived from the work of Mølhave (1986a) and Mølhave et al., (1986b; 1993), who studied the health and comfort effects of a mixture of 22 VOCs, and the subsequent complementing work carried out at the laboratories of the US Environment Protection Agency (US-EPA) using almost the same mixture (Otto et al., 1990; Hudnell et al, 1992; Koren et al. 1992). In view of the large number of known organic chemicals in indoor air there is a tendency to divide them into several classes for easier handling. The division can be made according to their chemical character (alkanes, aromatic hydrocarbons, aldehydes, etc.), their physical properties (boiling point, vapour pressure, carbon number, etc.), or their potential health effects (irritants, neurotoxics, carcinogens, etc.). Following the classification given by the World Health Organization (WHO) working group on organic indoor air pollutants (WHO, 1989), it has become common practice to divide organic chemicals according to boiling point ranges and to discriminate between Very Volatile Organic Compounds (VVOC), Volatile Organic Compounds (VOC), Semi Volatile Organic Compounds (SVOC) and Particulate Organic Compounds (POM), based on points of boiling, with a lower limit between 50-100° C and an upper limit between 240-260° C.

Table 4.2 Classification of indoor organic pollutants (Source: WHO, 1989).

Category	Description	Abbreviation	Boiling-Point Range*	Sampling media tipically used in field studies
1	Very Volatile (gaseous) Organic Compounds	VVOC	< 0 to 50-100	Batch sampling; adsorption on charcoal
2	Volatile Organic Compounds	VOC	50-100 to 240-260	Adsorption on Tenax, graphitized carbon black or charcoal
3	Semivolatile Organic Compounds	SVOC	240-260 to 380-400	Adsorption on polyurethane foam or XAD-2
4	Organic Compound associated with Particulate matter or particulate organic matter	POM	>380	Collections on filters

* Polar compounds appear at the higher end of the range

If a VOC mixture is analysed in indoor air, the result is often expressed as TVOC. This means that one single value is taken to represent the VOC mixture. It is important to note that although the TVOC value is mostly determined by the content of VOC in the air, the analytical conditions are often such that it may include part of what belongs to the classes of VVOC, and SVOC (Table 4.2). Unfortunately, there is no general agreement on which compounds should be included in the procedure to generate the TVOC value. Hence, the number and the nature of VOCs on which the TVOC value is based varies between studies reported in the literature. This is also one of the problems if the TVOC value is used as an indicator of health effects (ECA Report 19, 1997).

The TVOC entity may be used for a number of applications (ECA Report 19, 1997):

1. *Testing of materials.* When testing materials for emission of chemicals, TVOC may be used for categorising or screening the materials, except for substances that should not be found in the air at any concentration. In order to calculate the steady-state concentrations in a given space, the amount of the source (material) and the quantity and quality of the supply air to the space (ventilation) must be known in addition to the emission rate or factor. In the absence of IAQ guideline values for most VOCs found in indoor air, the principle of As Low As Reasonably Achievable (ALARA**)** provides a sensible procedure.
2. *Indicator of insufficient or poorly designed ventilation.* The concentration of any pollutant in a space is a balance between the net emission in the space and what is removed and supplied by the ventilation. If high TVOC concentrations occur in a building, this may either indicate that there are strong indoor or outdoor sources or, if this is not the case, that general or local ventilation is inadequate. In the first case source control measures should be taken. In the second case or if source control cannot be applied, ventilation has to be improved. In these cases TVOC has the same function as CO_2 for human occupancy.
3. *Identification of high polluting activities.* If measured with an instrument with sufficiently high time resolution, TVOC may be used to identify high emitting processes such as working with some old type correction fluids by comparing concentration variations with the activity pattern.

Further agencies, in addition to WHO have proposed different definitions of VOC; the European Concerted Action (ECA) in the document *"Evaluation of VOC emissions from building products: solid flooring materials"* gives a classification of VOC according to the chromatographic retention time: "all volatile organic compounds, eluted in a capillary column coated with 100 % of dimethylpolysiloxane, in the range of retention between the n-hexane (C6) and hexadecane (n-C16) "; this range corresponds to boiling points between 50-290° C.

The *UNI EN ISO 16000-5 Part 5: Sampling strategy for volatile organic compounds (VOCs*) takes over the classification of VOC according to the WHO, while the European Union (EU) with Directive 1999/13 / EC on the limitation of emissions of volatile organic compounds due to the use of organic solvents in certain activities and in certain facilities, implemented in Italy by Ministerial Decree 44/04, defines VOCs as *"any organic compound having at 293,15 K a vapor pressure of 0,01 kPa*[21] *or more, or having a corresponding volatility under the particular conditions of use."* Subsequently in the EU Directive 2004/42 on the limitation of emissions of volatile organic compounds due to the use of solvents in certain paints and varnishes, as well as for vehicle refinishing products, implemented in Italy with Legislative Decree 161/06, defined as VOCs *"any organic compound having an initial boiling point less than or equal to 250° C measured at a standard pressure of 101.3 kPa"* (Fuselli et al., 2013a).

Some VOCs, such as benzene and formaldehyde are classified by International Agency for Research on Cancer (IARC) as carcinogenic - Group 1: Carcinogenic to humans found (IARC, 2012). Moreover the WHO in the guidelines for indoor air quality indicates guide values for a number of pollutants, including certain VOCs, such as benzene, formaldehyde, trichlorethylene, tetrachlorethylene, and naphthalene (the latter also included in the VOC) in addition to nitrogen dioxide, carbon monoxide, polycyclic aromatic hydrocarbons (particularly benzo [a] pyrene) (WHO, 2010). VOCs listed above were considered as priorities for the INDEX project of the European Commission (Kotzias et al., 2005; Koistinen et al., 2008).

Fuselli et al. (2013), in ISTISAN 13/4 Reports, provide a list of the main VOCs that may be present in indoor environments, which is reported in Table 4.3.

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[21] The Pascal (symbol: Pa) is the SI derived unit of pressure used to quantify internal pressure, stress, Young's modulus and ultimate tensile strength. It is defined as one newton per square meter. It is named after the French polymath Blaise Pascal. Common multiple units of the pascal are the hectopascal (1 hPa = 100 Pa) which is equal to one millibar, the kilopascal (1 kPa = 1000 Pa), the megapascal (1 MPa = 1,000,000 Pa), and the gigapascal (1 GPa = 1,000,000,000 Pa). The unit of measurement called standard atmosphere (atm) is defined as 101.325 kPa and approximates to the average pressure at sea-level at the latitude 45° N. Meteorological reports typically state atmospheric pressure in hectopascals (www.wikipedia.org).

Table 4.3 List of major VOCs that may be present in indoor environments (Source: Fuselli et al., 2013a)

CHEMICAL COMPOUND	***BOILING POINT °C***
Aromatic hydrocarbons	
Benzene	80
Chlorobenzene	132
Benzyl chloride	179
1,2,4-Trichlorobenzene	231
1,4-dichlorobenzene	173
Nitrobenzene	211
Toluene	110
Ethylbenzene	136
M-Xylene	139
P-Xylene	138
O-Xylene	144
N-Propylbenzene	159
1,2,4-trimethylbenzene	169
1,3,5-trimethylbenzene	165
2-ethyltoluene	165
Styrene	145
Naphthalene	218
Methylnaphthalene	240-243
Aniline	184
N, N-Dimethylaniline	192
O-Cresol	191
Catechol	240
Phenol	182
Cumene	153
4-Fenilcicloesene	251
Aliphatic hydrocarbons	
N-Hexane	69
N-heptane	98
N-Octane	126
N-Nonane	151
N-Dean	174
N-undecane	196
N-dodecane	216
N-tridecane	235
N-Tetradecane	253

N-pentadecane	270
N-Hexadecane	287
2-Methylpentane	60
3-Methylpentane	63
1-octene	121
1-Decene	170
2,2,4-Trimethylpentane	99.2
1,3-butadiene	-4.5
Isobutene	-7
Octen-3-ol	175
Cycloalkanes	
Methylcyclopentane	/
Cyclohexane	81
Methylcyclohexane	101
Terpenes	
3-Carene	167
A-Pinene	156
B-Pinene	164
Limonene	170
Linalool	198-199
Geraniol	230
A-Terpineol	214-224
Alcohols	
Propanol	96
Methanol	65
Ethanol	78.4
2-propanol	82
1-Butanol	118
2-ethylhexanol	182
Benzyl alcohol	205
Glycols/ethers/glycol ethers	
2-Methoxyethanol	124-125
2-Ethoxyethanol	135
2-Butoxyethanol	171
1-methoxy-2-propanol	118
2-Butossietossietanolo	231
Chloromethyl methyl ether	59
1,2-butylene oxide	63
Methyl-tert-butylether	55.2
Bis-clorometiletere	104

Bis (2-chloroethyl) ether	178
2-phenoxyethanol	245
Aldehydes	
Formaldehyde	-19.5
Propionaldehyde	49
Acetaldehyde	21
Acrolein	52.5
Glutaraldehyde	101
Crotonic aldehyde	102.2
O-Tolualdeide	199-200
M-Tolualdeide	199
P-Tolualdeide	204-205
Methacrolein	69
Butanal	76
Pentanal	103
Hexanal	129
Nonanal	190-192
Benzaldehyde 1	179
4-oxopentanale	70
Ketones	
Methyl ethyl ketone	80
Methyl isobutyl ketone	117
Cyclohexanone	156
Acetophenone	202
3,5,5-Trimethyl-2-cyclohexen-1-one	215
Acetone	56.2
2-Butanone	79.6
6-methyl-5-heptene-2-one	171
Halogenated hydrocarbons	
Chloromethane	-23.7
Trichloroethene	87
Tetrachloroethene	121
Chloroethane	12.5
Hexachloroethane	/
Hexachlorobutadiene	215
2-Chloro-1,3-butadiene	59.4
1,2-dichloropropane	97
1,2-Dichloroethane	83.5
3-chloropropene isomer	44.5
1,1-Dichloroethane	57

Epichlorohydrin	117
1,1-dichloroethene	31.7
Trichloromethane	61.2
Chloroethene	-14
1,1,2-Trichloroethane	114
1,2-Dibromoethane	132
1,1,2,2, -Tetracloroetano	146
1,1,1-Trichloroethane	74
Pentachlorophenol	/
Phosgene	8.2
Vinilbromuro	15.8
Iodomethane	42.4
Tribromomethane	149
Methylbromide	3.6
Carbon tetrachloride	76.7
dichloromethane	40
1,3-Dichloropropene	112
1,2-Dibromo-3-chloropropane	196
1,4-dichlorobenzene	173
Esters	
Ethyl acetate	77
Butyl acetate	126
Isopropyl acetate	85
Vinyl acetate	72.2
Methoxypropylacetate	145-146
2-Etossietilacetate	156
Dimethylphthalate	284
2,2,4-Trimethyl-1,3- pentandiolmonoisobutirrato	244
Methyl methacrylate	101
Ethyl acrylate	100
Beta-propiolactone	162
2,2,4-Trimethyl-1,3-pentandioldiisobutirrato	280
Others	
2-Pentilfuran	> 120
Tetrahydrofuran	67
2-Propennitrile	77.3
Nicotine	247
1,2-propyleneimine	66
Triethylamine	89.5
Carbon disulfide	46.5

Carbonyl sulfide	-50
Methyl isocyanate	59.6
1,1-Dimethylhydrazine	63
Acetonitrile	82
Methylhydrazine	87.8
Ethylenimine	56
2-Nitropropane	120
N-nitroso-N-methylurea	124
N-nitrosodimethylamine	152
Chloride of N, N-dimetilcarbammide	166
Ethyl carbamate	183
N, N-Dimethylformamide	153
N-Nitrosomorfolina	225
Acrylamide	125
Dietilsulfate	208
Dimethyl sulfate	188
Diazomethane	-23
Ethanolamine	171
Oxides	
Ethylene oxide	10.7
Styrene oxide	194
Propylene oxide	34.2
1,4-Dioxane	101
Acids	
Acrylic acid	141
Chloro acetic acid	189
Cresylic acid	202
Acetic acid	118
Hexanoic acid	205
For acetic acid	25

4.2.2 How to monitor VOC

To carry out the monitoring of VOCs, including carbonyl compounds in indoor environments, you need to define an appropriate strategy to ensure accurate measurement of the concentration levels of those pollutants. This activity may be used for a subsequent exposure assessment of this population in these environments (Fuselli et al., 2013a). The levels of VOC concentrations depend on the emission of the sources, the volume of the environment investigated, the chemical reactivity of the substances, the interaction with the surfaces of the materials present in the environment (eg. construction materials, furniture), the outside air and the presence of ventilation systems. (UNI EN ISO 16000-2:2007; UNI EN ISO 16000-5:2006; Bruno et al., 2008). The VOC monitoring activities in indoor environments are mainly conducted to know the concentration levels of VOCs in different function of their chemical-physical and toxicological features to identify the sources of emission. These measures are necessary to:

1. answer to the complaints made by the users of the environments;
2. conduct surveillance activities as a result of recorded situations of pollution;
3. conduct surveillance activities to evaluate the effectiveness of a possible remedy adopted;
4. carry out the collection of specific information to facilitate decision making when assessing the exposure of the population with regard to the various residence times in a given environment;
5. verify compliance with guide values set by the competent authorities.

Duration and frequency of sampling

To plan the monitoring activities and to identify the appropriate sampling and analysis of VOCs techniques, you need to define the time period of observation (duration of the measure) in order to get the concentration value of interest (instantaneous, average hourly, daily average, average weekly, monthly average). If the goal is the knowledge of the maximum concentration value at one time or specific phase, you need to make short-term sampling; but if you want to compare the concentration obtained with a guideline value, the sampling period must be equal to the time associated with the guide value. If the sampling period is less than the duration provided by the guide value, the measurement is only an orientation reference. If the goal is to assess the effectiveness of actions taken, the procedures for monitoring (eg. duration) must be the same before and after the action performed. The sampling period, constrained by the performance of the sampling systems and the limits of quantification of the analytical methods adopted, must be chosen also in relation to:

- the nature and the potential health effects of VOCs considered;
- the concentration of VOCs;
- the emission characteristics of the sources (UNI EN ISO 16017-1:2002).

According to the duration of sampling, it is called short-term or long-term monitoring (periods exceeding several hours).

Reference procedures for monitoring activities

As for the reference procedures of VOC monitoring activities, particular importance has the work done by International and National Certification Bodies (CB) such as the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN) who are committed in the development of specific standardized methods to make samplings in indoor environments. In particular, the standard "EN ISO 16000: Air in confined environments" (EN ISO 16000:2006), which is constituted by more specific parts has been implemented also in Italy by the Italian Unification Boby (UNI). The use of unified and updated official methods may represent a step forward in study and controls activities; this permits also the correct comparison between the different data on IAQ produced at an European level emphasizing the need for a correct application of standards for the sampling phase (eg. the choice of the sampling point, the sampling height, the distance from walls, preliminary activities) that represents the start of the investigation procedure and therefore it affects the final result. Table 4.4 shows a list of EN ISO standards for confined spaces transposed in Italy by the Italian Unification Boby (UNI).

Table 4.4 List of EN ISO Standards for confined spaces implemented in Italy by UNI (Source: Fuselli et al., 2013a)

UNI EN ISO 16000
Air in confined environments
Part 1 General aspects of sampling strategy
Part 2 Sampling strategy for formaldehyde
Part 5 Sampling strategy for volatile organic compounds (VOC)
Part 7 Part 7: Sampling strategy for determination of airborne asbestos fibre concentrations
Part 9 Determination of the emission of volatile organic compounds from building products and furnishing. Emission test chamber method
Part 10: Determination of the emission of volatile organic compounds from building products and furnishing. Emission test cell method
Part 11: Determination of the emission of volatile organic compounds from building products and furnishing. Sampling, storage of samples and preparation of test specimens
Part 12: Sampling strategy for polychlorinated biphenyls (PCBs), polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs) and polycyclic aromatic hydrocarbons (PAHs)
Part 15 Sampling strategy for nitrogen dioxide (NO2)
Part 26 Sampling strategy for carbon dioxide (CO2)
UNI EN ISO 16017
Indoor, ambient and workplace air Sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/capillary gas chromatography
Part 1 Pumped sampling

Part 2 Diffusive sampling
UNI EN 13779 Ventilation for non-residential buildings - Performance requirements for ventilation and air conditioning
UNI EN 14412 Air quality in confined spaces. Diffusive samplers for the determination of the concentration of gases and vapors. Guide for the selection, use and maintenance
UNI EN 15242 Ventilation for buildings: methods of calculation for the determination of air flow rates in buildings including infiltration
UNI EN 15251 Criteria for the indoor environment design and for assessing the energy performance of buildings, with regard to indoor air quality, thermal environment, lighting and acoustics

Active sampling with sorbent cartridges

The sampling tubes containing adsorbent materials, is carried out with suitable suction systems (sampling pumps) appropriately tailored to the required flow (Martin et al., 2010). This sampling procedure is applicable to a wide range of VOCs. It may be useful to perform the replicates of the measures and retain a number of samples for subsequent analysis or duplicate tests. In the case of the subsequent desorption with solvent, this method provides that a known volume of sample air is passed through a tube (small, medium, large) which consists of two sectors denominated analytic and witness sectors, while one or more pipes are used in series in the case of subsequent thermal desorption. The opportunity to use this method depends on the indoor concentrations of VOCs. This method is generally appropriate for concentrations, for single compound, starting from 0.5 g/m$_3$. The adsorbent materials must comply with the specifications in UNI EN ISO 16017-1 and in ISO 16000-6 standards.

4.2.3 Human Exposure to Indoor Air Pollution

The concept of exposure is important, both from the point of view of assessing the impact of a pollutant on health and from that of risk management, which often focuses (directly or indirectly) on reducing people’s exposure. Exposure to Indoor Air Pollution (IAP) is largely determined by the concentration of air pollutants in the environments where people spend their time, and the amount of time they spend within them. On a global scale, the bulk of exposure to air pollution is experienced indoors, as most people spend most of their time there. Assessment of “total exposure” can be essential for the evaluation of health effects from air pollution. The concept of total exposure includes the consideration of outdoor and indoor concentrations of pollutants (and how they vary with time) as well as personal exposure to them (WHO, 2006). Human exposure can be defined as *“the event* *when a person comes into contact with a pollutant of a certain concentration during a certain period of time"* (Ott, 1982).

Conceptually, this occurs along the "environmental pathway" between concentration and dose, as follows:

SOURCE → EMISSIONS → CONCENTRATIONS → EXPOSURE → DOSE → HEALT EFFECTS

"Exposure" should be distinguished from "concentration", which is a quantitative expression of the amount of pollutant within a given environmental medium. High air pollution concentrations do not necessarily result in high exposures. For example, while air pollution concentrations may be very high near an emitting industrial facility, high exposures will occur only if people spend time near the facility. Exposure should also be differentiated from "dose", which refers to the amount of pollution that actually crosses one of the body boundaries. The dose will be defined by the characteristics of exposure (as defined above) as well as a wide range of factors specific to the pollutant (e.g. its solubility or pattern of deposition in the lung) and by physiological factors such as the person's level of activity, and skin condition.

WHO developed and supported a common unit for all the different Burden of Disease (BoD) assessments called Disability Adjusted LifeYear (DALY/year), for the quantification and comparison of a wide variety of health effects (Murray *et al.* 1996, Prüss-Üstün *et al.* 2003 and 2006). The impact of environmental (passive exposure to) tobacco smoke is excluded in following three attributions of the IAQ associated EU-27 BoD to the different diseases, exposures and sources. The reason is that tobacco smoke is, when present, so dominant that even small differences in the assessment of numbers of smokers, how much and where they smoke will destabilise all other assessments (Jantunen et al., 2011). The total calculated BoD attributable to IAQ in EU-26 is ca. 2 million DALYs per year, that is two million years of healthy life is lost annually. This equals about 3% of the total BoD due to all diseases from all causes in Europe. Not all of this loss is preventable, even in principle, partly because all exposures cannot be reduced to zero (e.g. radon, fine Particle Matters or bio-aerosols from outdoor air), and partly because the dose/response and attributable risk coefficients are derived from epidemiological data around the current exposure levels and may not be valid at lower exposure levels. Figure 4.1 shows the prevalence of diseases due to IAP; it can be noted the dominating presence (60%) of Cardio Vascular (CV) diseases, followed by the 35% of the respiratory diseases, asthma, lung cancer, upper and lower respiratory infections and Chronic Obstructive Pulmonary Diseases (COPD).

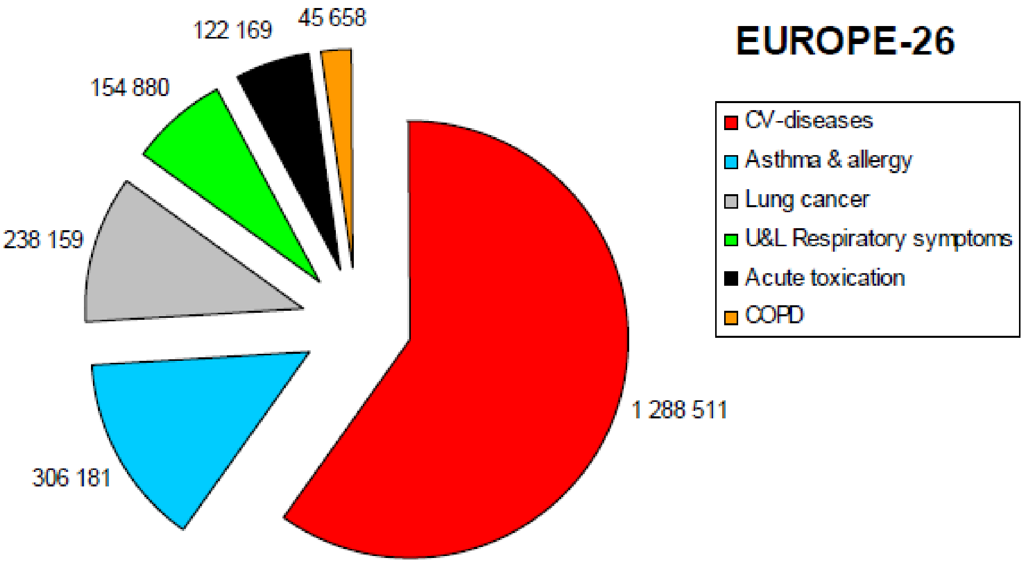

Figure 4.6 The IAQ associated BoD attributed to the key health outcomes (Source: Jantunen et al., 2011).

Jantunen et al. (2011) defined also IAQ associated BoD in the EU-26 countries separating the

contribution from outdoor air and from indoor sources (the latter includes radon) shown in Figure 4.2. The list is rank ordered by the contribution from indoor sources; blue bars define the national BoD in DALY(year*million from indoor exposure) to pollution originating from outdoor air, while red bars define the contribution from all indoor sources. The overall IAQ-BoD levels and differences between specific countries in Figure 4.2 need to be interpreted very cautiously. The underlying public health data are robust and comparable, but the indoor exposure data are more or less incomplete, often non-representative and both quantitatively and qualitatively poorly comparable. However, general observations are that the inter-European differences in IAQ and, respectively, its public health impacts are huge, and the greatest problems in IAQ occur in some Easter European countries.

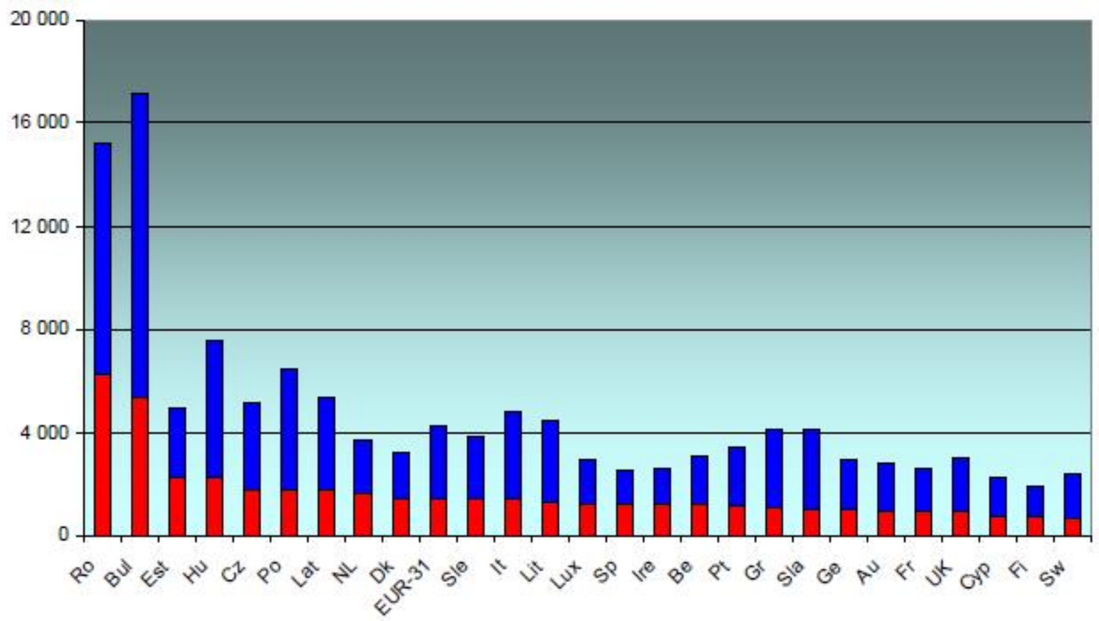

Figure 4.7 IAQ associated DALYs in 26 European countries (2005+/-5 years) (Source: Jantunen et al., 2011).

Figure 4.3 presents the same information concerning the BoD caused by exposures from indoor sources on the map, colour coded for the DALY quartiles. It shows also the assessment results for some non-EU countries. As it can be seen, there is a general dominance of the East European and Balkan countries at the high end and Western and Northern countries are in the low end of the BoD estimates.

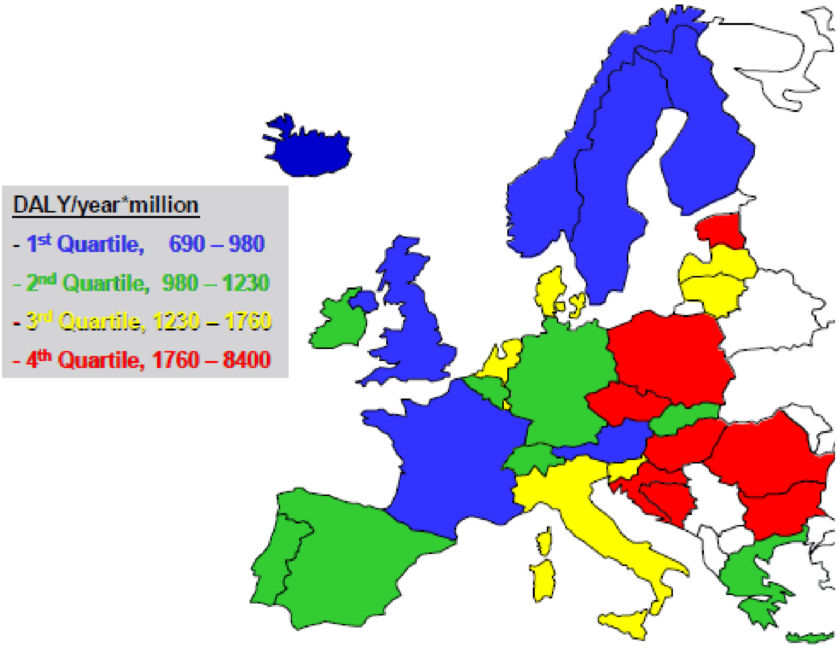

Figure 4.8 European countries divided into 4 quartiles according to BoD caused by exposures from indoor sources (Source: Jantunen et al., 2011).

Most research on the health effects of air pollution has focused on respiratory and cardiovascular effects occurring following inhalation. It should be noted, however, that exposure refers to contact with any part of the human body and does not refer to inhalation alone. Other health-damaging routes of exposure to air pollution include dermal absorption and ocular exposure. For example, acute exposure to airborne pollutants can result in eye or skin irritation. Assessment of exposure to air pollution is the study of how people experience such exposure. Exposure assessment is thus an integral part of air quality management and health impact assessment.

Human exposure occurs where people spend their time. Air pollution levels can show substantial spatial and temporal variation, and people encounter different concentrations as they move from place to place throughout the day. Human exposure is determined by the amount of air pollution in the environments where people spend their time and by the amount of time they spend in them. The environments where people stay are often referred to as “microenvironments”. Technically, a microenvironment is defined as a three-dimensional space where the pollutant level at some specified time is uniform or has constant statistical properties. In practice, however, microenvironments are often taken to be a few selected spaces that are considered to make the greatest contribution to total exposure (WHO, 2006, Haub, 2004).

There is robust scientific evidence indicating that exposure to air pollutants can affect human health in a variety of ways, ranging from subtle biochemical and physiological changes to severe illness and death. WHO and the American Thoracic Society (ATS), (2000) have provided guidance on definitions of what constitutes an adverse effect of air pollution. ATS, for example, has identified a broad range of respiratory health effects associated with air pollution that should be considered “adverse”. These range from death from respiratory diseases to reduced quality of life, and including some irreversible changes in physiological function (ATS, 2000). Since the publication of the second edition of *Air quality guidelines for Europe* in 2000 (WHO, 2000), evidence on the effects of air pollution on health has evolved quite substantially. It was found that the frequency of occurrence of a health effect associated with exposure to air pollution is inversely related to its severity (WHO, 2001). In the presence of exposure, the proportion of the population affected by less severe outcomes is much larger than that affected by the more severe outcomes (Figure 4.4). Subclinical or subtle effects, such as temporary deficits in lung function or pulmonary inflammation, may occur in most of those exposed while mortality may occur in a few. It is usually the more susceptible who suffer the more severe effects.

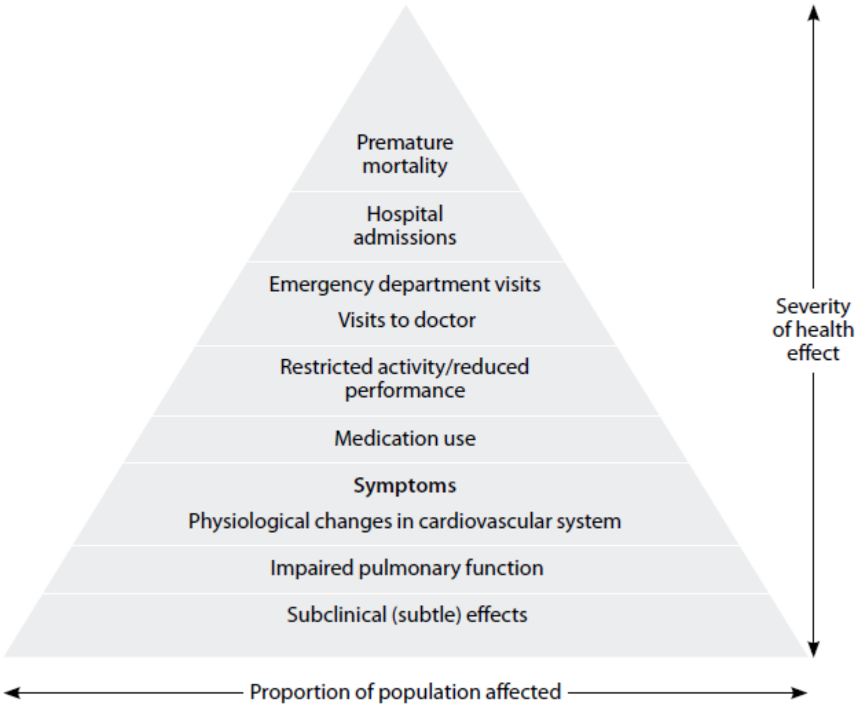

Figure 4.9 Pyramid of health effects associated with air pollution (ATS, 2000)

In detail, for indoor air, the most common pollutants and their respective sources are (ECA, 2006):

- *urban ambient air pollutants* (e.g. NOx, CO, O3, and particles) that enter the building through ventilation or by infiltration (building envelop permeability);
- the majority of *natural allergens* that come from soil and vegetation (pollens, spores) and the outdoor mould;
- most of the respirable particles as well as *semi-volatile compounds* found outdoors, such as pesticides, might also infiltrate inside the building giving high concentration in the indoor environment;
- other contaminants are more specific to the indoor air such as formaldehyde, *volatile organic compounds* (VOCs) and semi-volatile organic compounds (SVOCs). Their indoor sources are emissions from building materials and furnishings, vaporisation of household chemicals, and human activities;
- *tobacco smoke*, re-suspended dust, mineral fibers and biocides are other important indoor pollutants coming from indoor sources. Microbial pollutants are also associated with water damages in the (often hidden) building structures.

The main diseases and adverse health effects which can be caused by indoor air pollutants have been discussed in several reports (ECA, 1991, ECA, 1997, Katsouyanni et al. 1995, 1997, Mølhave et al., 2000a, 2000b, 2002, 2004); IAP can be responsible for an increased occurrence of cancer, chronic and acute pulmonary diseases, upper airways inflammatory diseases, allergic diseases such as asthma and allergies, particularly to house-dust mites, ocular and mucosal reactions, infectious diseases, and respiratory infections, intoxications. Moreover, indoor pollutants can increase the occurrence of frequent and severe diseases such as myocardial infarction and other cardiovascular diseases responsible for a great part of mortality and disability of the population. Less severe, but socially very relevant adverse health effects, include discomfort, odour perception, sensorial irritation and annoyance and the so-called Sick Building Syndrome (SBS)[22], another illness of epidemic nature that may affect occupants of a building.

In fact according to Nicolini et al. (2006), diseases related to exposure to IAP can be attributed to three main groups:

- those with a defined clinical picture and for which it can be identified a specific causative agent, called *Building Related Illness* (BRI). Among the diseases belonging to this group there are extrinsic allergic alveolitis, virus and fungus infections, bronchial asthma, humidifier fever, Pontiac fever and Legionnaire's disease; the diseases in this group are characterized by low incidence between the occupants;
- those characterized by a faded clinical picture, not easily traceable to a single causative agent, called *Sick Building Syndrome* (SBS). The SBS includes an actual pathological condition characterized by multiple symptoms, of a non-specific type such as mucosal, conjunctiva and upper airways irritations and manifestations on the respiratory, digestive, cardiovascular, musculoskeletal, nervous and cutaneous

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[22] The Sick Building Syndrome (SBS) appears with unspecific symptoms related to nose, eye, respiration, skin, and the nervous system. It is a problem that occurs in buildings worldwide. Contrary to building related illnesses that usually affect one or few subjects in a building, SBS tends to affect a larger number of the building occupants. SBS symptoms vary in nature, but there are a small number of characteristic symptoms, which may occur singly or in combination:
- Nasal: most commonly nasal obstruction (usually described as nasal stuffiness) or nasal irritation with rhinorrhoea.
- Ocular: dryness or irritation of the eyes.
- Oropharyngeal: dryness of the throat.
- Cutaneous: dryness and irritation of the skin, occasionally associated with a rash on exposed skin surfaces.
- General manifestations: abnormal fatigue or tiredness, general malaise, headache or heavy-headed feeling.

The important point to elicit is the timing and frequency of the SBS symptoms.The symptoms typical for SBS are unspecific symptoms that may also occur for reasons not related to being in a building.To identify SBS, symptoms have to occur at amuch higher frequency than normal (e.g. 20% vs. 2-4%) and improve on days away from the problem building and re-occur on return to the building.

systems. These disorders affect the great majority of people exposed, by definition 80% or more, occur repeatedly in time, they appear predominantly but not exclusively between the occupants of conditioned buildings. The manifestations are closely related with the permanence in the building and are resolved or fade rapidly with the removal of the same.

- those comprising a syndrome characterized by negative human body reactions to chemicals and environmental influences, present at concentrations generally tolerated by the majority of subjects: *Multiple Chemical Sensitivity* (MCS). The aetiology and pathogenesis of the syndrome are not yet clear: the symptoms are numerous and more or less intense; mainly concern the central nervous system with insomnia or drowsiness, difficulty in concentration, excessive fatigue, depression, anxiety. Other frequent complaints are nasal congestion, altered taste, olfactory hypersensitivity.

In spite of the progress in knowledge that has gained over the past years, there are still uncertainties on the relations between indoor air pollution and health effects. This has several reasons ECA, 2006):

- the complexity and variety of indoor air pollutants in different contexts;
- the limited knowledge about the toxicological and sensorial properties of many indoor pollutants at low concentration levels under the given "chronic" exposure conditions;
- the multi-factorial characteristics of several human diseases that can be caused by a multiple combination of factors;
- the possibility of interaction among pollutants that can have synergistic mechanisms of action (cocktail effect);
- the combination of indoor air risk factors with other environmental agents related to food, water, ambient air, noise, and with personal characteristics of the individual subjects.

To implement strategies aimed at preventing health effects related to indoor air pollution, a key element consists in carrying out a systematic risk assessment and risk analysis for indoor related health effects.

4.3 Indoor Air Quality: guidelines at an European and National level

The European Commission's activity has been characterized over the past twenty-five years by a growing attention to indoor pollution.

It should be remembered that the General Direction Environment of the European Union (EU), in the Document *Cleaner Air for All* (General Direction for the Environment, 2013), drawn up at the conclusion of the Green Week, which took place in the 2013 European air year, have argued that the Indoor Air Quality closed deserved a policy response on its own, alongside the EU's broader strategy on air quality. The same document identifies in the smoking prohibition, as the cheapest and most effective way to improve air quality in indoor environments and thus health.

There are numerous studies funded, as *Towards Health in Air Dwellings in Europe Project* (THADE) (Franchi et al., 2004), *Indoor Air Quality and Health Effects Project* (EnVIE) (De Oliveira et al., 2009), *European Indoor Air Monitoring and Exposure Assessment Project* (AIRMEX) (Kotzias et al., 2009), EXPOLIS Study (Jantunen et al, 1998), which have tried at least in part, to increase the knowledge framework on the subject and to set priorities or objectives to be achieved. In dealing with the complex issues related to confined spaces under the concerted Action *European Collaborative Action* (ECA) on *Indoor Air Quality and its Impact on Man* currently *Urban Air, Indoor Environment and Human Exposure*, the European Commission implemented a multidisciplinary collaboration among scholars, who worked in an integrated manner on aspects related to indoor environments (source, quality and quantity of chemical and biological products, thermal comfort, energy consumption and ventilation) making a series of reports/specific monographs; Table 4.5 shows a list of reports produced by ECA.

As for the emission levels produced by the materials, in Europe, there has been in recent years a growing interest in making compulsory labeling with indication of their emissions before they are placed on the market (Fuselli et al, 2013b).

Table 4.5 Chronological list of ECA reports on Indoor Air Pollution (Source: Fuselli et al., 2013b)

Number of Report/Year	*Title*
Report 01 1988	Radon in *indoor* air
Report 02 1989	Formaldehyde emission from wood-based materials: guideline for the determination of steady state concentrations in test chambers
Report 03 1989	*Indoor* pollution by NO2 in European countries
Report 04 1989	Sick building syndrome a practical guide
Report 05 1989	Project inventory

Report 06 1989	Strategy for sampling chemical substances in *indoor* air
Report 07 1990	*Indoor* air pollution by formaldehyde in European countries
Report 08 1991	Guideline for the characterization of volatile organic compounds emitted from *indoor* materials and products using small test chambers
Report 09 1991	Project inventory 2nd updated edition
Report 10 1991	Effects of *indoor* air pollution on human health
Report 11 1992	Guidelines for ventilation requirements in buildings
Report 12 1993	Biological particles in *indoor* environments
Report 13 1993	Determination of VOCs emitted from *indoor* materials and products. Interlaboratory comparison of small chamber measurements
Report 14 1994	Sampling strategies for volatile organic compounds (VOCs) in *indoor* air
Report 15 1995	Radon in *indoor* air
Report 16 1995	Determination of VOCs emitted from *indoor* materials and products; second interlaboratory comparison of small chamber measurements
Report 17 1996	*Indoor* Air Quality and the use of Energy in Buildings
Report 18 1997	Evaluation of VOC emissions from building products: solid flooring materials
Report 19 1997	Total volatile organic compounds (TVOC) in *indoor* air quality investigations
Report 20 1999	Sensory evaluation of *indoor* air quality
Report 21 1999	European Interlaboratory Comparision on VOCs emitted from building materials and products
Report 22 2000	Risk assessment in relation to *indoor* air quality
Report 23 2003	Ventilation, good *Indoor* air quality and rational use of energy
Report 24 2005	Harmonisation of *indoor* material emissions labelling systems in the EU
Report 25 2006	Strategies to determine and control the contributions of *indoor* air pollution to total inhalation exposure (STRATEX)
Report 26 2007	Impact of Ozone-initiated Terpene Chemistry on *Indoor* Air Quality and Human Health
Report 27 2012	Harmonised Framework for *Indoor* Material Labelling Schemes

In the latest report *Harmonised Framework for Indoor Material Labelling Schemes*, the growing efforts and diversity of approach and methods adopted by the bodies of the various European countries, in the definition of the tests and the emissions estimates are highlighted. This report is a reference point for harmonizing the different labeling systems of the developed materials and for the identification of possible overlapping in the existing test methodologies, the use of TVOC parameters and sensory evaluation (ISO 16000-28). The indications of the standards for use issued by the CEN and ISO committees, which have developed specific parts of EN ISO 16000: Part 9, 10, 11, 23, 24, 25 have been shown. Among the most important studies carried out at an European level there is the project *Critical Appraisal of the Setting and Implementation of Indoor exposure Limits in the EU Project (*INDEX) coordinated and implemented by the Joint Research Centre in Ispra (Varese) Italy, that could make use of experts in various fields (Kotzias et al., 2009).

The experience developed on the INDEX project was also used in the work of the WHO for the preparation of guidelines for Indoor Air Quality (WHO, 2010). The attention that for many has been given to the subject of indoor environment, has led some international scientific bodies, including the WHO, to prepare for the European Region a set of guidelines for Indoor Air Quality, relating to a number of pollutants, often present in confined spaces for which the scientific findings on the effects on humans have been deemed sufficiently secure. Table 4.6 shows main current EU policies/guidelines to prevent exposure to indoor hazards.

Table 4.6 Main current EU policies /guidelines to prevent exposure to indoor hazards

	POLICY	*DESCRIPTION*	*YEARS*
AMBIENT ENVIRONMENT	**Clean Air for Europe Directive (CAFE, Directive)**	SO2, NO2, NOx, PM, Pb, benzene, CO, O3)	2008
	2008/50/EC		
	2004/107/EC	(As, Cd, Hg, Ni, PAH),	*2007*
	WHO Air Quality Guidelines, Global Update 2005 (WHO, 2006a)	The WHO air quality guidelines offer guidance on reducing the effects on health of air pollution. This book presents revised guideline values for the four most common air pollutants - particulate matter, ozone, nitrogen dioxide and sulfur dioxide - based on a recent review of the accumulated scientific evidence. The special case of indoor air pollution is explored.	2006
	WHO guidelines for indoor air quality: dampness and mould	A comprehensive overview of the scientific evidence on the health problems associated with this ubiquitous pollution and provides WHO guidelines to protect public health. It also describes the conditions that determine the presence of mould and provides measures to control its growth indoors.	2009
	WHO guidelines for indoor air quality: selected pollutants	Guidelines for the protection of public health from a number of chemicals commonly present in indoor air. The substances considered – benzene, carbon monoxide, formaldehyde, naphthalene, nitrogen dioxide, polycyclic aromatic hydrocarbons (especially benzo[a]pyrene), radon, trichloroethylene and tetrachloroethylene have indoor sources, are known for their hazardousness to health and are often found indoors in concentrations of concern to health. For each substance, the chapter covers a general description, the sources and pathways of exposure,	2012

		the indoor–outdoor relationship, kinetics and metabolism, the health effects, a health risk evaluation, the guidelines, a summary box and references.	
	Radon levels are regulated by Directive 90/143/Euratom	Recommendation on the protection of the public against indoor exposure to radon	1990
	96/29/Euratom (EU Basic safety standard for radiation protection)	Laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionising radiation	1996
BUILDING EMISSION	**REACH**		2006
	2006/121/EC		
	Construction	from building materials	
	product directive		1989
	89/106/EEC		
	Classification of indoor climate produced by FiSIAQ		
	WHO guidelines for indoor air quality: dampness and mould 2009	water system	2009
	90/396/CE;	fixed hose equipment/appliance	1990
	92/42/EEC;	Indoor fuel burning	1992
	92/42/EEC	Central heating boilers	2004
	COM 2004/8/EC	Environmental and economical benefit	2005
	COM 2005/32/EC	Eco-design requirements	
VENTILATION	**EN 13779**	European standard for ventilation and room conditioner	2007
	EN 152151	Parameter related to energy performance of buildings	2007
	CEN CR 1752	Design criteria for ventilation	1996
	VDI (6022 blat 1	Professional standard guidelines which	2006/7
	(2006) 2 (2007))	are applied beyond national borders	2007
	RHEVA (2007)		2007
	ASHARE (2007)		
CONSUMER PRODUCTS	**REACH directive;**	Furnishing, interior surface materials and	2001
	GPSD (2001/95/EC)	electrical appliances	
	Directive 2004/42/CE	safety of products	2004
	2002/95/CE;	Covers paints and varnishes	2002/05
	2005/32/EC	Covers electrical appliances	2005
	REACH a	Cleaning and other products	2006
	GPSD /2001/95/CE		2001
OCCUPANTS BEHAVIOUR	**VDI 6022 (2006-7) and ASHARE 62,2 (2007) ISIAQ (1966);**	Maintain ventilation	2007
	EN 15239.2007	European standard	2007
	EN 1524:2007	For energy inspection of building	2007

	EPBD (2002/91/EC) **(Smoking ban)**	For conditioning system; smoking (cooking, hobbies, pets)	2002

In the European context, several countries in recent years have enabled working groups with a specific mandate to develop guiding values for air quality in confined environments; among these there is ***Germany***, with a Working Group on *Indoor Guideline Values of the Federal Environmental Agency and the States Health* (AG IRK/AOLG 2008) (Fuselli et al., 2013b), that used a methodology from Lowest Observed Adverse Effect Level (LOAEL), or lower level of exposure to a toxic substance, for which negative effects on health, introducing safety factors were observed. A different display is the one of the ***UK***, with the Commission on the effects of air pollution to human health called *Committee On The Medical Effects Of Air Pollutants*, (COMEAP) (COMEAP, 2004), that has drawn up guide values based on the WHO studies.

France was among the first to respond with a series of integrated legislation, to the growing problems related to indoor environments and air pollution; it introduced into its legislation, with *Décret no 2011-1727 du 2 décembre 2011 relatif aux valeurs-guides pour l'air intérieur pour le Formaldehyde et le benzene*, guide values for formaldehyde and benzene, with different dates of entry into force of the same, with a timing of implementation for the new values staggered in time, in detail:

- from 1 January 2015 for confined spaces such as recreation centers, swimming pools, health facilities, social services and nursery with children under six years;
- from 1 January 2018 for elementary education institutions;
- before 1 January 2020 to juvenile detention facilities and education institutions or vocational training of first and second degree;
- from 1 January 2023 for all other confined spaces.

The *Agence Nationale de Sécurité Sanitaire de l'Alimentation, de l'Environnement et du Travail* (ANSES) has continued the development of new guide values for indoor pollutants with the publication of the document "*Proposition de valeurs de qualité d'air guides for intérieur : chlorure de vinyle, Acetaldehyde, dioxyde d'azote, Acrolein*".

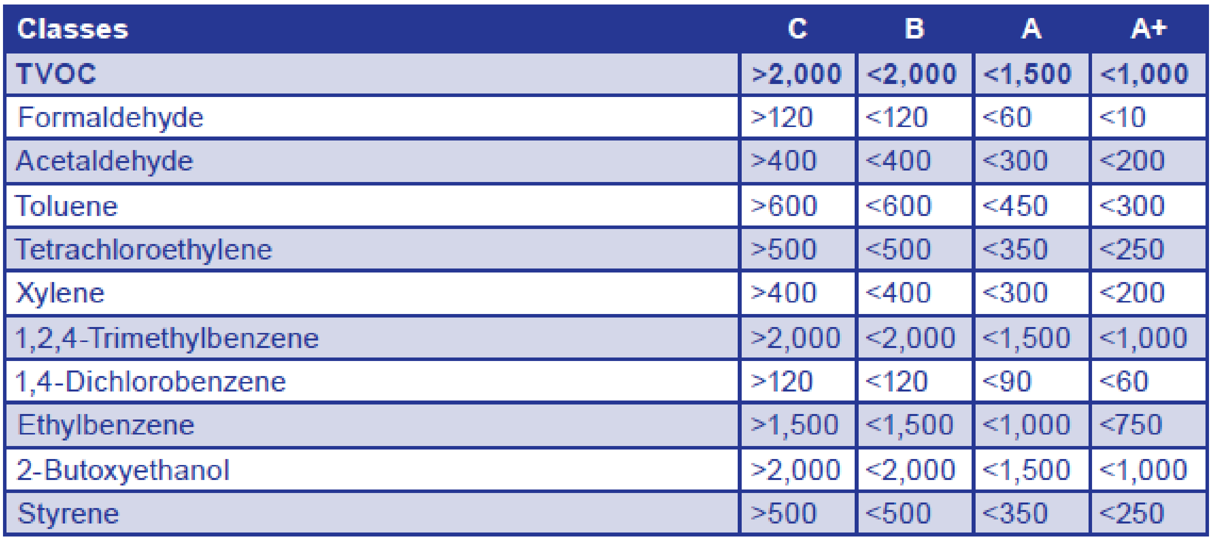
France is also considering to eliminate periodic measurements of Indoor Air Quality for those institutions and/or communities that will implement specific prevention according to rules to be laid down in a guide of good practice of the Ministry of Ecology.

With the decrees of 23 March 2011 n. 2011-321, and of 19 April 2011 concerning the labelling of construction and decoration products, with an indication of their emissions in terms of airborne pollutants, the French regulation foresees a mandatory labelling of (http://www.eurofins.com/):

- walls, ceiling, floor coverings and coatings;
- panels for rooms partition and suspended ceiling;
- insulation products;
- doors and windows;
- all products used for the installation of the products listed above.

The regulation does not cover untreated metal or glass, lockers, iron, screws etc. This regulation foresees that from 1 January 2012, any covered product newly placed on French market has to be labelled with emission classes based on their emissions after 28 days, as tested with ISO 16000 and calculated for European Reference Room. Products that are in French market before that date need to be labelled from 1 September 2013.

The limit values for the emission classes are listed in Figure 4.5, all given as μg/m^3 in the European Reference Rooms after 28 days ventilated storage.



Classes	C	B	A	A+
TVOC	**>2,000**	**<2,000**	**<1,500**	**<1,000**
Formaldehyde	>120	<120	<60	<10
Acetaldehyde	>400	<400	<300	<200
Toluene	>600	<600	<450	<300
Tetrachloroethylene	>500	<500	<350	<250
Xylene	>400	<400	<300	<200
1,2,4-Trimethylbenzene	>2,000	<2,000	<1,500	<1,000
1,4-Dichlorobenzene	>120	<120	<90	<60
Ethylbenzene	>1,500	<1,500	<1,000	<750
2-Butoxyethanol	>2,000	<2,000	<1,500	<1,000
Styrene	>500	<500	<350	<250

Figure 4.10 Limit values for VOC emissions in France (Source: Ministère de l'écologie, du développement durable, des transports et du lodgement (2011)).

The label on the products includes a letter indicating the highest (worst) emissions class of the listed individual substances and the TVOC (Figure 4.6).

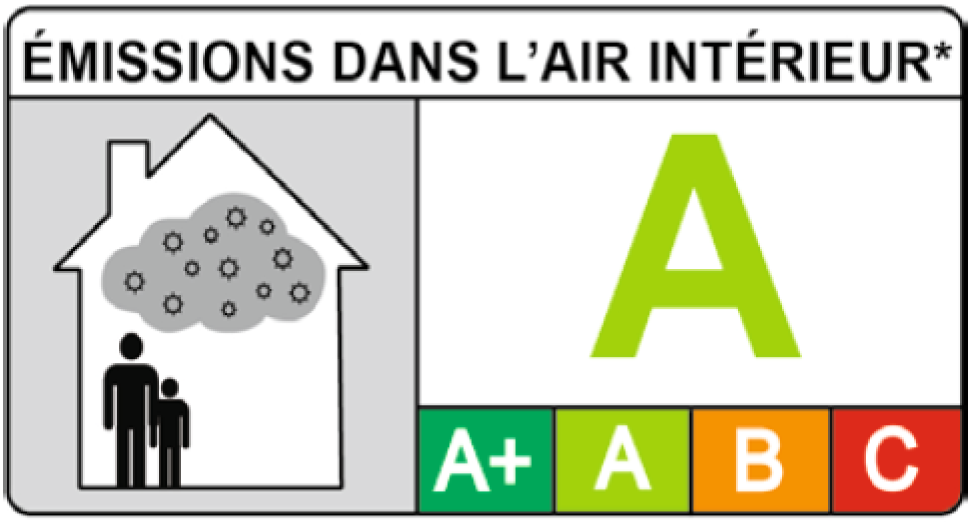


Figure 4.11 Label for VOC emission in France (Source Ministère de l'écologie, du développement durable, des transports et du lodgement, 2011).

Moreover France in late 2013, has come up with a new proposal called *Plan d'action sur la Qualité de l'Air intérieur* (www.sante.gouv.fr) for the short, medium and long term. This proposal highlights that actions on energy efficiency of buildings will be accompanied by special vigilance on Indoor Air Quality; it introduces a whole series of actions such as for example (Santarseni et al., 2015):

- the need to anticipate the obligation of monitoring IAQ in hospitals and healthcare facilities, originally scheduled for 2023;
- the labelling of the products used for cleaning and for deodorants (incense, candles, etc.);
- the sale ban of incense that emit more than 2 g/m$_3$ of benzene;
- actions to improve the Indoor Air Quality on trains and subways;
- for furniture and furnishings present in schools and kindergartens, a voluntary agreement will be provided, for the complete absence of some carcinogenic, mutagenic or toxic substances;
- the development of new reference values for indoor air;
- the improving in knowledge on the presence of nanomaterials in indoor environments, the strengthening of training on workers and on population and the evaluation of the performance and activity of industrial innovation.

Also the ***Netherlands*** with the work of the National Institute for Public Health and the Environment (RIVM) (RIVM, 2007), got the guide values from Maximum Permissible

Risk (MPR), which represents the level of exposure to a toxic substance for which there aren't adverse health effects.

Among the Nordic countries, ***Finland***, with a working group coordinated by the Ministry of Social Affairs and Health, has developed guiding values for 5 substances such as ammonia, carbon monoxide, carbon dioxide, hydrogen sulphide and PM_{10}, which have been proposed in the decrees of the *Ministry of the Environment Housing and Building Department D2 National Building Code of Finland-Indoor Climate and Ventilation of Buildings Regulations and Guidelines* (www.ym.fi), in force since 1 October 2003. As for the other pollutants guide values can be derived using the approach of a 1/10 of the limits for industrial environments (OEL). If there are more substances, the following formula is applied: $\Sigma (Ci / OEL) > 0.1$, where Ci is the measured concentration of the individual substance. The guideline values for indoor environment apply to buildings that are occupied for at least six months and where the ventilation system is constantly kept on.

Alongside these references there are those developed by the Finnish Society of Indoor Air Quality and Climate Classification (FiSIAQ, 2001), an initiative promoted and financed by the Ministry of Environment in collaboration with experts from the producers of the materials sector, which led to the identification of the target values defined as S1, S2 and S3.

As for ***Belgium***, however, the government has fixed by decree entered into force on 1 October 2004, the reference values for 15 substances (such as acetaldehyde, formaldehyde, total aldehydes, benzene, asbestos, carbon dioxide, nitrogen dioxide, toluene, ozone, carbon monoxide, volatile organic compounds, trichlorethylene, tetrachlorethylene, PM10 and PM2.5); for 5 of these substances a category of concentration levels defined as intervention values or concentrations of substances corresponding to a maximum allowable level of risk that ca not be exceeded, has been identified.

In ***Austria*** in the late 90s, the Ministry of Environment in collaboration with the Academy of Sciences, established a multidisciplinary working group to draft guideline values for indoor environments, using a methodology from *No Observed Adverse Effect Level* (NOAEL), that is to say, dose without adverse effect observed for exposure to a toxic substance. With this approach, guide values were developed for 6 substances, such as formaldehyde, styrene, toluene, carbon dioxide, volatile organic compounds and trichloroethylene.

Even ***Portugal***, in April 2006, by Decree No. 79, of the Ministry of public work, transport and communications fixed the maximum concentrations reference for 6 substances such as

PM_{10}, carbon dioxide, carbon monoxide, ozone, formaldehyde, and TVOC. The decree in force since June 2006, establishes the obligatory nature of the monitoring related to the type and size of the building, and provides corrective action within 30 days, if the result of monitoring shows that the concentrations of pollutants have levels that are greater than predicted by article 29 paragraph 8 of the decree. In this case also the owner or tenant must submit, within the next 30 days, the results obtained by the new measurements. If the necessary conditions are not met, the owner or the tenant, is subject to the sanctions provided in the decree, that is the immediate closure of the apartment or the payment of a fine (Fuselli et al., 2013b).

In all countries, the guide values proposed, are related by the relevant methods of sampling and analysis developed or received by the various national training bodies, such as the German Institute for Standardization called *Deutsches Institut für Normung*, (DIN), *Association Française de Normalisation* (AFNOR), *Bureau de Normalisation* (NBN), *Finnish Standards Association* (SFS), *Austrian Standards Institute* (ASI), *Nederlands Instituut Normalisatie* (NEN), *the British Standards Institution* (BSI), for a proper evaluation.

4.3.1 Indoor Air Quality in Italy

Even in Italy there is a growing awareness of the Indoor Air pollution problem, and in recent years many efforts have been done, even if until now, it was not possible to draw up a national law on IAQ. The Italian scientific community is interested in this issue since 1990, when it was established the first *National Commission for Pollution of Confined Spaces*; this Commission, recommended a series of interventions and proposals including (Santarsiero et al., 2015):

- the formulation of guidelines on air quality levels of different pollutants;
- the development of rules on pollution sources and standards for materials and products with allowed emission limits;
- the oreparation of remedial action.

Such proposals remained on a level of study and never followed through a national legislation. After that various commissions and working groups have been set up, with the aim to establish concrete benchmarks, which helped both public and private operators, to respond on different specific topics. Important initiatives have been undertaken for the promotion of health in indoor environments and for the primary prevention of effects of pollutants on health. The indoor Commission, established by the Ministry of Health with Ministerial Decree 8.4 in 1998, conducted a national survey on indoor pollution in Italy and identified priority areas for action. On the basis of information provided by the Commission, the Ministry has developed specific measures for the control of the main indoor pollutants, such as tobacco smoke, radon, Legionella and allergens,

The agreement signed in 2001 between the Ministry of Health, and autonomous Regions and Provinces, concerning "Guidelines for the protection and promotion of health in confined environments" (Agreement September 27, 2001), is a further step forward, but still far from providing signs of times, procedures, and the guiding values or standards to be adopted for IAP. In any case, it has contributed to the development of a set of guidelines and procedures that have filled in the specific complex issues, such as (www.gazzettaufficiale.it):

- guidelines for the predisposition of technical protocols for predictive definition on air-conditioning systems;
- operating procedure for the assessment and management of risks linked to hygiene of air treatment plants;
- guidelines for school-based prevention of risk factors for indoor allergies and asthma.

Moreover the Ministry of Health in 2009 has also funded a specific three-year project of the Center for Disease Prevention and Control called *Exposure to indoor pollutants: Guidelines for the evaluation of risk factors in the school environment and the definition of measures for the protection of health* with the aim to implement in primary and secondary schools of first instance specific guidelines on the control of risks due to poor IAQ. Subsequently, with the relation between State and Regions of 29 April 2010, the National Plan of Prevention 2010-2012 was launched, that included targeted strategies to improve the hygienic requirements of IAQ in schools and other areas frequented by children.

Finally, as part of Global Alliance against Chronic Respiratory Diseases for Italy (GARD-I) , a voluntary alliance among the Ministry of Health and the major associations of patients and Italian scientific societies was set, in order to combat chronic respiratory diseases in our country. In the GARD-I it was established an ad hoc working group for indoor prevention in schools, which conducted an analysis of the context on indoor pollution situation in Italian schools, their relative risks to health and proposed technical guidance for an effective implementation of prevention strategies based on evidence. These initiatives are consistent with the Government Gaining Health Program, approved by the

Council of Ministers February 16, 2007, with the aim to promote health in all policies and to have a positive impact on lifestyles and the environment of child and teenager (Fuselli et al., 2013).

Of particular importance for the development of reference documents, is the activity of the National Institute of Health (ISS), which since 2010 has enabled the "Nationsl Group of Study on Indoor Pollution. This study group has already developed reference documents for the monitoring strategies of:

- Volatile Organic Compounds (VOCs) in indoor environment (Fuselli et al., 2013);
- biological pollution in indoor air environment (Bonadonna et al., 2013);

reporting a series directions on how to operate in such environments, on preliminary operations, the choice of the points for the appropriate sampling, on technical sampling, and on the preservation and analysis of samples.

4.4 Indoor Air Qualiy and 3D printing

Three-dimensional (3D) printers are gaining popularity as rapid prototyping and small scale manufacturing devices. The development of low-cost desktop versions has made this technology widely accessible for use in home and office settings. Even if there are several types of 3D printing technologies (Afshar-Mohajer et al., 2015), most desktop printers use the Fused Deposition Modeling (FDM) technique in which a heated nozzle melts a solid thermoplastic filament, usually Acrylonitrile Butadiene Styrene (ABS) or Polylactic Acid (PLA), and deposits multiple thin layers of extruded plastic to form a solid three-dimensional shape (Kim et al., 2015; Ragan, 2013; Stephens et al., 2013).

Primary differences between ABS and PLA based printers are feedstock origin and nozzle and baseplate temperatures during operation. PLA is a biodegradable, corn-based plastic that prints at nozzle temperatures of ∼180 °C and baseplate temperatures near room temperature. ABS is a stronger thermoplastic that typically prints at ∼220 °C nozzle temperatures and ∼80 °C baseplate temperatures in most commercially available devices (Stephen et al., 2013). Other thermoplastic feedstock sources include Polyvinyl Alcohol (PVA), Polycarbonate (PC), and High-Density Polyethylene (HDPE), although they are not widely used in commercially available devices (Ragan, 2013). It is well known that office equipment such as laser printers and photocopiers that consume thermoplastic toner powder are emitters of Ultrafine Particles (UFP) with a diameter of less than 100 nm and various chemicals (Destaillats et al., 2008).

Even during the melting process of 3D printers, plastics both emit gaseous substances, commonly called Volatile Organic Compounds (VOCs), and UFP of size order of several tens of nm. Already in the mid-90s the study of Contos et al., (1995) has shown that moderately high temperature (e.g., 170–240 °C nozzle temperatures) thermal processing of thermoplastics in large scale industrial extrusion equipment, both gases and particles are emitted during operation and these findings have been confirmed in recent studies (He et al., 2007; Unwin et al., 2012; Azimi et al., 2016). Primary gas-phase products of ABS thermal decomposition at very high temperatures have been shown to include carbon monoxide and hydrogen cyanide, as well as a variety of volatile organics (Rutkowski and Levin, 1986). Exposure to thermal decomposition products from ABS has also been shown to have toxic effects in both rats (Zitting and Savolainen, 1980) and mice (Schaper et al., 1994).

Through laboratory tests (Schaper et al., 1994) the variation of VOC concentration during the printing process of plastics has been monitored and studies have shown, that ABS is more toxic than PLA, but that the PLA under certain conditions is not free from harmful emissions to health issues, especially if melted at temperatures over 200 ° C (Rutkowski and Levin, 1986; Kopinke et al., 1996; Liu et al., 2010). The work of Stephens et al., (2013) compared the amount of nanoparticles produced in a first case in which there were two printers with only PLA filaments with another case in which the same two printers were together with three printers employing filaments of ABS. The results of this comparison showed that the concentration of particles emitted in the second case ranged from about 3 to 30 times the concentration of particles emitted from only printers working with filaments of PLA. The test also wanted to highlight that after the shutdown of the printers, the decay time, that is the time necessary for halving the concentration of particulate matter in the environment, varied according to the size of the nanoparticles and that such period ranged between about 10 to 30 minutes to get a healthy "enough" environment.

Non-manufacturing environments such as offices, homes, classrooms, and libraries are usually designed for occupant comfort, not exposure mitigation. Hence, use of 3D printers in non-manufacturing or private settings potentially represents another contribution to UFP exposure for indoor workers and the general public to particles with potentially unique physicochemical properties from these other known sources (Yi et al, 2016).

Toxicological studies confirmed that UFP penetrate into the alveolar region of the lungs and produce inflammatory responses (Carosino et al., 2015; Oberdorster, 2001), headache

(Chamng et al., 2015), and cardiovascular effects (Lee et al., 2014; Nurkiewicz et al., 2008).

Further studies (Nemmar et al., 2002; Akerman et al., 2002; Nel et al., 2006) have shown that the nanoparticles are able to enter the bloodstream in the human blood system in under a minute. Once absorbed at a respiratory, cutaneous and gastrointestinal level, the particles may reach the systemic circulation and subsequently migrate in different organs and tissues.

Therefore as stated by Yi et al., (2016), since most desktop 3D printers are not equipped with exhaust ventilation or filtration accessories and users in home and public settings typically do not utilize appropriate personal protective equipment, it is important to characterize the physicochemical properties of 3D printer emissions to understand exposure potential and risk as early on as possible in the adoption of this technology to non-industrial settings.

To this end, in collaboration with the laboratory Cosmob Spa, this study performed air sampling of indoor air environments, while a 3D printer was under function, with different types of plastic materials (PLA, ABS, PET) in order to understand and assess the potential dangerousness to human health of this technological tool.

4.5 The research: are 3D printing materials nocive for human health?

4.5.2 Methodology

It is possible to distinguish the VOC sources according to the time trends of the emission levels. In general, the sources can be distinguished in continuous or intermittent (UNI EN ISO 16000-5:2006). The continuous sources can in turn be distinguished in constant or irregular sources. Continuous-constant sources are those that generate uniform emissions over time, for example furnishing materials that emit formaldehyde for long periods of time or those used in construction such as linoleum, cork, parquet, wood finishes, etc. Continuous-irregular sources are those that generate emissive flows that decrease over time, also depending on the variations in microclimatic conditions (air speed, humidity and ambient temperature). An example is represented by a wall subjected to the application of paints and / or adhesives (in particular the emission coming from organic solvents and the degradation of products for the protection of materials). Intermittent sources can be either recurring or occasional. A typical example of an intermittent source is cooking food. The products used in the cleaning of rooms belonging to the airfreshener family (deodorants, scented candles, incense sticks, fragrances, wood oils, etc.), are typical sources with an intermittent-occasional emissive profile. Emissions from processing of 3D printers is a typical example of a recurring intermittent source. Data collection in our research was performed by means of a membrane pump through an activated carbon vial (following the line of the ISO standard 16000-3: 2011), on plastics such as Polylactic Acid (PLA), Polyethylene Terephthalate (PET) and Acrinolitrile Butadiene Styrene (ABS). The air quality analyses were carried out at Cosmob S.p.A. and I was joined by my chemical colleagues, Christian Gabbani and Ainara Melus Regidor.

The sampling was carried out firstly when the 3D printer was on and brought to the temperature required for use, with the material inserted in the extruder but not in operation (it is said that the sampling was done in a white environment), and later while the same was working.

As in our research the objective is the knowledge of the maximum concentration value of VOCs when the 3D printer is working, short-term sampling was carried out, thus performing short-term monitoring (80 minutes for each sampling).

As regards this activity, an initial screening was carried out on different types of materials (PET, ABS, PLA, and PLA layer ABS) for the identification of critical emissions, and on two white environments (ABS and PLA) to evaluate subsequently if these values had been stable on several production lots.

Subsequently, 5 vials of "white ABS" and 5 of "white PLA" were sampled, that is, we analyzed the level of VOC emissions of the printer with heated plate according to the temperatures necessary to print the plastic materials of ABS and PLA, in such a way as to be able to compare such data with those present when the printer is operating; white PET was not sampled since the processing temperature of the PET is very similar to that of the PLA therefore it was considered possible to compare the values of the PET with the white PLA. Subsequently the air was sampled even when the printer was working, while it was making objects both with PET plastic material and with PLA and then with ABS.

Sampling was carried out from November 2016 to September 2017. The data sampled by the vial, were then sent to the laboratory for analysis Analysis Control, which has provided the results. The obtained data were elaborated, trying to figure out the average composition of substances emitted during the 3D printing process of these plastics, making a comparison between the values of the "white environment" and those of the printer in operation. It has also been compared the values obtained with those present in the French decree (Fig. 4.5), so as to be able to understand if these values are above or below the threshold values defined by the decree. It has been taken as reference the values of the French decree, because, as mentioned in paragraph 4.3.1 in Italy there is no reference legislation that defines threshold values for indoor environments. Finally, it has been tried to identify for each sampled material the "fingerprint" of the same, considering the percentages of presence of the substances analyzed on each (and taking into the fingerprint only those materials that are present for a percentage that is higher or equal to 5%), with the possibility to carry out an evaluation of the harmfulness of the material.

4.5.3 Results

4.5.3.1 TVOC, which substances are nocives?

Before starting with the analysis of the presence of VOC on the materials used to print objects with 3D printing, it is necessary to understand which are the substances which compose VOC that can be dangerous for human health. This is shown in Table 4.7, where the main substances which compose the Total Volatile Organic Compounds (TVOC) are shown. These are divided into three different type of dangerous substances: carcinogens substances defined with the code HP7, that are substances that can cause cancer; teratogenic substances (HP10) which can cause fetal malformations and finally mutagenic substances (HP11) that can cause mutations or alterations in the genetic material. As it can be seen in Table 4.7 some of the substances which compose TVOC are not considered dangerous at all for human health and therefore they do not fall into these three categories listed above.

Table 4.7 TVOC: nocives substances

	Carcinogens (HP7)	**Teratogenic substances (HP10)**	**Mutagenic substances (HP11)**
Volatile Organic Compounds (TVOC)			
Benzene	X		X
Toluene		X	
Ethylbenzene			
Styrene		X	
Xylenes			
N-Hexane		X	
Cyclohexane			
1,2-Dichloroethane	X		

Trichlorethylene	X		X
Tetrachlorethylene	X		
Dichloromethane	X		
Ethanol			
Isopropanol (Isopropyl alcohol)			
Isobutanol			
N-Butanol (n-butyl alcohol)			
Ethyl acetate			
Isobutyl			
N-Butyl acetate			
Acetone			
Cyclohexanone			
Methyl isobutyl ketone (MIK)			
Methylethylketone (MEK)			
2-Metossietilacetato		X	
1,4-Dioxane			
4-Fenilcicloesene			

HP7 = substances that can cause cancer
HP10 = substances that can cause fetal malformations
HP11 = substances that can cause mutations or alterations in the genetic material

4.5.3.2 Preliminary Analysis

The analysis of the presence of VOC on the plastic materials used to print objects with 3D printing has started with a preliminary analysis made on four different plastic materials, that is
ABS, PLA, PET and a fourth material that is a PLA with some features of hardness of ABS, called PLA layer ABS.
This initial screening has been performed for the identification of the critical emissions of each material, to subsequently evaluate if these values were stable on multiple production batches. At the end of the screening it was decided to focus on the three pure materials for the next analysis, leaving the evaluation of the composite materials (i.e. PLA layer ABS) to a subsequent step. During the initial screening also two “white environments” have been tested, in detail those for ABS and PLA. A white environment for PET, was not tested because quite similar as temperature conditions to that of the PLA. Table 4.8 shows the initial screening done in November 2016.

Table 4.8 Preliminary analysis on materials

UM mg/m³	**White ABS**	**White PLA**	**ABS**	**PLA**	**PET**	**PLA layer ABS**
Volatile Organic Compounds (TVOC)	0.147	0.194	0.383	0.163	0.255	0.400
Benzene	0.000	0.000	0.004	0.002	0.002	0.000
Toluene	0.015	0.004	0.015	0.007	0.015	0.018
Ethylbenzene	0.000	0.000	0.022	0.000	0.001	0.002
Styrene	0.010	0.000	0.116	0.003	0.017	0.022
Xylenes	0.003	0.000	0.008	0.003	0.000	0.004
N-Hexane	0.000	0.000	0.003	0.003	0.000	0.007
Cyclohexane	0.000	0.000	0.000	0.000	0.000	0.101
1,2-Dichloroethane	0.000	0.000	0.000	0.000	0.000	0.000
Trichlorethylene	0.006	0.000	0.000	0.000	0.000	0.009
Tetrachlorethylene	0.000	0.000	0.000	0.000	0.000	0.000
Dichloromethane	0.000	0.000	0.000	0.000	0.000	0.009
Ethanol	0.030	0.018	0.032	0.018	0.043	0.031
Isopropanol (Isopropyl alcohol)	0.000	0.000	0.000	0.000	0.000	0.000
Isobutanol	0.000	0.000	0.000	0.000	0.000	0.000
N-Butanol (n-butyl alcohol)	0.004	0.003	0.004	0.000	0.005	0.005
Ethyl acetate	0.003	0.003	0.014	0.005	0.026	0.007
Isobutyl	0.003	0.000	0.003	0.000	0.003	0.002
N-Butyl acetate	0.004	0.003	0.006	0.003	0.007	0.007
Acetone	0.000	0.085	0.087	0.098	0.113	0.000
Cyclohexanone	0.000	0.000	0.000	0.000	0.000	0.000
Methyl isobutyl ketone (MIK)	0.000	0.000	0.001	0.000	0.000	0.000
Methylethylketone (MEK)	0.000	0.001	0.004	0.001	0.003	0.000
2-Metossietilacetato	0.000	0.000	0.000	0.000	0.000	0.000
1,4-Dioxane	0.000	0.000	0.000	0.000	0.000	0.000
4-Fenilcicloesene	0.000	0.000	0.000	0.000	0.000	0.000

4.5.3.3 PLA, ABS and PET, are they harmful?

After this first step, the complete analysis on the materials was done. Table 4.9, 4.10 and 4.11 show the differences among PLA, PET and ABS, and their corresponding “white environments”, in order to evaluate the differences for each substance when the 3D printer is ready for printing but it does not work and when it is working with the material. Negative differences among the “white environment” and the material are due to the sampling error that can even reach 30%, due to the very sensitive sampling method, considering that it is assumed in theory that the “white environment” has a level of emissions certainly lower than the level encountered when the printer is operating with the inserted material. Considering Table 4.9, it can be seen that the differences among the two sampling are really minimal and not significant, while considering the PET material (Table 4.10), the differences among the two sampling is more evident only for the ethanol substance (watching Table 4.7 is not dangerous for human health). Finally considering the ABS material (Table 4.11), in this case it is present, even if in a slightly way, a difference between the white sampling and the one with the material, and such difference is present both in the total value of VOC and in the level of styrene which is a teratogenic substance, and therefore potentially dangerous for human health.

Table 4.9 Comparison between white and PLA

	White PLA		**PLA**		
UM mg/m³	**Mean**	**SD**	**Mean**	**SD**	**Difference (Δ)**
Volatile Organic Compounds (TVOC)	0.311	0.137	0.314	0.120	0.003
Benzene	0.003	0.006	0.003	0.002	0.000
Toluene	0.029	0.022	0.033	0.008	0.004
Ethylbenzene	0.000	0.001	0.003	0.005	0.003
Styrene	0.005	0.004	0.012	0.027	0.007
Xylenes	0.003	0.003	0.007	0.003	0.004
N-Hexane	0.042	0.092	0.022	0.039	-0.020
Cyclohexane	0.009	0.015	0.008	0.019	-0.001
1,2-Dichloroethane	0.000	0.000	0.000	0.000	0.000
Trichlorethylene	0.008	0.011	0.010	0.003	0.002
Tetrachlorethylene	0.000	0.000	0.001	0.001	0.001
Dichloromethane	0.001	0.001	0.001	0.001	0.001
Ethanol	0.016	0.013	0.024	0.008	0.008
Isopropanol (Isopropyl alcohol)	0.005	0.007	0.004	0.003	-0.001
Isobutanol	0.001	0.001	0.001	0.001	0.001
n-Butanol (n-butyl alcohol)	0.001	0.002	0.003	0.001	0.001
Ethyl acetate	0.009	0.013	0.009	0.003	0.000
Isobutyl	0.002	0.002	0.004	0.003	0.003
N-Butyl acetate	0.003	0.001	0.006	0.003	0.003
Acetone	0.101	0.084	0.055	0.043	-0.046
Cyclohexanone	0.000	0.000	0.000	0.000	0.000
Methyl isobutyl ketone (MIK)	0.000	0.000	0.001	0.001	0.001
Methylethylketone (MEK)	0.001	0.001	0.003	0.001	0.001
2-Metossietilacetato	0.000	0.000	0.000	0.000	0.000
1,4-Dioxane	0.000	0.000	0.000	0.000	0.000
4-Fenilcicloesene	0.000	0.000	0.000	0.000	0.000

Table 4.10 Comparison between white and PET

	White PLA		PET		
UM mg/m³	**Mean**	**SD**	**Mean**	**SD**	**Difference (Δ)**
Volatile Organic Compounds (TVOC)	0.311	0.137	0.151	0.112	-0.160
Benzene	0.003	0.006	0.001	0.002	-0.002
Toluene	0.029	0.022	0.011	0.011	-0.018
Ethylbenzene	0.000	0.001	0.000	0.005	0.000
Styrene	0.005	0.004	0.006	0.028	0.001
Xylenes	0.003	0.003	0.002	0.002	-0.001
N-Hexane	0.042	0.092	0.004	0.032	-0.038
Cyclohexane	0.009	0.015	0.013	0.019	0.004
1,2-Dichloroethane	0.000	0.000	0.000	0.000	0.000
Trichlorethylene	0.008	0.011	0.002	0.004	-0.006
Tetrachlorethylene	0.000	0.000	0.000	0.001	0.000
Dichloromethane	0.001	0.001	0.001	0.002	0.000
Ethanol	0.016	0.013	0.063	0.010	0.047
Isopropanol (Isopropyl alcohol)	0.005	0.007	0.004	0.003	0.000
Isobutanol	0.001	0.001	0.001	0.001	0.000
N-Butanol (n-butyl alcohol)	0.001	0.002	0.001	0.002	0.000
Ethyl acetate	0.009	0.013	0.011	0.004	0.003
Isobutyl	0.002	0.002	0.001	0.001	-0.001
N-Butyl acetate	0.003	0.001	0.004	0.003	0.001
Acetone	0.101	0.084	0.087	0.024	-0.014
Cyclohexanone	0.000	0.000	0.000	0.000	0.000
Methyl isobutyl ketone (MIK)	0.000	0.000	0.000	0.000	0.000
Methylethylketone (MEK)	0.001	0.001	0.003	0.001	0.002
2-Metossietilacetato	0.000	0.000	0.000	0.000	0.000
1,4-Dioxane	0.000	0.000	0.000	0.000	0.000
4-Fenilcicloesene	0.000	0.000	0.000	0.000	0.000

Table 4.11 Comparison between white and ABS

	White ABS		ABS		
UM mg/m³	**Mean**	**SD**	**Mean**	**SD**	**Difference (Δ)**
Volatile Organic Compounds (TVOC)	0.311	0.121	0.391	0.135	0.080
Benzene	0.003	0.002	0.002	0.001	-0.001
Toluene	0.029	0.027	0.016	0.001	-0.013
Ethylbenzene	0.000	0.004	0.012	0.003	0.012
Styrene	0.005	0.008	0.069	0.002	0.064

Xylenes	0.003	0.006	0.006	0.002	0.003
N-Hexane	0.042	0.002	0.005	0.028	-0.037
Cyclohexane	0.009	0.006	0.050	0.002	0.041
1,2-Dichloroethane	0.000	0.000	0.000	0.000	0.000
Trichlorethylene	0.008	0.008	0.005	0.000	-0.004
Tetrachlorethylene	0.000	0.002	0.000	0.001	0.000
Dichloromethane	0.001	0.001	0.004	0.000	0.004
Ethanol	0.016	0.025	0.031	0.006	0.015
Isopropanol (Isopropyl alcohol)	0.005	0.004	0.000	0.001	-0.005
Isobutanol	0.001	0.002	0.000	0.001	-0.001
n-Butanol (n-butyl alcohol)	0.001	0.002	0.004	0.000	0.003
Ethyl acetate	0.009	0.005	0.011	0.003	0.002
Isobutyl	0.002	0.006	0.002	0.003	0.001
N-Butyl acetate	0.003	0.004	0.007	0.000	0.004
Acetone	0.101	0.007	0.044	0.066	-0.057
Cyclohexanone	0.000	0.000	0.000	0.000	0.000
Methyl isobutyl ketone (MIK)	0.000	0.002	0.001	0.001	0.000
Methylethylketone (MEK)	0.001	0.003	0.002	0.001	0.001
2-Metossietilacetato	0.000	0.000	0.000	0.000	0.000
1,4-Dioxane	0.000	0.000	0.000	0.000	0.000
4-Fenilcicloesene	0.000	0.000	0.000	0.000	0.000

Subsequently to have an order of comparison of the emission levels with reference legislation, the French decree *“Arrêté du 19 avril 2011 relatif à l’étiquetage des produits de construction ou de revêtement de mur ou de sol et des peintures et vernis sur leurs emissions de pollutants volatils”* was taken into consideration, because as previously mentioned in Italy there is no regulation with reference threshold values. This decree has four different classes of emission values that range from the best class A+, to the lower one that is C; what is more as it can be seen from Table 4.12 the legislation does not take into consideration all the values of TVOC as we considered in previous tables, but it chooses to focus on 11 substances, among which we have not considered in our sampling formaldehyde and acetaldehyde, since these two substances requires another type of sampling to be analyzed and cannot be considered together with the others, and also 1,2,4-trimethylbenzene, 1,4-dichlorobenzene, 2-butoxyethanol were not taken into consideration. These differences among the substances considered derive from the fact that the UNI EN ISO 16000-9 standard for the determination of emissions of Volatile Organic Compounds from construction products and finishing products by emission test chamber method, does not defines a clear list of substances to be considered for analysis but leave this choice to the laboratories carrying out the analysis.

However comparing the values we get from the sampling of ABS PLA and PET with the values defined in the decree it can be seen that the level of emissions reached allows to reach the emission class A + and therefore the substances emitted when the 3D printer is in function do not seem to exceed threshold values that make them harmful for human health.

Table 4.12 Comparison between the VOC emissions of ABS PLA and PET and the French legislation

	Classes defined by the French legislation				*ABS*		*PLA*		*PET*	
UM mg/m^3	*C*	*B*	*A*	*A+*	*Value*	*Class*	*Value*	*Class*	*Value*	*Class*
Formaldehyde	>0.120	<0.120	<0.060	<0.060	-	**A+**	-	**A+**	-	**A+**
Acetaldehyde	>0.400	<0.400	<0.300	<0.200	-		-		-	
Toluene	>0.600	<0.600	<0.450	<0.300	0.016		0.026		0.011	
Tetrachlorethylene	>0.500	<0.500	<0.350	<0.250	0.000		0.001		0.000	
Xylenes	>0.400	<0.400	<0.300	<0.200	0.006		0.006		0.002	
1,2,4-trimethylbenzene	>2.000	<2.000	<1.500	<1.000	-		-		-	
1,4-dichlorobenzene	>0.120	<0.120	<0.090	<0.060	-		-		-	
Ethylbenzene	>1.500	<1.500	<1.000	<0.750	0.012		0.005		0.000	
2-butoxyethanol	>2.000	<2.000	<1.500	<1.000	-		-		-	
Styrene	>0.500	<0.500	<0.350	<0.250	0.069		0.021		0.006	
TVOC	>2.000	<2.000	<1.500	<1.000	0.391		0.255		0.151	

4.5.3.4 Materials’ fingersprint

Finally, it has been tried to identify for each material its "fingerprint", that is the substances which compose the same, making an assessment of its harmfulness. Table 4.13 shows the presence of VOC substances on PLA and Figure 4.7 summarizes Table 4.13, indicating in the graph only those substances present in the material for a percentage greater than or equal to 5% of the total. Figure 4.7 shows how in the PLA fingerprint the most present substances are acetone (22.3%), followed by N-Hexane (13.1%), and Toluene (12%). Among the substances that are present in PLA material there are three which are potentially harmful for human health as indicated in Table 4.7; these are Toluene (12.0%), Styrene (9.6%) and n-Hexane (13,1%). All the three substances are classified as HP10 and therefore as substances that might cause fetal malformations.

Table 4.13 Presence of Volatile Organic substances on PLA

	PLA		
UM mg/m³	**Mean**	**SD**	**%**
Volatile Organic Compounds (TVOC)	0.255	0.120	
Benzene	0.003	0.002	1.4%
Toluene	0.026	0.008	12.0%
Ethylbenzene	0.005	0.005	2.1%
Styrene	0.021	0.027	9.6%
Xylenes	0.006	0.003	2.6%
N-Hexane	0.029	0.039	13.1%
Cyclohexane	0.018	0.019	8.0%
1,2-Dichloroethane	0.000	0.000	0.0%
Trichlorethylene	0.009	0.003	4.0%
Tetrachlorethylene	0.001	0.001	0.2%
Dichloromethane	0.002	0.001	0.8%
Ethanol	0.023	0.008	10.6%
Isopropanol (Isopropyl alcohol)	0.004	0.003	1.7%
Isobutanol	0.001	0.001	0.6%
n-Butanol (n-butyl alcohol)	0.003	0.001	1.2%
Ethyl acetate	0.009	0.003	4.3%
Isobutyl	0.004	0.003	1.8%
N-Butyl acetate	0.005	0.003	2.2%
Acetone	0.049	0.043	22.3%
Cyclohexanone	0.000	0.000	0.0%
Methyl isobutyl ketone (MIK)	0.001	0.001	0.5%
Methylethylketone (MEK)	0.002	0.001	1.0%
2-Metossietilacetato	0.000	0.000	0.0%
1,4-Dioxane	0.000	0.000	0.0%
4-Fenilcicloesene	0.000	0.000	0.0%
Total substances		**0.219**	

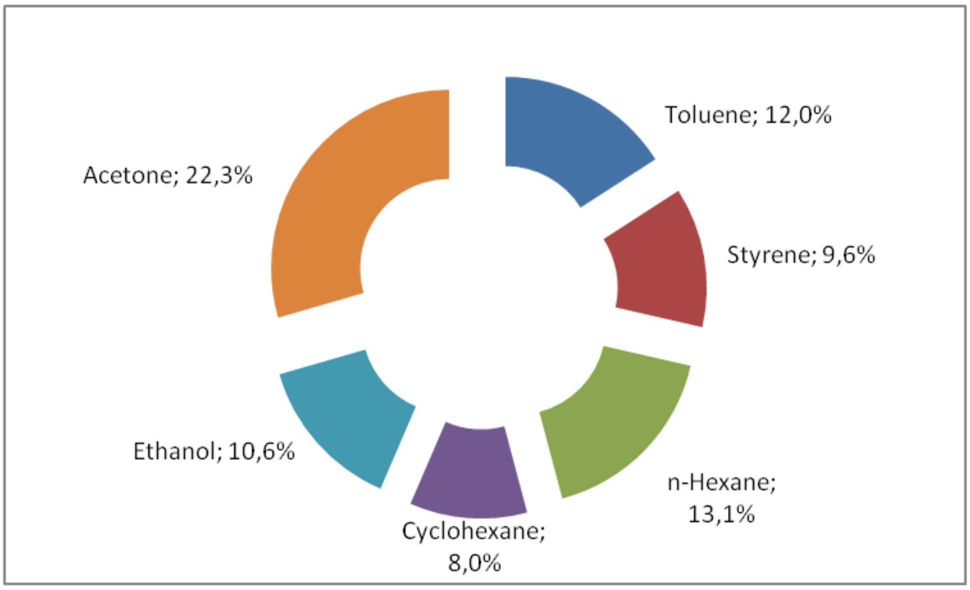


Figure 4.12 PLA Fingerprint

Subsequently Table 4.14 shows the presence of VOC substances on ABS and its relative fingerprint. As shown in Figure 4.8 the most present substances in ABS are Styrene (25.4%), Cyclohexane (18.5%), and Acetone (16.1%). Among all these, two of them are potentially dangerous, that is Toluene (6.0%) and Styrene (25.4%), and as in the case of PLA both of them are classified as HP10 substances.

Table 4.14 Presence of Volatile Organic substances on ABS

		ABS	
UM mg/m³	**Mean**	**SD**	**%**
Volatile Organic Compounds (TVOC)	0.391	0.135	
Benzene	0.002	0.001	0.8%
Toluene	0.016	0.001	6.0%
Ethylbenzene	0.012	0.003	4.5%
Styrene	0.069	0.002	25.4%
Xylenes	0.006	0.002	2.3%
N-Hexane	0.005	0.028	1.8%
Cyclohexane	0.050	0.002	18.5%
1,2-Dichloroethane	0.000	0.000	0.0%
Trichlorethylene	0.005	0.000	1.7%
Tetrachlorethylene	0.000	0.001	0.0%
Dichloromethane	0.004	0.000	1.6%
Ethanol	0.031	0.006	11.5%
Isopropanol (Isopropyl alcohol)	0.000	0.001	0.0%
Isobutanol	0.000	0.001	0.0%

N-Butanol (n-butyl alcohol)	0.004	0.000	1.6%
Ethyl acetate	0.011	0.003	4.0%
Isobutyl	0.002	0.003	0.9%
N-Butyl acetate	0.007	0.000	2.5%
Acetone	0.044	0.066	16.1%
Cyclohexanone	0.000	0.000	0.0%
Methyl isobutyl ketone (MIK)	0.001	0.001	0.2%
Methylethylketone (MEK)	0.002	0.001	0.8%
2-Metossietilacetato	0.000	0.000	0.0%
1,4-Dioxane	0.000	0.000	0.0%
4-Fenilcicloesene	0.000	0.000	0.0%
Total substances		**0.272**	

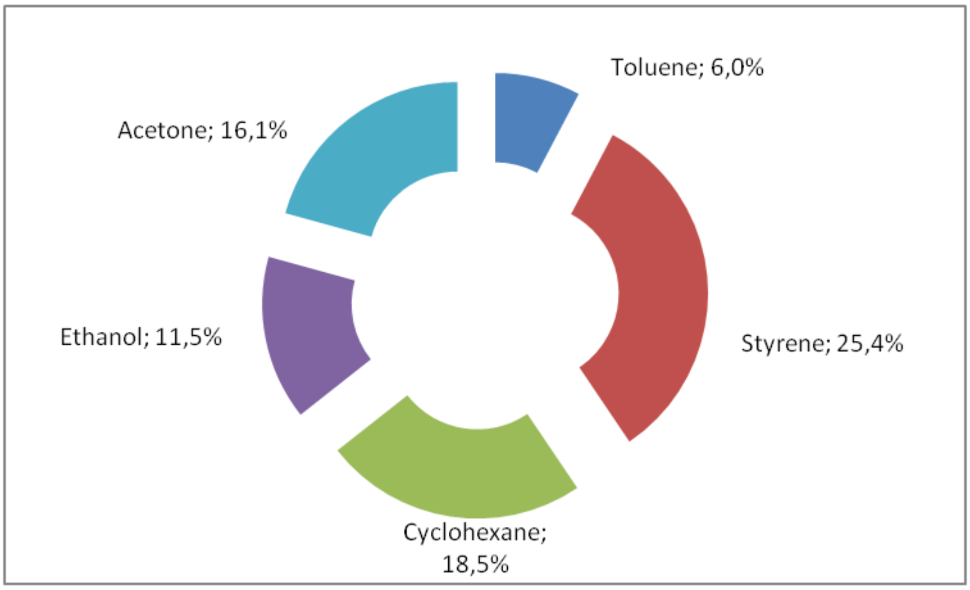


Figure 4.13 ABS Fingerprint

Finally Table 4.15 shows the presence of VOC substances on PET material and as it can be seen from Figure 4.9, the most present ones are Acetone (40%) and Ethanol (29.1%). However there is also a presence of Toluene (4.9%), that is considered a teratogenic substance (HP10) potentially dangerous for human health. Nevertheless considering the three materials taken into consideration, PET seems to be the one with a more healthy fingerprint in terms of the presence of dangerous substances.

Table 4.15 Presence of Volatile Organic substances on PET

		PET	
UM mg/m³	**Mean**	**SD**	**%**
Volatile Organic Compounds (TVOC)	0.151	0.112	

Benzene	0.001	0.002	0.7%
Toluene	0.011	0.011	4.9%
Ethylbenzene	0.000	0.005	0.1%
Styrene	0.006	0.028	2.8%
Xylenes	0.002	0.002	1.0%
N-Hexane	0.004	0.032	1.8%
Cyclohexane	0.013	0.019	6.2%
1,2-Dichloroethane	0.000	0.000	0.0%
Trichlorethylene	0.002	0.004	1.0%
Tetrachlorethylene	0.000	0.001	0.0%
Dichloromethane	0.001	0.002	0.4%
Ethanol	0.063	0.010	29.1%
Isopropanol (Isopropyl alcohol)	0.004	0.003	2.0%
Isobutanol	0.001	0.001	0.3%
N-Butanol (n-butyl alcohol)	0.001	0.002	0.7%
Ethyl acetate	0.011	0.004	5.2%
Isobutyl	0.001	0.001	0.4%
N-Butyl acetate	0.004	0.003	2.0%
Acetone	0.087	0.024	40.0%
Cyclohexanone	0.000	0.000	0.0%
Methyl isobutyl ketone (MIK)	0.000	0.000	0.0%
Methylethylketone (MEK)	0.003	0.001	1.5%
2-Metossietilacetato	0.000	0.000	0.0%
1,4-Dioxane	0.000	0.000	0.0%
4-Fenilcicloesene	0.000	0.000	0.0%
Total substances		**0,217**	

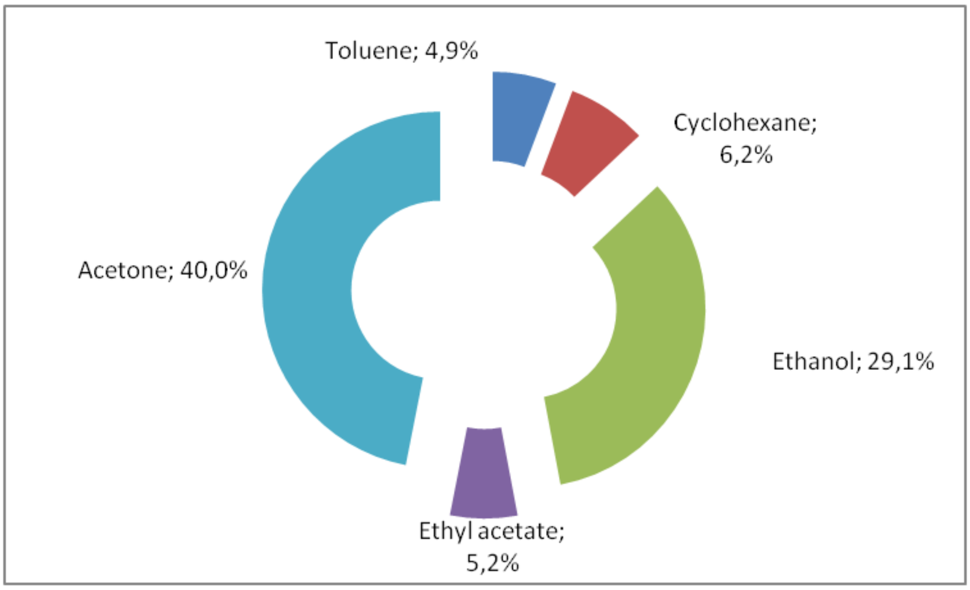


Figure 4.14 PET Fingerprint

4.5.4 Conclusions

Desktop 3D printers use a heated nozzle to melt a solid thermoplastic filament. During this process, filament polymers and additives may react with oxygen, resulting in particulate emissions from by-products formed during heating (Contos et al., 1995). The greater the difference between the extruder (ABS, 230°C; PLA, 215°C) and filament melting temperatures (ABS, 105°C; PLA, 150°C), the more vapour can be generated and condense to form UFP by gas-to-particle conversion via nucleation and/or condensation processes. For ABS the temperature difference is 125°C and for PLA it is only 65°C. Thus, particle emissions from ABS are expected to be higher than PLA (Yi et al., 2016). Our results show that this is true but the difference between VOC emission of PLA (0.314) and ABS (0.391) is very low. These results are in line with what has been previously found in literature and indicate that ABS is more toxic than PLA, but that the PLA under certain conditions is not free from harmful emissions to health issues, especially if melted at temperatures over 200 ° C (Rutkowski and Levin, 1986; Kopinke et al., 1996; Liu et al., 2010).What is more adding PET to the comparison, this is the material which emitted less substances (0.151).

If we take into consideration the material fingerprint on Figures 4.7, 4.8 and 4.9, some harmful substances for human health are present in materials used for 3D printing, in detail these are teratogenic substances (HP10), that is substances that can cause fetal malformations. However these substances do not exceed the thresholds defined by the French decrees that regulate them. Italy has not defined a tolerance thresholds for these substances and therefore it is important to underline that there should be the need to create a proper legislation on this issue. Nevertheless in order to have a clear definition of the harmfulness of 3D printing materials more investigations in the field should be needed.

Some advice can be given to make the emissions of 3D printers in operation less harmful, such as the use of printers in ventilated places, even better if they are equipped with a primary air exchange system with a power of at least 3 volumes of the room per hour (e.g. a room of 100 m^3 should be equipped with at least one ventilator and a corresponding ventilation hole allows at least 300 m^3 / h of treated air). In another way, if using closed chamber printers, it would be important for the room to be equipped with active carbon filtering systems, selected according to the type of printing material; in fact the different materials do not emit all the same type of substances and therefore filters have been created that are able to absorb the VOCs according to the type of plastic used.

4.5.4.1 Limitations and future research directions

A first limitation of the research is linked to the limited sampling carried out for each material, in fact only 5 sampling for each material have been done, and considering the high sampling error (that can reach 30%), more sampling for each material should be needed in future research. What is more, it has been decided to have a small time of sampling, that is 80 minutes for each one. Future research could consider sampling VOC emissions, using longer sampling times, to check if for a long time the presence of VOC, during 3D printing at work, increases constantly or exponentially. A third limitation could be linked to the fact that the study analyzes only three different type of materials, that is PLA, ABS and PET, therefore future research should take into consideration the possibility of expanding the research to other types of materials, or to materials of the same type, but with different production lots, supplied by different suppliers.

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Appendix 1: FABLABS' QUESTIONNAIRE SURVEY (Europe and America)

SECTION 1: FAB LABS PROFILE

1. Where is your FabLab located?

- ○ France
- ○ The Netherlands
- ○ Germany
- ○ Spain
- ○ USA

2.1 How many volunteer workers do you have in your Fab Lab? (Choose a number from 1 to 20; or more than 20)

2.2 How many paid staff do you have in your Fab Lab? (Choose a number from 1 to 20; or more than 20)

3. What is the size of your Fab Lab? (5-24 SQM; 25-74 SQM; 75-200 SQM; >200 SQM)

4. What is approximately your annual revenue? (Consider the year 2016)

5. How many registered or associated users your Fab Lab has? (Choose a number from 1 to 100; or more than 100)

6. What is the average number of users who use the Fab Lab each month? (Choose a number from 1 to 100; or more than 100)

7.1 How much are the investments in your Fab Lab for machinery and technology? (Consider the year 2016)

- ○ < 10.000 euro/$
- ○ 10.001 - 50.000 euro/$
- ○ 50.001 - 100.000 euro/$
- ○ 100.001 - 300.000 euro/$
- ○ 300.001 - 500.000 euro/$

- 500.001 - 1.000.000 euro/$
- > 1.000.000 euro/$

7.2 Have you ever received state or European incentives to purchase machinery and new digital technologies for your Fab Lab?

- Yes
- No

7.3 How much are State or European incentives important, or would be important (if you have not benefited from them) for the sustainability of your Fab Lab? (Five-point Likert scale: 1 = not at all; 2 = few; 3 = indifferent; 4 = enough; 5 = a lot)

SECTION 2: FAB LABS' CONSUMERS, KNOWLEDGE AND SERVICES DELIVERED

8. Who are your main customers? Quantitatively indicate how much each of these figures addresses your Fab Lab. (Five-point Likert Scale: 1 = never, 2 = a few times a year; 3 = at least 1 time per month; 4 = once a week; 5 = daily)

- Manufacturing companies
- Individual customers
- Practitioners
- Institutions / schools
- University
- Artists
- Designers

9. To which sectors belong the products / prototypes that you make in your Fab Lab? Quantitatively indicate how much each of these sectors weight in your production. (Five-point Likert Scale: 1 = not at all; 2 = few; 3 = indifferent; 4 = enough; 5 = a lot)

- Fashion
- Furniture industry / furniture components
- Mechanics
- Automotive
- Food
- Technology - Electronic

- Technology - IoT
- Technology – Software

10. How often do you make these products in your Fab Lab? (Five-point Likert Scake: 1 = never, 2 = a few times a year; 3 = at least 1 time per month; 4 = once a week; 5 = daily)

- Products to be marketed
- Finished products for a single customer
- Prototypes for companies
- Prototypes for a single customer

11. How much do you feel is the usability of the prototypes / products once made in your Fab Lab? (Five-point Likert Scake: 1 = not at all; 2 = few; 3 = indifferent; 4 = enough; 5 = a lot)

12. How often do you use this machines / tools in your Fab Lab? (Five-point Likert Scale: 1 = never, 2 = a few times a year; 3 = at least 1 time per month; 4 = several times a month; 5 = daily)

- 3D printer
- 3D scanner
- Laser cutter
- CNC milling machines
- Vinyl cutter
- Lathe
- Control Cards (Arduino or similar)
- Precision punches for printed circuits

13. How much are each of these services delivered to your customers? (Five-point Likert Scale: 1 = not at all; 2 = few; 3 = indifferent; 4 = enough; 5 = a lot)

- Printing of products
- Support to the creation of prototypes
- Support to the design of new products
- Support for finding the most suitable 3D printer
- Support to the redefinition of the production process
- Consultancy on materials
- Provision of materials

- Courses and training

14. Do you think that your Fab Lab has these skills? (Five-point Likert Scale: 1 = not at all; 2 = few; 3 = indifferent; 4 = enough; 5 = a lot)

- Arduino Programming skills
- Skills on materials
- Hardware skills
- Skills on business processes
- Software programming skills
- Skills in using design softwares
- Skills on company products
- Skills on Internet of Things (IoT)
- Digital Manufacturing Skills

15. Do you feel that the products realized in your Fab Lab exalt these features? (Five-point Likert Scale: 1 = not at all; 2 = few; 3 = indifferent; 4 = enough; 5 = a lot)

- Design
- Product Quality
- Ergonomics
- Territoriality
- Security

16.1 Do you make in your Fab Lab products / prototypes with eco-sustainability features (products/prototypes that respect the environment)?

- Yes
- No

16.2 If you answered YES to the previous question, how many products / prototypes do you realize annually? (Indicate an approximate annual number)

16.3 Indicate some eco-sustainable products / prototypes you have made

16.4 For what purposes have you developed these eco-sustainable products / prototypes?

- External customers

- Community
- Territorial requirements
- Other….

17. Do you think new digital technologies can have an impact on working environment conditions?

- Yes, positive
- Yes, negative
- I don’t know
- No

18. Do you think that the use of 3D printers can lead to emissions (due to the melting techniques of the materials they are using) that will affect the air quality of the work environment? (Five-point Likert Scale: 1 = not at all; 2 = few; 3 = indifferent; 4 = enough; 5 = a lot)

19.1 Do you think 3D printers and other digital technologies can represent the turning point that will allow the industry to enter a new industrial revolution? (Five-point Likert Scale: 1 = not at all; 2 = few; 3 = indifferent; 4 = enough; 5 = a lot)

19.2 If you have given a value greater than 3 to the previous question (19.1), and you think that new digital technologies can revolutionize the industry, why do you think that?

Appendix 2: FABLABS’ QUESTIONNAIRE SURVEY (Italy)

SECTION 1: FAB LABS PROFILE

1. Where is your Fab Lab located?

- ○ Abruzzo
- ○ Basilicata
- ○ Calabria
- ○ Campania
- ○ Emilia Romagna
- ○ Friuli Venezia Giulia
- ○ Lazio
- ○ Liguria
- ○ Lombardia
- ○ Marche
- ○ Molise
- ○ Piemonte
- ○ Puglia
- ○ Sardegna
- ○ Sicilia
- ○ Toscana
- ○ Trentino Alto Adige
- ○ Umbria
- ○ Valle d'Aosta
- ○ Veneto

2.1 How many volunteer workers do you have in your Fab Lab? (Choose a number from 1 to 20; or more than 20)

2.2 How many paid staff do you have in your Fab Lab? (Choose a number from 1 to 20; or more than 20)

3. What is the size of your Fab Lab? (5-24 SQM; 25-74 SQM; 75-200 SQM; >200 SQM)

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7.1 How much are the investments in your Fab Lab for machinery and technology? (Consider the year 2016)

○ < 10.000 euro/$
○ 10.001 - 50.000 euro/$
○ 50.001 - 100.000 euro/$
○ 100.001 - 300.000 euro/$
○ 300.001 - 500.000 euro/$
○ 500.001 - 1.000.000 euro/$
○ > 1.000.000 euro/$

7.2 Have you ever received state or European incentives to purchase machinery and new digital technologies for your Fab Lab?

○ Yes
○ No

7.3 How much are State or European incentives important, or would be important (if you have not benefited from them) for the sustainability of your Fab lab? (Five-point Likert scale: 1 = not at all; 2 = few; 3 = indifferent; 4 = enough; 5 = a lot)

SECTION 2: FAB LABS' CONSUMERS, KNOWLEDGE AND SERVICES DELIVERED

8. Who are your main customers? Quantitatively indicate how much each of these figures addresses your Fab Lab. (Five-point Likert Scale: 1 = never, 2 = a few times a year; 3 = at least 1 time per month; 4 = once a week; 5 = daily)

○ Manufacturing companies
○ Individual customers
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○ Institutions / schools
○ University
○ Artists
○ Designers

9. To which sectors belong the products / prototypes that you make in your Fab Lab? Quantitatively indicate how much each of these sectors weight in your production. (Five-point Likert Scale: 1 = not at all; 2 = few; 3 = indifferent; 4 = enough; 5 = a lot)

- Fashion
- Furniture industry / furniture components
- Mechanics
- Automotive
- Food
- Technology - Electronic
- Technology - IoT
- Technology – Software

10. How often do you make these products in your Fab Lab? (Five-point Likert Scake: 1 = never, 2 = a few times a year; 3 = at least 1 time per month; 4 = once a week; 5 = daily)

- Products to be marketed
- Finished products for a single customer
- Prototypes for companies
- Prototypes for a single customer

11. How much do you feel is the usability of the prototypes / products once made in your Fab Lab? (Five-point Likert Scake: 1 = not at all; 2 = few; 3 = indifferent; 4 = enough; 5 = a lot)

12. How often do you use this machines / tools in your Fab Lab? (Five-point Likert Scale: 1 = never, 2 = a few times a year; 3 = at least 1 time per month; 4 = several times a month; 5 = daily)

- 3D printer
- 3D scanner
- Laser cutter
- CNC milling machines
- Vinyl cutter
- Lathe
- Control Cards (Arduino or similar)
- Precision punches for printed circuits

13. How much are each of these services delivered to your customers? (Five-point Likert Scale: 1 = not at all; 2 = few; 3 = indifferent; 4 = enough; 5 = a lot)

- Printing of products
- Support to the creation of prototypes
- Support to the design of new products
- Support for finding the most suitable 3D printer
- Support to the redefinition of the production process
- Consultancy on materials
- Provision of materials
- Courses and training

14. Do you think that your Fab Lab has these skills? (Five-point Likert Scale: 1 = not at all; 2 = few; 3 = indifferent; 4 = enough; 5 = a lot)

- Arduino Programming skills
- Skills on materials
- Hardware skills
- Skills on business processes
- Software programming skills
- Skills in using design softwares
- Skills on company products
- Skills on Internet of Things (IoT)
- Digital Manufacturing Skills

15. Do you feel that the products realized in your Fab Lab exalt these features? (Five-point Likert Scale: 1 = not at all; 2 = few; 3 = indifferent; 4 = enough; 5 = a lot)

- Design
- Product Quality
- Ergonomics
- Territoriality
- Security

16.1 Do you make in your Fab Lab products / prototypes with eco-sustainability features (products/prototypes that respect the environment)?

- Yes

- No

16.2 If you answered YES to the previous question, how many products / prototypes do you realize annually? (Indicate an approximate annual number)

16.3 Indicate some eco-sustainable products / prototypes you have made

16.4 For what purposes have you developed these eco-sustainable products / prototypes?

- External customers
- Community
- Territorial requirements
- Other….

17. Do you think new digital technologies can have an impact on working environment conditions?

- Yes, positive
- Yes, negative
- I don’t know
- No

18. Do you think that the use of 3D printers can lead to emissions (due to the melting techniques of the materials they are using) that will affect the air quality of the work environment? (Five-point Likert Scale: 1 = not at all; 2 = few; 3 = indifferent; 4 = enough; 5 = a lot)

19.1 Do you think 3D printers and other digital technologies can represent the turning point that will allow the industry to enter a new industrial revolution? (Five-point Likert Scale: 1 = not at all; 2 = few; 3 = indifferent; 4 = enough; 5 = a lot)

19.2 If you have given a value greater than 3 to the previous question (19.1), and you think that new digital technologies can revolutionize the industry, why do you think that?

Appendix 3: 3D CONSUMERS QUESTIONNAIRE SURVEY

SECTION 1: SOCIO-DEMOGRAPHIC FEATURES OF CONSUMERS

1. Gender:

- Male
- Female

2. Age:

- 18-24
- 25-34
- 35-44
- 45-54
- 55-64
- >65

3. Education:

- Primary School Diploma
- Middle School Diploma
- Diploma
- Bachelor Degree
- Master Degree
- Ph. D.

4. Region of birth:

- North
- Center
- South and Islands

5. Express an objective judgment on the degree of importance of the following factors during the purchase of a product (Five-point Likert Scale: 1= not at all important; 2= few important; 3= indifferent; 4= enough important ; 5= a lot important).

- Design (peculiarity, beauty and modernity of the product)
- Quality of materials (better materials that last longer)
- Sustainability (least possible waste of resources and possibility to recycle)

- Made in Italy
- Price
- Customization (characteristic of the product that allows it to be tailored to your needs)
- Technology Innovation
- Brand
- Corporate image (in terms of trust, reliability, importance)

6. Indicate how much you agree with each of the following statements (Five-point Likert Scale: 1 = totally disagree; 2 = disagree; 3 = I do not know; 4 = fairly agree; 5 = totally agree). Today:

- I'm willing to pay more for customized products
- I'm willing to pay more for sustainable products
- I'm willing to pay more for Made in Italy products
- I'm willing to pay more for Quality Products
- I'm willing to pay more for Design products

6.1 Indicate how much you agree with each of the following statements (Five-point Likert Scale: 1 = totally disagree; 2 = disagree; 3 = I do not know; 4 = fairly agree; 5 = totally agree):

- I'm interested to learn new skills, in order to do more alone and rely less on others
- I'm willing to repair items (shoes, bags, home appliances...) in order not to have to replace them
- I try to transform the difficulties in new opportunities for work and social life (*Indestructible spirit)*
- I maintain my faith and my traditions and actively try to improve my community and myself (*Retooling)*
- I'm adopting an approach to life simpler and parsimonious (*Liquid life)*
- I believe that the crisis push people to work together to solve problems and create new opportunities (*Cooperative consumerism)*
- I think that the old status symbols have no value, but character, authenticity, and creativity become the new life paths (*From materialism to the material)*

SECTION 2: 3D PRINTERS

7. Do you know what a 3D printer is?

- Yes
- No
- Only vaguely

7.1 If you answered "Yes" or "Only vaguely" to the previous question, indicate where you heard about it (multiple answers are possible)

- Magazines and newspapers
- Tv
- Radio
- Internet
- Conferences
- Training courses (School/University)
- Friends
- Working environment
- Other:

If you do NOT know what a 3D printer is:

3D printers allow the production of three-dimensional objects through the perfect superposition of layers of various materials (plastic, metal, resin, wood, glass ...) able to aggregate to form real solid matter. The result is the realization of a concrete object that respects the image previously created on the computer.

8. Indicate how much you agree with each of the following statements (Five-point Likert Scale: 1 = totally disagree; 2 = disagree; 3 = I do not know; 4 = fairly agree; 5 = totally agree):

- 3D printers allow the realization of products with a minimum use of resources and such as to be recycled
- 3D printers allow the creation of products with high quality materials that last long
- 3D printers allow the creation of customized products, completely customized to my tastes and my needs

- 3D printers allow the creation of products with the features of Made in Italy (eg. the quality of materials and design)
- 3D printers allow the creation of modern, special and trendy products

9. Indicate how much you agree with each of the following statements (Five-point Likert Scale: 1 = totally disagree; 2 = disagree; 3 = I do not know; 4 = fairly agree; 5 = totally agree):

- I am interested in purchasing products made with 3D printers trying to use the least amount of resources and likely to be recycled
- I am interested in purchasing products made with 3D printers tailored and customized according to my tastes and my needs
- I am interested in buying Italian products made with 3D printers that have quality of materials and design
- I am interested in purchasing products made with 3D printers that are modern and trendy

10. Indicate which of these categories of products made with 3D printing would you preferably buy (Five-point Likert Scale: 1= not at all; 2= few; 3= indifferent; 4= enough; 5= a lot)

- Food and beverages
- Electronics
- Furnitures
- Fashion
- Toys
- Accessories

11. If you had the economic possibility, would you buy a 3D printer (approximate cost between 900 and 1500 €) for the domestic creation of Do It Yourself (DIY) products?

- Yes
- No

12. Which products would you like to be able to do independently with a 3D printer? (*multiple answers are possible*):

- Food and beverages

- Electronics
- Furnitures
- Fashion
- Toys
- Accessories

13. Indicate how much you agree with each of the following statements; (Five-point Likert Scale: 1 = totally disagree; 2 = disagree; 3 = I do not know; 4 = fairly agree; 5 = totally agree):

- I think it is important to pay attention to the air quality of the environment where I spend most of my time
- I believe that 3D printers can pollute the air of the environment in which they operate uses more strongly than the current production techniques because of the melting of materials they use
- I believe that 3D printers and other digital technologies can represent the breakthrough that will allow the advent of a new Industrial Revolution
- I believe that Italian companies are not taking full advantage of the opportunities offered by 3D printers and other digital technologies for the development of national economy
- I believe that 3D printers in the future will be daily used by each individual (as it is common now using 2D printers)

SECTION 3: FAB LABS' KNOWLEDGE

14. Have you ever heard about Fabrication Laboratories (Fab Labs)?

- Yes
- No
- Only vaguely

If you do NOT know what Fab Labs are:

Fab Labs are laboratories open to the public equipped with machines for digital manufacturing (3D printers, 3D scanners, CNC milling machines, screen printing machines and cutting machines), places where individuals and companies have access to equipment, processes and people able to transform ideas into prototypes and products.

15. If you answered "Yes" or "Only vaguely" to the previous question, indicate where you heard about it (multiple answers are possible)

- Magazines and newspapers
- Tv
- Radio
- Internet
- Conferences
- Training courses (school/University)
- Friends
- Working environment
- Other:

16. Have you ever addressed to a Fab Lab for the realization of an object or for other requests?

- Yes
- No

17. If you answered YES to the previous question, what did you ask to do within a Fab Lab?

18. If you answered NO to the previous question, would you be interested in contacting a Fab Lab for the realization of your idea, of a project, of a product totally designed by yourself?

- Yes
- No

19. Indicate what you would be interested in realizing within a Fab Lab

Appendix 4: COMPANIES QUESTIONNAIRE SURVEY

THE USE OF ADDITIVE MANUFATURING IN THE WOOD-FURNITURE INDUSTRY

SECTION 1: COMPANIES PROFILE

1. With reference to the number of employees your business can be classified as:
    - Micro business (<10 employees)
    - Small business (11-49 employees)
    - Medium business (50-249 employees)
    - Large business (More than 250 employees)

2. Your company's turnover is (refer to the financial year 2015):
    - ≤ 2 million €
    - Between 2 and 10 million €
    - Between 10 and 50 million €
    - > 50 million €

3. To which sector of the wood-furniture industry do your company belong?
    - Accessories
    - Bathroom furnishings
    - Furnishings for bars and shops
    - Outdoor furnishings
    - Collectivity
    - Bedroom furnishings
    - Kitchen furnishings
    - Living room furnishings
    - Matresses
    - Upholstered furnishings
    - Classic furnishings
    - Domestic multiproducts
    - Panels
    - School furnishings

- Semi finished products
- Office furnishings
- Other

4. Where is your company located in Italy??

- Northern regions
- Center regions
- South regions and Islands

5. What is your company's reference market?

- Italy
- Italy and Europe
- Italy, Europe and International markets

6. Your company makes products with a price range that is (make a comparison with competitors in your industry):

- Low
- Lower-middle
- Medium
- Upper-middle
- High

7. How much do you pay attention to (Five-point Likert Scale: 1= not at all important; 2= few important; 3= indifferent; 4= enough important ; 5= a lot important):

- Creation of customized products
- Creation of modern and innovative products with high design
- Creation of quality products that meet the standards of the "Made in Italy"
- Creation of sustainable products (recyclable and with the least possible waste of resources)
- The quality of the materials used for the creation of products
- The enhancement of the brand to be competitive on the market
- The image of the company communicated to customers

8. Do you realize prototypes in your company?

- ○ Yes
- ○ No
- ○ At other suppliers

9. Does your company own or use a 3D printer?

- ○ Yes
- ○ Yes, we do external machining
- ○ No, but we would like to buy it in the short term
- ○ No

SECTION 2: RESERVED TO COMPANIES THAT WORK (internally or externally) WITH 3D PRINTERS

10. What percentage of your total production (including prototypes) is made in 3D?

- ○ < 10%
- ○ 11-20%
- ○ 21-35%
- ○ 36-50%
- ○ 51-80%
- ○ > 80%

11. Indicate the benefits you have gained from the introduction of 3D printing (Five-point Likert Scale: 1= not at all important; 2= few important; 3= indifferent; 4= enough important ; 5= a lot important):

- ○ Reduction in time to define technical specifications of products
- ○ Reduction in prototyping time
- ○ Reduction in production time
- ○ Reduction in time to market
- ○ Reduction in costs of materials
- ○ Reduction of inventory and unsold costs
- ○ Reduction in transport costs
- ○ Reduction of labor costs
- ○ Energy saving
- ○ Creation of new products with complex geometries, increased performance and quality

  - Creation of a new business model: offer of a virtual model
  - Greater chance of internationalization
  - Shift of production to retail outlets
  - Product customization
  - Ability to co-design with the customer
  - Reduction in environmental impact
  - Ability to serve niche markets

12. Indicate what may be the main barriers to the implementation of 3D printing techniques in the wood-forniture industry (Five-point Likert Scale: 1= not at all; 2= few; 3= indifferent; 4= enough; 5= a lot):

  - Technology is not suited to the wood-furniture sector
  - Lack of interest in the market
  - Lack of knowledge of potential benefits and problems
  - Lack of staff training
  - Excessively high investment

13. How much are you oriented to the realization with 3D printers of (Five-point Likert Scale: 1= not at all important; 2= few important; 3= indifferent; 4= enough important ; 5= a lot important):

  - Prototypes
  - Small finished product series
  - Customized products
  - Eco-sustainable products

14. How much do you feel that 3D printers can allow the creation of customized products reflecting the typical features of Italian "Made in Italy" products? (Likert 1-5: 1= not at all; 2= few; 3= indifferent; 4= enough; 5= a lot)

SECTION 3: RESERVED TO COMPANIES THAT ARE NOT WORKING WITH 3D PRINTERS

15. Why don’t your company use 3D printers? (Five-point Likert Scale: 1 = totally disagree; 2 = disagree; 3 = I do not know; 4 = fairly agree; 5 = totally agree)

- Technology is not suited to the wood-furniture sector
- Lack of interest in the market
- Lack of knowledge of potential benefits and problems
- Lack of staff training
- Excessively high investment

16. Indicate how much you think you can achieve the following benefits introducing 3D printing in your production (Five-point Likert Scale: 1 = totally disagree; 2 = disagree; 3 = I do not know; 4 = fairly agree; 5 = totally agree):

- Reduction in time to define technical specifications of products
- Reduction in prototyping time
- Reduction in production time
- Reduction in time to market
- Reduction in costs of materials
- Reduction of inventory and unsold costs
- Reduction in transport costs
- Reduction of labor costs
- Energy saving
- Creation of new products with complex geometries, increased performance and quality
- Creation of a new business model: offer of a virtual model
- Greater chance of internationalization
- Shift of production to retail outlets
- Product customization
- Ability to co-design with the customer
- Reduction in environmental impact
- Ability to serve niche markets

17. How much would you be oriented to the realization with 3D printers of (Five-point Likert Scale: 1= not at all; 2= few; 3= indifferent; 4= enough; 5= a lot):

- Prototypes
- Small finished product series
- Customized products
- Eco-sustainable products

18. How much do you feel that 3D printers can allow the creation of customized products reflecting the typical features of Italian "Made in Italy" products? (Likert 1-5: 1= not at all; 2= few; 3= indifferent; 4= enough; 5= a lot)

SECTION 4: CONCLUSIVE SECTION

19. How do you feel that working environment conditions (safety, ergonomics, noise, dust, temperature) affect worker productivity? (Five-point Likert Scale: 1= not at all; 2= few; 3= indifferent; 4= enough; 5= a lot)

20. How much do you pay attention to the working environment of your workers and employees? (Five-point Likert Scale: 1= not at all; 2= few; 3= indifferent; 4= enough; 5= a lot)

21. Do you think new digital technologies can affect the working environment?

- ○ Yes, in a positive way
- ○ Yes, in a negative way
- ○ I don’t know
- ○ No

22. How much do you think the use of 3D printers can lead to emissions (due to the melting techniques of the materials they use) that will affect the air quality of the working environment? (Five-point Likert Scale: 1= not at all; 2= few; 3= indifferent; 4= enough; 5= a lot)

23. Indicate the degree of adoption of 3D printing by actors in your supply chain (Five-point Likert Scale: 1= not at all; 2= few; 3= indifferent; 4= enough; 5= a lot)

- ○ Supply chain partners
- ○ Linked companies
- ○ Competitors
- ○ Suppliers
- ○ Contractors

24. How do you feel it is important to start or continue investing in Additive Manufacturing and digital technologies so that your company could remain competitive on its reference markets? (Five-point Likert Scale: 1= not at all; 2= few; 3= indifferent; 4= enough; 5= a lot)

25. How do you feel that 3D printers and other digital technologies can represent the turning point that will allow the advent in the industry of a new Industrial Revolution? (Five-point Likert Scale: 1= not at all; 2= few; 3= indifferent; 4= enough; 5= a lot)