POLITECNICO DI TORINO

Master's degree in Engineering and Management

Master of Science Thesis

Additive Manufacturing technology in the goldsmith industry. Economic benefits, sustainability issues and diffusion in the Arezzo district.

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Abstract

In the last decades, most sectors, such as communications, engineering, images, and architecture have all experienced their own digital transition.

The Additive Manufacturing technology is a technological process born from this evolution from analogue to digital processes. For this reason, it is now possible to apply Additive Manufacturing in order to make the operations more flexible and efficient.

Additive manufacturing has actually been around for several decades, while it seems new to many. Although the terms ‘3D printing’ is wrongly used to discuss additive manufacturing, it is actually a subset of additive manufacturing. In the right applications, additive manufacturing delivers improved performance, complex geometries, and simplified fabrication.

In this study will be analysed the main technologies of the AM family, particularly the jewels production in the goldsmith industry. Indeed, as part of this transitional phase, jewellery’s printing state of art needs to be examined to see whether it is better to stay anchored to the classical lost wax casting method or adopt a new technology.

The main objective of this thesis is to provide a general review of the state-of-art of the Additive Manufacturing technology along with its diffusion.

In the first chapter the Additive Manufacturing technology is presented: the evolution, the main process steps, and the different technologies classification, starting from the 7 main categories then explaining deeply some of the most important technologies of each sub-category.

The second chapter focuses more deeper on the AM technological innovations, analysing in detail the principal advantages and disadvantages due to adoption; moreover the process materials most commonly used, and the sectors of application are described as well.

Then the attention is shifted from the general AM technology to the specific application in the goldsmith industry sector. In the third chapter it is discussed the revolution, due to the AM introduction, in the craftsmanship art of jewellery manufacturing process, the changes that involves, the benefits and the materials adopted. Furthermore, the three techniques of goldsmith production, the Classic Microfusion, the Direct Microfusion and the Selective Laser Melting (SLM), are examined in detail and compared.

The study proceeds in the fourth chapter with an overview of the Italian goldsmith industry sector in general. Then, particularly, on the Italian goldsmith sector, analysing its structure, the organization

along the Italian area and the main economic aspects. An excursion about future improvements and developments of the AM technology in the sector, concludes the chapter.

In the fifth chapter the sustainability issues are analysed: after a general introduction on the theme in manufacturing processes, the analysis proceeds with an overview on the sustainability of the goldsmith sector and on the materials supply chain. Then, the additive manufacturing technology impact on sustainability is assessed and compared to the one of the traditional manufacturing processes.

Finally, in the last chapter, the analysis of a case study on the Arezzo goldsmith market is carried out. The study is performed throughout the submission of a questionnaire to a sample of Arezzo craftsmen of the goldsmith industry. Then, the results collected are analysed in order to understand the rate of diffusion of the Additive Manufacturing technology in the Italian goldsmith sector. This analysis allows to provide interesting conclusions on the diffusion of the 3D printing in the goldsmith sector in specific area and on future opportunities for the industry.

Summary

Chapter 1- The evolution of the Additive Manufacturing

In this chapter, after a general overview of the AM evolution, technologies will be presented, followed by the production process phases and materials classification, in order to familiarize with the AM world.

1.1 Introduction

The Additive Manufacturing technology, or 3D printing, has all the potentialities to become the monopolist of enabling technologies for Industry 4.0. It is a quite young technology, indeed the first patents was obtained in the mid-80s; despite this, it has already reached a good level of maturity, which allows it to be compared with the traditional subtractive technologies, in different sectors, and at time, to exceed them in flexibility and time consuming.

In a nutshell, the AM refer to "technologies that grow three-dimensional objects one superfine layer at a time. Each successive layer bonds to the preceding layer of melted or partially melted material. Objects are digitally defined by computer-aided-design (CAD) software that is used to create .stl files that essentially "slice" the object into ultra-thin layers. This information guides the path of a nozzle or print head as it precisely deposits material upon the preceding layer".[1]

Looking for definitions in literature, we report the standard terminology for Additive Manufacturing as claimed by the ISO (International Organization for Standardization) and the ASTM (American Society for Testing and Materials), defining the AM as "the processes that aggregate materials in order to create objects starting from their three dimensional mathematical models, usually by overlapping layers, proceeding in the opposite way to what happens in subtractive processes (chip removal)".[2]

Moreover, AM is often associated with multiple definition as synonym, to the rapid prototyping (in the past, now obsolete due to the uselessness of demonstration pieces) and to the 3D printing, processes to realize three-dimensional objects through additive production, starting from a digital 3D model.

3D technology is predicted to be a disruptive technology within the manufacturing sector.
Indeed, the global additive manufacturing industry, is promised to move from the prototyping to the mass production of accessories, objects, and parts. A recent study, predicted that, by 2030, the

additive manufacturing technologies will be able to sustain companies on the large-scale production of final products. This market is predicted to triple between 2020 and 2026.

As SmartTech Analysis (the main trusted source on AM deliverables) report that based on the annual report, the latter sees the global market of additive production in 2019 to raise over 10.4 billion of dollars. SmartTech continue predicting the AM annual market becoming a 50 billion dollars one by 2029, consistent with the AM industry aim of being the 2% of the global manufacturing market by 2030.

According to data, this target, would require a raising and significantly growing period in the next years. Between the 2020 and 2023 the market is expected to grow at a rate of 17% annually, as illustrated in the Figure 1.1 below.

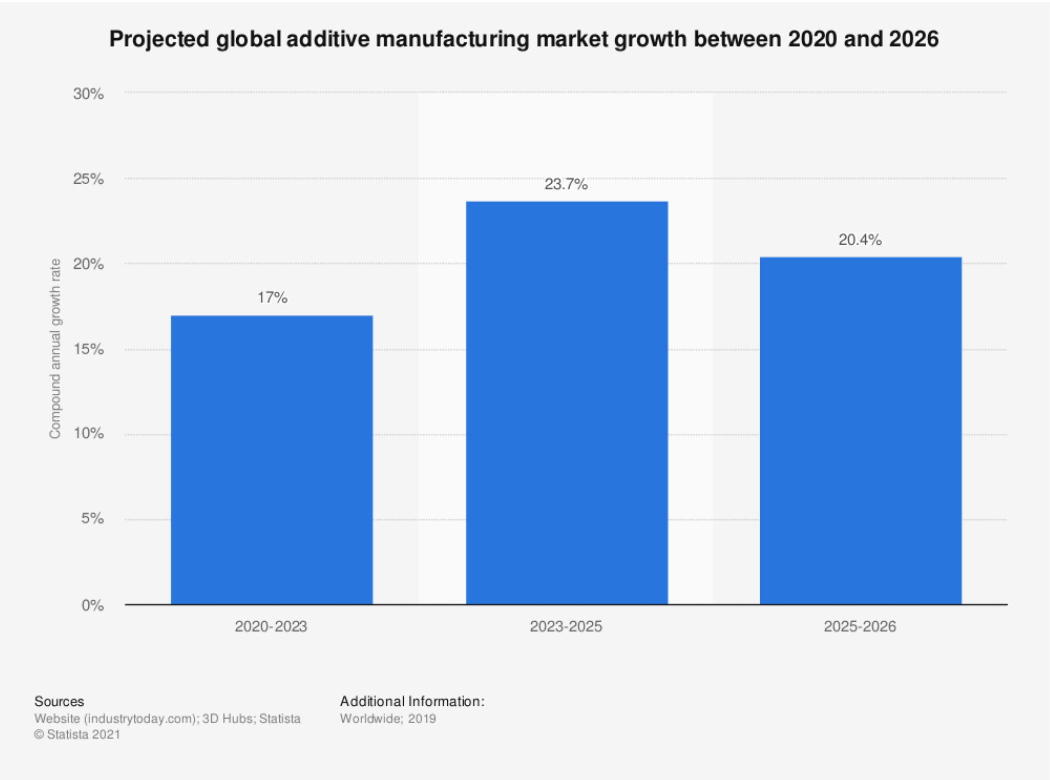


Figure 1.1- "Projected global additive manufacturing market growth between 2020 and 2026." [3]

1.2 The process of additive manufacturing

The additive manufacturing is a specific 3D printing process, it is a computer-controlled based process that creates 3D objects.

This process builds objects layer by layer, by depositing material – usually a plastic, ceramic or metal powder- creating a layer structure finally strengthened with some specific actions.

But the additive manufacturing process is really more complex, and it can be schematized into four main steps:

- **Design of a model using CAD software**: the first requirements of the AM process is a 3D model that completely represents geometry of the object. Here a crucial role is played by the CAD software (like AutoCAD, Creo, SolidWorks) used to reproduce the virtual model. In this case there are no restriction to the designer creativity, not as traditional processes.

- **Pre-Processing:** this step between design and manufacturing, require different activities. After a preventing simulation modelling activity used to test the design, to start working the 3D printing needs a conversion. Indeed, the 3D printers doesn't understand CAD files and while they need the STL file format, that every CAD software can produce. The STL (Stereolithography) file format represent the original shape of the CAD format but splitting curves into small straight lines, into layers, describing the external shape, in order to allow the right positioning. Then, the 3D printing must be prepared with some set up activities, for example regarding the material bond, the duration, and the sizes.

- **Printing:** depending on the AM technology used this phase can be very different. However, at this step, the 3D printing start the generation of the object, layer by layer. This is an automated passage, that can be monitored checking errors at a time. Time and material consumption is different at each process, based on the objects features.

- **Post-processing:** this can be considered the most expensive and time-consuming step. As the previous step, this phase depends on the different AM technology chosen too. And also in this case, there are additional activity. First, the excess material removal from the object; then the separation between parts and building tool or support and in the end, additional finishing activities such as cleaning, UV curing and others.

Finally, since every step is critical, to be sure to get a real and concrete object, every step of the process must be complete with diligence, experience, and care.

Below, a figure illustrating a common additive manufacturing process.

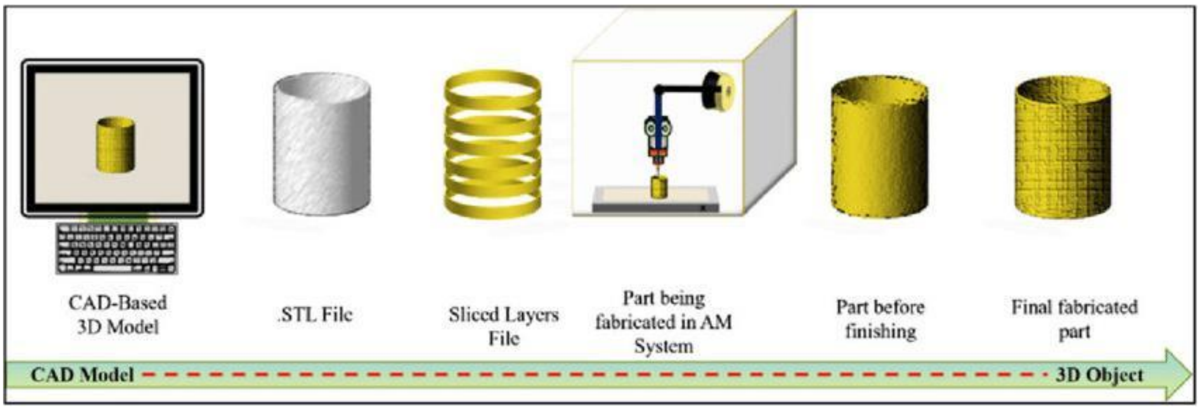


Figure 1.2-*"Basic additive manufacturing process" [4]*

1.3 Additive Manufacturing technologies

After a description of the general AM process and relative steps we now focus on the different technologies that exist.

Although 3D printing and Additive Manufacturing are used as synonyms, there are many different processes, each one with its method of layer manufacturing, depending on printing, on material, and on machine technology too.

Indeed, as the application and growth of AM occurs, to classify them, have been developed several systems, including one proposed by the American Society for Testing and Materials (ASTM) F42 Committee.

Hence, according to the ASTM F42 Committee, the range of AM technologies is classified into seven categories, that are*: binder jetting, material jetting, direct energy deposition, sheet laminations, material extrusion, powder bed fusion and vat photo-polymerization*.

Every category includes distinct processes, sharing together the selective modelling of the layers.

Below, a diagram, illustrating the ASTM classification (2012):

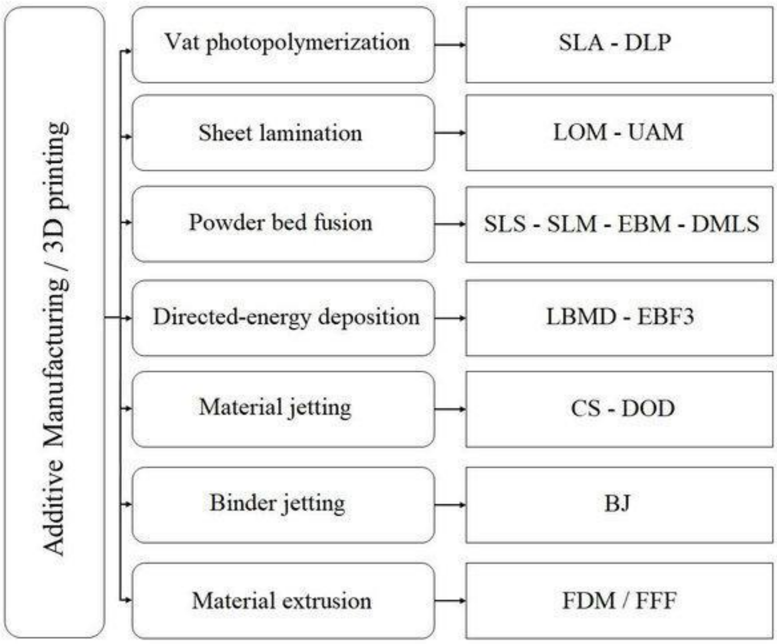


Figure 1.3*- "Standard classification of AM technologies based on ASTM F24 Committee" [5]*

Moreover, the AM processes can also be classified, based on the state of the starting material used:

State of Starting Material	Process	Material Preparation	Layer Creation Technique	Phase Change	Typical Materials	Applications
Liquid	SLA	Liquid Resin in a Vat	Light Scanning/Light Projection	Photo-polymerization	UV Curable Resin, Ceramic Suspension	Prototypes, Casting Patterns, Soft Tooling
	MJM	Liquid Polymer in Jet	Ink-Jet Printing	Cooling&Photo-polymerization		Prototypes, Casting Patterns,
	RFP	Liquid Droplet in Nozzle	On Demand Droplet Deposition	Solidification by Freezing	Water	Prototypes, Casting Patterns,
Element/ Paste	FDM	Filament Melted in Nozzle	Continuous Extrusion and Deposition	Solidification by Cooling	Thermoplastic, Waxes	Prototypes, Casting Patterns,
	Robo-casting	Paste in Nozzle	Continuous Extrusion	-	Ceramic Paste	Functional Parts
	FEF	Paste in Nozzle	Continuous Extrusion	Solidification by Freezing	Ceramic Paste	Functional Parts

Figure 1.4*- "Summary of AM process categories classified by materials" [6]*

In the following paragraphs, the most common AM process - from the Figure 1.3 - will be illustrated in detail.

1.3.1- Vat Photopolymerization

According to ISO/ASTM 52900:2015, Vat Photopolymerization (VP) is defined as an "[…] additive manufacturing process in which liquid photopolymer un a vat is selectively cured by light-activated photopolymerization." [7]

The VP process uses liquid raw material that led to micro-layer manufacturing or layer-less continuum manufacturing. The light types applied on the resin depends on the three-dimensional drawing of the part; the latter, after the layer's stratification and solidification, is created similar to the initiator drawing. The light used can be a visible one or an ultraviolet (UV), depending on the resin adopted in the process.

The process creates 3D objects starting from a liquid resin, called a photopolymer, selectively curing or hardening it, where required, throughout an ultraviolet (UV) light that emits wavelengths that can quickly bond photopolymer molecules to create the solid-state part.

The VP manufacturing process, after having received the 3D CAD information, starts from the downwards lowering of the printing platform into the vat containing the resin photopolymer, by the layer thickness. An UV light cures the photopolymer resin layer by layer and the platform, immersed again in the liquid, continues to move downwards, building additional layers on top of the previous until the object is finished.

Here, in Figure 1.5, a representation of the process above described:

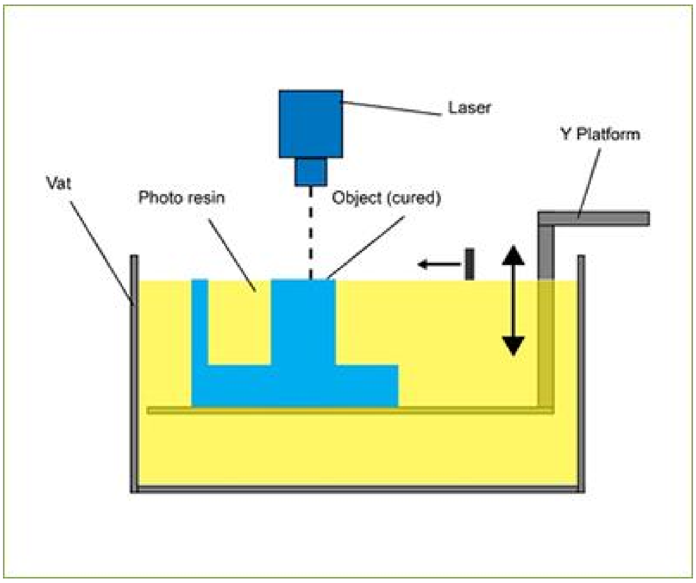


Figure 1.5 *-"Vat Photopolymerization process" [8]*

Vat Photopolymerization is commonly divided in the literature into three types, since they are different but at the same time similar: *Stereolithography (SLA), Digital Light Processing (DLP)* and *Continuous Liquid Interface Production (CLIP).*

The *Stereolithography (SLA),* is one of the early and widely used 3D printing technology. This process produces parts layer by layer, using a photochemical process in which light causes monomers to link together to form polymers. Those polymers then make the body of the three-dimensional object.

The core difference between SLA and DLP is that the latter uses a light source for the solidification of the resin. This is a digital light projector screen which flashes the image of the layer and cures the resin in the form of the layer. The digital light projector of a DLP 3D printer flashes the entire image of a layer at once and cures the layer, so layers are made faster compared too SLA process.

The limitation of DLP in comparison with SLA is the possible lack of details on a complex curved structure and the imprecise curved surfaces.

Then in the *Continuous Liquid Interface Production (CLIP)* process there is the creation of an oxygen-containing "dead zone" between the solid part and the liquid precursor where solidification cannot occur. The precursor liquid is then renewed by the upward movement of the growing solid part.

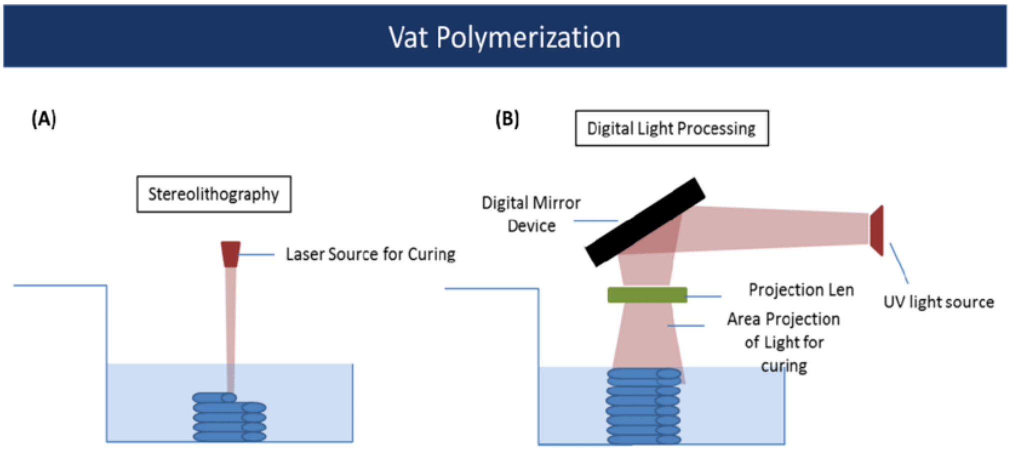


Figure 1.6-*" Stereolithography (SLA) and Digital Light Processing (DLP) processes " [9]*

1.3.1.1 Stereolithography (SLA)

SLA is the most diffuse process of the Vat Photopolymerization family, like a 3D printing process which uses a computer-controlled moving laser beam, pre-programmed using a CAD software. With SLA objects can be produced in a wide selection of materials, high feature resolutions, and quality surface finishes. The materials used in SLA are photosensitive thermoset polymers at a liquid form. Today's machines offer a range of thermoplastic materials, with several variants, as mimic polypropylene, ABS, and glass-filled polycarbonate.

The Stereolithography's rapid prototyping technology process steps are:

- The machine begins the 3D printing process by drawing the layers of the support structures, followed by the part itself, with an ultraviolet laser pointed at the surface of a liquid thermoset resin.
- After the layer is imaged on the resin surface, the build platform shifts down and the bar moves across the platform to apply the next layer of resin. The process is repeated layer by layer until the build is complete.
- The built parts are taken out of machine and put in contact with solvents used to remove additional resins. When the parts are completely clean, the support structures are manually removed.
- Finally parts need a UV-curing cycle to fully solidify the outer surface.

Regarding application in real life, most common uses are cosmetic prototypes form and fit testing, more general whatever parts that require high accuracy and surface quality. SLA is considered one of the best surface finishes for an additive process. This is due to the technical characteristics of the material used.

Indeed, SLA involves materials with high elasticity appropriate for prototype, testing and for easily duplicates complex geometries. Moreover SLA involves use of epoxy resins -among all- for excellent surface details, that guarantee a resin transparent finish.

As a result of the variety of the resins available, the SLA 3D printing process, got many applications in different industries: **standard resins** for general prototyping, **dental & medical resins**, **castable resins**, with no ash content after burnout and **engineering resins** with thermal properties.

The Figure 1.7 below illustrates a schematic representation of the SLA process:

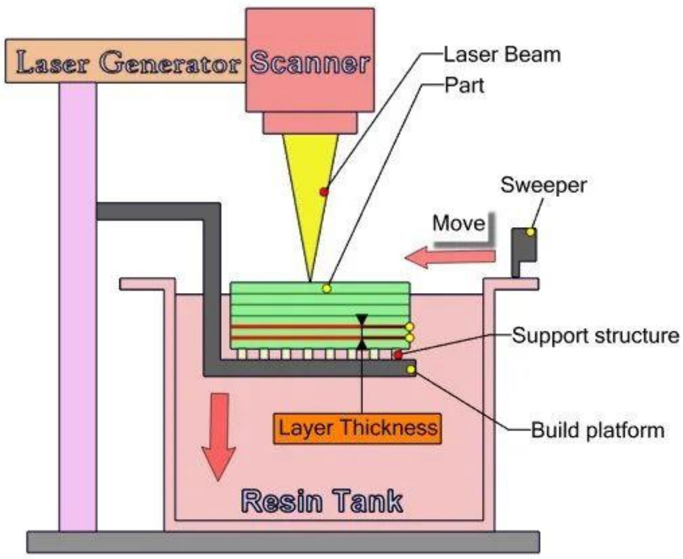


***Figure 1.7**- Stereolithography (SLA) process [10]*

1.3.2 – Material Jetting

According to ISO/ASTM 52900:2015, Material Jetting is defined as an "additive manufacturing process in which droplets of build materials are selectively deposited." [11]

The Material Jetting process is the only one –among all- that can use different printing materials within the same 3D printed model.

This process creates objects in a similar way to a technology that exist in standard home 2D inkjet printer. Indeed, the material is jetted into a build platform using a continuous or Drop On Demand (DOD) approach. The material is putted into the platform where, after solidification, the model is built layer by layer; the material deposition is carried out by a moving nozzle across the platform. The layers of material are cured or hardened using ultraviolet light (UV).

The Figure 1.8 illustrates a schematization of the Material Jetting process:

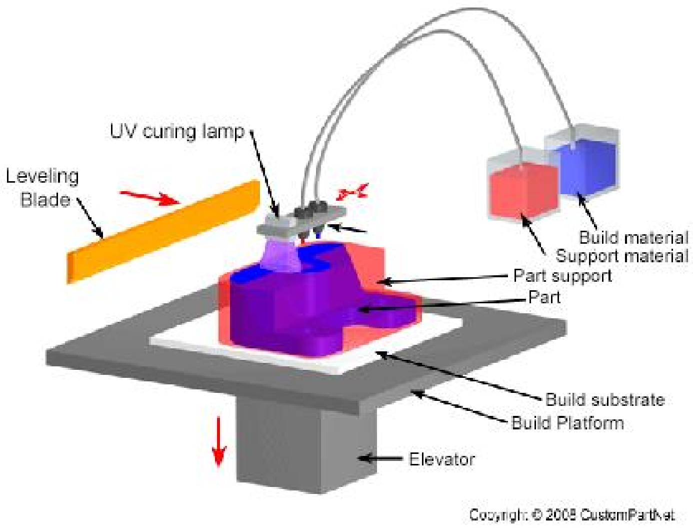


Figure 1.8-*"Material Jetting process scheme" [12]*

The Material Jetting prototyping process can be summarized in the following steps:

- The print head is placed under the platform.
- The print head bring little amounts of material to the surface, using thermal process.
- The material solidifies and forms the first layer.
- The previous steps are repeated, and additional layer are created on the top of the previous one, layer by layer.
- Layers are cooled and hardened or cured with an UV light.
- Post-processing the support structure is removed.

The advantage of this technology is the possibility to use multiple print heads together. Having multiple print heads allows these machines to print in different colours like traditional ink-jet printers, print faster by printing over the entire build surface in one pass, and print in multiple materials at the same time.

The surface quality of these objects is usually very high due to jetting very small droplets. Similar to normal inkjet printer, a 3D printer that is able to jet multiple materials, can vary material properties in the finished part and create digital materials, combining materials together.

However, the build time can be slow due to the nature of jetting very small amounts of material at a time over a small portion of the build area.

1.3.3 – Binder Jetting

The binder jetting process is defined as an "additive manufacturing process in which an industrial printhead selectively deposits a liquid binding agent on a layer of powder to build up parts and tooling" [13].

This process involves two materials: a powder-based material and a binder. The binder acts as an adhesive between powder layers, usually in liquid form while the build material in powder form. The print head moves horizontally along the machine and deposits materials, alternating layers of the build and the binder.

The binder jetting process can produce colour printing and can use three types of materials, metals (stainless steel), polymers (ABS, PA, PC) and ceramic materials (glass). The process is generally faster than others and can be more and more faster increasing the number of print head, however additional post processing adds significant time to the whole process.

The two-material approach allows for a large number of different binder-powder combinations and various mechanical properties of the final model to be achieved by crossing together the two materials.

The main process steps are:

- First, the powder material is spread on the build platform.
- The print head deposits the binder over the powder.
- The platform is lowered at the level of object's layer thickness.
- Another layer of powder is created.
- The powder linked with the liquid creates the object. The remaining powder is nearby the object.
- The steps are repeated until the creation of the object.

Below, Figure 1.9, is a visual description of the Binder Jetting process steps just illustrated above:

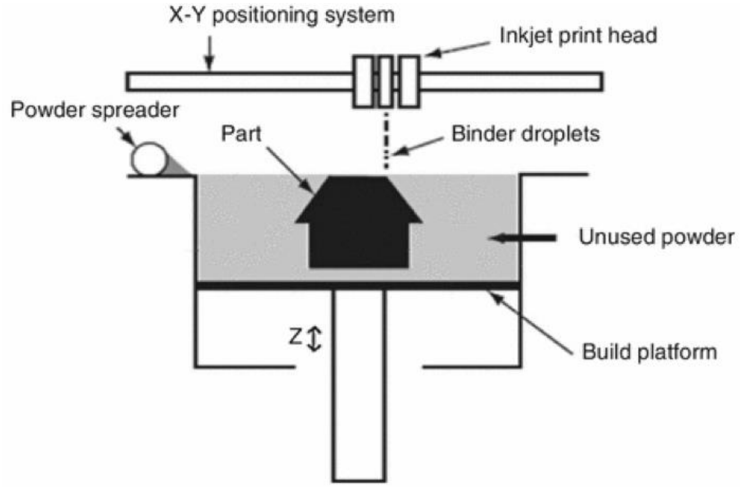


Figure 1.9- *"Binder Jetting process components" [14]*

1.3.4 – Direct Energy Deposition

The Direct Energy Deposition (DED) process is defined by the ASTM/ISO 52900:2015 as an "additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited." [15]

An example of DED machine involves a nozzle over a moving arm that deposits melted material on the surface and then solidify. Directed Energy Deposition (DED) is most commonly used for repair, rapid prototyping, and low volume part fabrication.

The base principle of the process is similar to material extrusion, but here the nozzle can move in multiple directions and is not fixed. The material, which can be deposited from any angle, is melted with a laser or electron beam. The process is used with polymers and ceramics; however its typical use is with metals in the form of either powder or wire. Typical applications are repairing and maintaining structural parts.

The most relevant steps include:

- The arm with the nozzle moves around a fixed model.
- The material -in wire or powder form- is deposited from the nozzle to the model's surface.
- The material is melted with a laser, an electron beam, or a plasma arc.
- Additional material is added layer by layer and solidifies, creating or repairing material.

The Figure 1.10 below, instead, illustrates the relevant process steps:

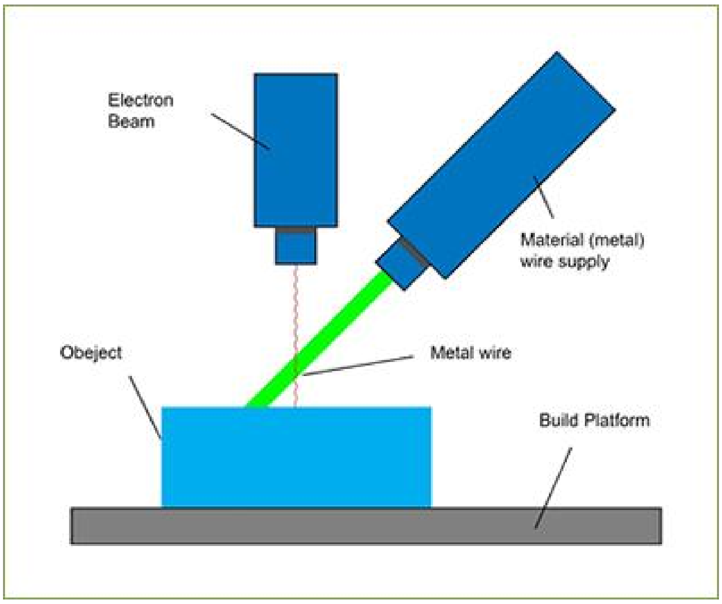


Figure 1.10 *-"Direct Energy Deposition process". Source: https://www.lboro.ac.uk/*

1.3.5 – Sheet Lamination

The ASTM/ISO 52900:2015 defined Sheet Lamination as "an additive manufacturing process in which sheets of material are bonded to form an object."

The possible lamination method is bonding, ultrasonic welding or brazing, instead the final shape is obtained by laser cutting or CNC machining. Sheet lamination processes involves ultrasonic additive manufacturing (UAM) and laminated object manufacturing (LOM).

Laminated Object Manufacturing (LOM) is one of the first AM technique born. It works with a layer-by-layer approach using paper as material and adhesive. The LOM process during the printing phase, uses a cross hatching method in order to remove easily post build. The laminated objects are aesthetic and visual models and are not useful for structural purpose. The main advantages involve the use if A4 paper, easily available and cheap, moreover a simply and cheap setup with respect to others.

The *Ultrasonic Additive Manufacturing* (UAM) process is a similar layer by layer approach, but uses sheets or ribbons of metal, instead of paper, which are then bound together using ultrasonic welding instead of adhesive. The process needs additional cnc machining and free metal removal, often during the welding process. UAM uses aluminium, copper, stainless steel, and titanium.

Below, an example of a Sheet Lamination process configuration and the relative steps:

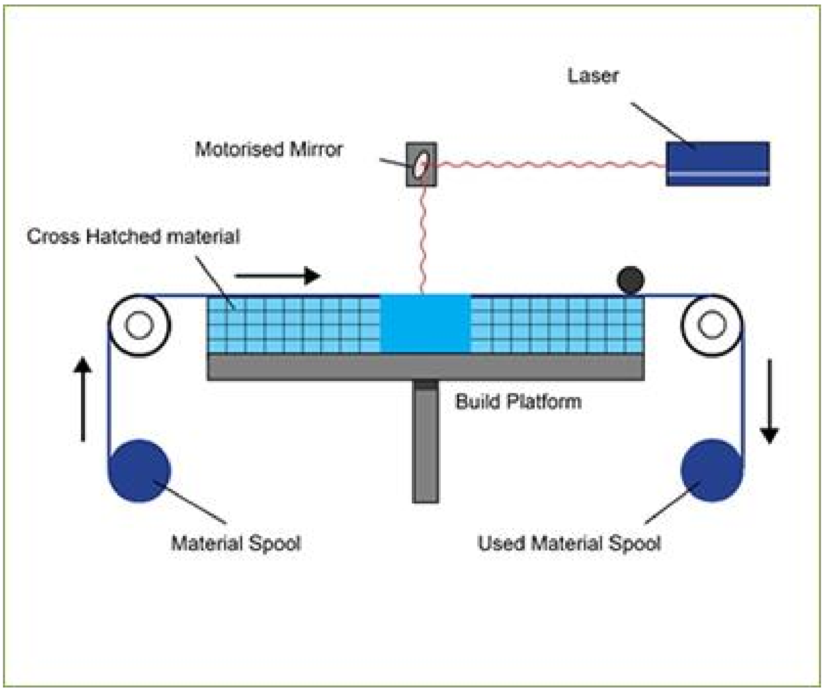


Figure 1.11 *- "Sheet Lamination manufacturing process" [16]*

The Sheet Lamination process steps can be summarized as follow:

- The material is placed in the cutting bed.
- The material is linked to the previous layer using adhesive.
- Using a laser or a knife the required shape is cut.
- An additional layer is added, and so on.
- If needed, the material can be cut before the positioning and bonding.

Between all the 7 types of AM technologies, the Sheet Lamination one creates objects with the least additive resolution. However, its low cost and faster manufacturing time allow producer to make low fidelity prototypes from easily available low-cost material.

1.3.6 – Material Extrusion

The ISO/ASTM define Material Extrusion as an "additive manufacturing process in which material is selectively dispensed through a nozzle or orifice." [15]

In the Material Extrusion process a spool of material (thermoplastic polymer) is pushed through a heated nozzle in a continuous stream and selectively deposited layer by layer to build a 3D model.

This methodology compared to other types of additive manufacturing is less fast and less accurate. However, the material extrusion technology is the most widespread and inexpensive one, along with its materials. This is the most popular process for hobby 3D printing at home. Moreover, manufacturing, and industrial sectors, material extrusion is mostly used for producing non-functional prototypes, or cheap rapid prototyping for multiple iterations of the same object.

The Material Extrusion process simplicity can be illustrated by the next steps:

- The nozzle deposits the material in the area of the first object slice and first layer is created.
- The next layers are added on top of previous layers.
- After material deposition, since the material is melted, layers are fused together.

Below – in Figure 1.12 - an exemplification of a Material Extrusion process:

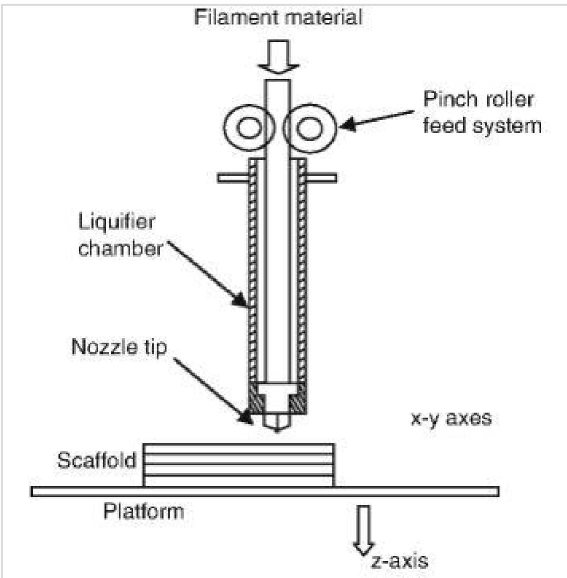


Figure 1.12 – *"Material Extrusion process"[17]*

Fused Filament Fabrication (FFF) and Fused Deposition Modelling (FDM) are the two main examples of material extrusion technology.

1.3.6.1 – Fused Deposition Modelling

In the FDM process the object is built by selectively depositing melted material in a pre-determined area layer-by-layer. The materials used are thermoplastic polymers that come in a filament form.

The FDM parts can be finished with a high standard using various post-processing methods, such as sanding and polishing, priming, and painting, cold welding, vapor smoothing, epoxy coating and metal plating.

Moreover, FDM is the most widespread used 3D Printing technology: it represents the largest installed base of 3D printers globally and is often the first technology that people came in contact with.

Regarding the defects the warping is the most common in FDM. Indeed when the extruded material cools during solidification, its dimensions decrease and different sections of the print cool at different speed. So this could be prevented by checking regularly the FDM system temperature and by increasing adhesion between the model and the platform.

Therefore a good adhesion between the layers is very important for an FDM model and this is guaranteed by the high temperature and the pressure against the previous layer.

The most relevant FDM process manufacturing steps are:

- First, a spool of thermoplastic filament is filled into the printer. Then the nozzle is brought to the desired temperature and the filament begin melted.
- The extrusion head is linked to 3-axis system that permits it to move along x,y and z directions. The material that is melted is then positioned layer by layer in determined areas where it solidifies. Sometime there can be cooling fans to accelerate the cooling.
- The step is repeated until the areas is completely filled. When a layer is completed, the platform is moved down, and an additional layer is created.
- This step is repeated until the model is complete.

In the Figure 1.17 a schematic representation of a typical FDM process:

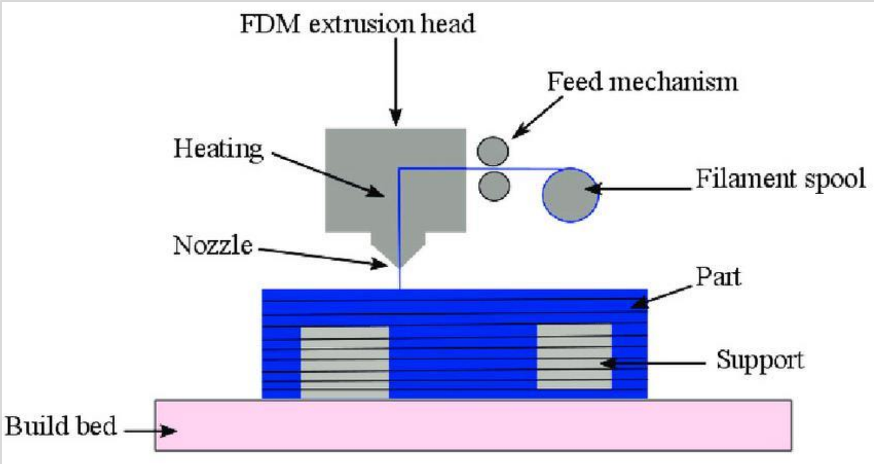


Figure 1.17 *- FDM process. Source: researchgate.net*

1.3.7 – Powder Bed Fusion

Starting from ISO/ASTM 52900:2015 definition, the Powder Bed Fusion (PBF) is an" additive manufacturing technology in which thermal energy selectively fuses regions of powder bed."

The PBF starts with the creation of a 3D CAD model then this is sliced into several layers, and a path is created for each one. Indeed, a heat source path is created defining the fill sequence and the boundary contour. Then, every layer involves the spreading of the powder material over the previous layers, and finally powder material is completely distributed in the powder bed by the means of a roller or a blade. Powder Bed Fusion uses both a laser or an electron beam to melt and fuse material power together. Post-processing, if required, permits to better make up the object for the required application. So, it can be the case of improving the quality surface finish, the improving of mechanical properties and reducing residual material.

The process can be summarized in steps as follows:

- The first layer of powder is spread over the bed platform.
- The laser melted the first layer of the object.
- A new layer is created in the same way.
- The previous step is repeated again, and additional layers are fused together with the others.
- The steps are all repeated until the whole object is created. After, post-processing operation.

In Figure 1.18 below an illustration of the PBF process:

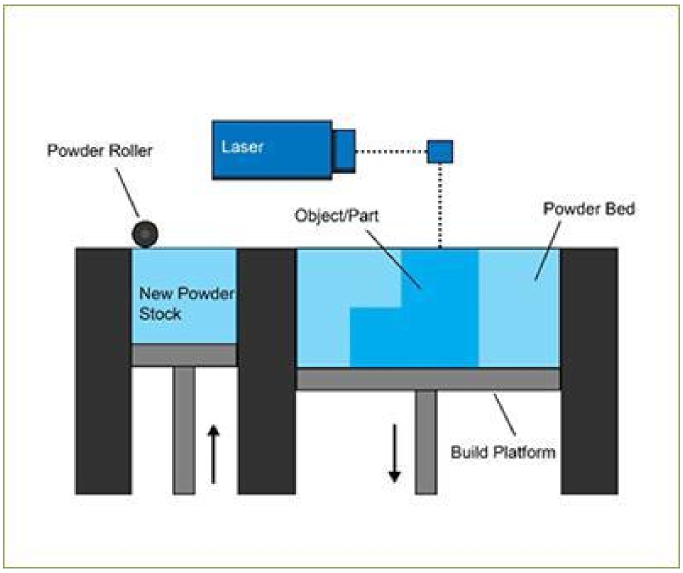


Figure 1.18 *- PBF process. Source: https://www.lboro.ac.uk*

There are many variants of PBF, depending on the heat source and the material used. The two main relevant printing techniques are: *Selective Laser Melting (LB), Selective Laser Sintering* (SLS) and *Electron Beam Melting (EBM).*

The Selective Laser Sintering is a process which sinters powder polymer material such as nylon and polyetherketoneketone (PEKK).

The Selective Laser Melting is a process similar to SLS, in which a laser is used to provide heat and fully melting the powder. This process is applicable to metal powders such as: stainless steel, aluminium alloys, and titanium. The process requires an inert atmosphere to prevent oxidation and nitriding of material.

The Electron Beam Melting is a process similar to SLM, using an electron beam instead of a laser. Below, they are explained in detail.

1.3.7.1 – Electron Beam Melting

The Electron Beam Melting (EBM) is an additive manufacturing process based on a powdered metal that is melted by an energy beam of electrons. The electron beam emits a stream of electrons that is guided by a magnetic field, melting layer over layer of powdered metal in order to create an object that perfectly respect the specifications defined by the starting CAD model. The manufacturing process takes place in a vacuum chamber to avoid the oxidation phenomenon that can affect the highly reactive materials.

The EBM technique using the implicit properties of the metal used in the process allows the building of high-strength parts. Thus, eliminating the impurities and material residues that can remain accumulate when using casting metals or other similar methods of manufacturing.

The EBM technology produces components for a wide range of industry sector such as aerospace, automotive, defence, petrochemical, and medical.

In the Figure 1.19 below, it is possible to see an EBM process schematization:

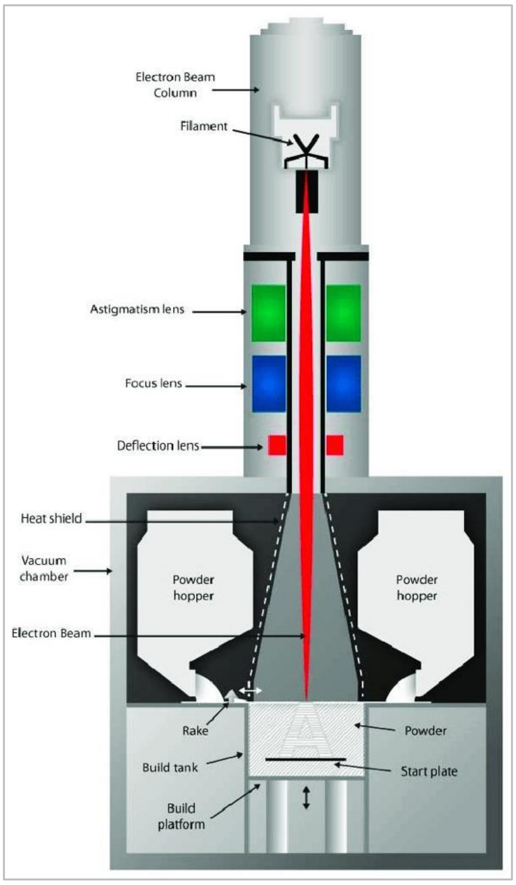


Figure 1.19 *- EBM process. Source: researchgate.net*

1.3.7.2 – Selective Laser Melting

The Selective Laser Melting (SLM) is one of the prime technologies for additive manufacturing of metal parts, used both for rapid prototyping and mass production.

The range of metal alloys available is highly large. Moreover the final object created has properties equivalent to those manufactured via traditional manufacturing processes.

As illustrated in the Figure 1.20 below, the laser melts the powder together, layer upon layer, until the model is complete.

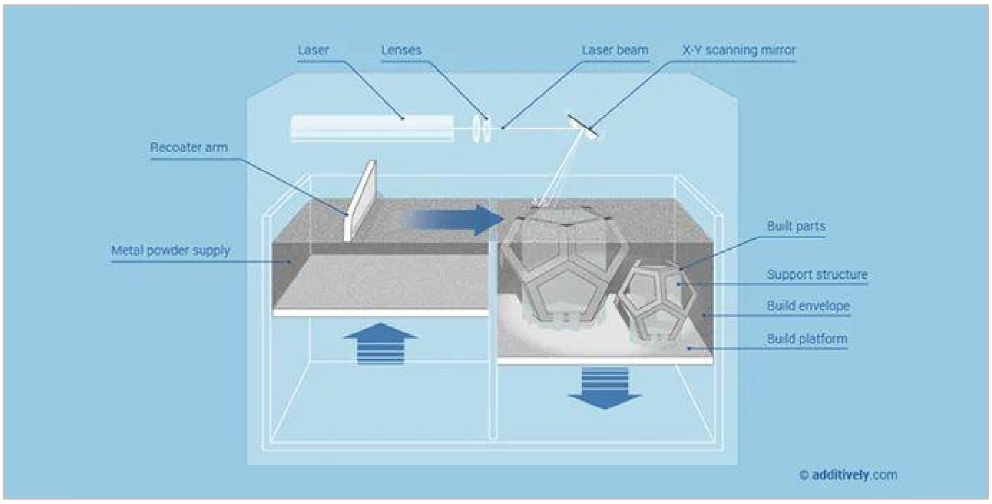


Figure 1.20 *- SLM process. Source:all3dp.com*

From a chemical perspective, the powder is melted together, resulting in a homogeneous part. The common printing materials natural ones, like titanium, but alloys are also used.

The powder bed needs support while printing, indeed SLM requires support structures to be added due to the weight of the material.

The SLM machine has a vacuum chamber filled with metal powder. The latter is then spread to the build plate in very thin layers by a coater blade.

The SLM main process steps could be schematized as follows:

- A laser melts the slice of the objects, by selectively melting the powdered material. The build plate comes back to the previous layer, and the coater spreads another layer of powder across the surface. The process is repeated until the finished part is completed.
- The entire process is performed in a controlled atmosphere (vacuum) into the machine. Once the part is complete, it can be removed from the machine. SLM parts need to be removed from the build plate. Then the support has to be removed. Although the support material is the same as the part material, the process is hard and expensive.
- The surface finish objects are rough and needs post-processing operations, depending on the material.

1.4 – Future Development of AM

The AM industry after going through a difficult, from years now is in a continuous and expanding evolution. There are different key aspects that are going to delineate the future progress of AM.

Firstly, the additive software that are considered one of the main bottlenecks of the 3D printing process. For a long-time software and hardware didn't advance together causing inefficiencies in the process. Indeed, software are crucial for AM process manufacturing steps such as part design and preparation.

Then, by relevant importance, there is the Artificial Intelligence (AI) that is gradually integrating in the AM process. From material to machine preparation, to part design, every part of the AM can get advantages from using AI. "For example, Inkbit is now developing an AI- based vision system integrated into a polymer system. This system will be able to scan each of the 3D printing layers and predict material behaviour during the print process." [18] This is why AI is going to develop more and more in order to closer integrate with the additive manufacturing process.

Another aspect is the necessity of having a better integration of software and hardware with the production environment. In fact, companies need to easily connect their machine software and production environment. This is certainly a focus point for the future development of 3D technology. As example, HP collaboration permits HP AM systems to be integrated with MES software.

Chapter 2 – The AM technology: benefits and drawbacks of adoption

2.1- Introduction

From complex engineering parts to dental prothesis and hearing aids, the 3D printing has involved a wide variety of industries to make small lots of high-performing and customized parts. In fact, additive manufacturing has firstly served niche markets, fabricating prototypes, small lots, and copy items.

Nowadays, the 3D printing is ready to enter more high-volume sector paths. The 3D printing continuous expansion will allow manufacturing of much larger objects and costs droppings. Moreover process materials are more readily available and print speeds have been doubling within two years. So, the 3D printing mass production is still present, along with its pros and cons.

According to the research report produced by MarketsandMarkets [19] "the global 3D printing market size is expected to grow from USD 12.6 billion in 2021 to USD 34.8 billion by 2026, at a CAGR of 22.5%." Moreover, the increasing demand for healthcare supplies due to the COVID-19 outbreak generated more opportunities for the providers of 3D printing solutions in the market.

The multiplicity of advantages of 3D printers over traditional manufacturing processes permitted 3D printing to gain consents from the early start. The 3D manufacturing process offers multiple advantages, such as design flexibility, rapid prototyping, print-on-demand, minimal wastage, fast designing and production, ease of access, and time and cost efficiency, amongst others. Furthermore, the reduction of time and logistics, and transport cost with respect to the traditional process, due to the increasing spreading of 3D printers and providers along the globe.

However, from the other hand, there are factors that could prevent the expansion and growth of the market in the future years, such as limited availability and high cost of materials, limitation of product size, lack of standard process control, and the threat of copyright violation.

2.2- Benefits

The Additive Manufacturing with its technologies is in a continuous evolution and non-stop development that completely change the manufacturing process. The high potential and the associated benefit of this technology induces the shift from the traditional process manufacturing to the rapid prototyping one.

Below some of the main advantages and the relative entailments are described in detail, the significant ones are Production Speed, Cost-effective, Customization and freedom, Design efficiency and Sustainability.

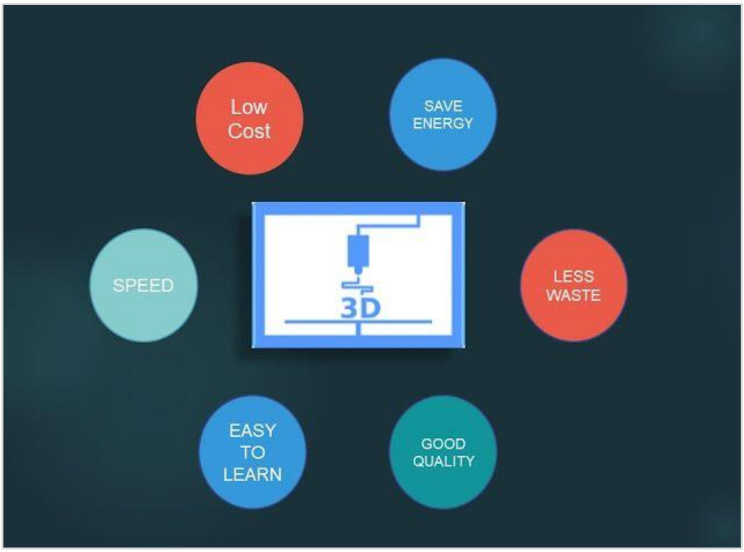


Figure 2.1 *- 3D printing benefits. Source: 1.bp.blogspot.com*

2.2.1 – Production Speed

Differently from traditional manufacturing method, the AM technique eliminate the need for tooling that led to several advantages. One of the main benefits is the decreasing time needed to manufacture a product and so the improved time to market. This advantage due to AM introduction, that allows gaining a competitive advantage, is the speed on launching a product on the market. Indeed 3D printing allows for Rapid Prototyping: designing, manufacturing, and testing a customized model in the lower time possible.

With the traditional method, before the AM outbreak, the time needed for a company to design and manufacture a prototype takes days longer. They need to do market research and proper tooling setup to operate step by step. Moreover, every time there is a change in the model, additional time is needed, the manufacturing process become longer and so time to market.

Instead, with the 3D printing techniques, it can be possible to design and manufacture the model directly on a 3D (maybe owned) printer, and finally test it in few hours. Furthermore it can be possible to make the appropriate adjustments without affecting the speed of the printing process.

The difference is significant as 3D printing enhance the freedom and creativity without additional time or costs. The lead times becomes shorter, without having to outsource complex manufacturing objects. For small business production, such as goldsmith businesses, the 3D printing prototyping is the best option concerning speed.

Figure 2.2 *- Rapid iteration prototyping. Source: bcn3d.com*

2.2.2 – Cost-effective

The majority of the businesses evaluate a new technique based on the cost reduction. One of the main benefits of introducing AM technology is that with this manufacturing process the costs decline. This reduction in particular regards the machine costs, the labour costs, and the material costs.

Indeed, for small production businesses and applications, the 3D printing process is the most convenient. The traditional printing technique such as the injection moulding require a greater number of machines, that are expensive and high labour costs due to experienced machine operators. This is opposite to the 3D printing process, where are used only 1 or 2 machines with 1 or 2 relative operators to manufacture a model.

In fact, labour costs are smaller, since the 3D process differentiate from traditional manufacturing where different people could be required to operate on different machines and may need to be formed about the work. So, the 3D printing process involves the smaller number of machines, along with only one operator, to start the design creating step. In fact, with the AM technique the whole process can be conducted from the start to the end by one operator in one machine, without outsourcing any step.

Finally regarding the material costs, in the previous chapter we said that there is a wide variety of rapid design material. The spreading and growing of these materials permit the price to decline, and to lower the total costs with respect to traditional process.

2.2.3 Customization and freedom

Another big advantage derived from the additive manufacturing technology use is the mass customization. This approach allows customers participation in the creation process and at the same time the integration to a mass production level.

The mass-customization approach redesigns the old mass-production approach theory; in fact, groups of customers are not uniformed anymore and in turns products are not satisfactory anymore to the mass as it was before.

Regarding mass-customization the Additive Manufacturing represents an interesting alternative with respect to traditional method. The 3D printing benefits it’s about that there isn’t the need for specific tools that normally are needed for traditional manufacturing processes. Indeed, with the right digital instruments, the customization by customers can be implemented within the 3D file directly, and then go to production.

Mass-customized products with 3D printing process are produced without additional costs since the manufacturing process cost didn’t change either for 1 or 1000 3D objects.

Moreover the 3D process doesn’t involve amount of fixed costs as traditional techniques, so the cost of manufacturing for specific products is lower, and in turn, there isn’t the need to apply series production to amortize costs. The AM technology, differently from injection moulding or tradition technique, doesn’t depend on cast and so immediately match to any product. The design can be replicated with several variations without any cost increases or any production loss. This advantage highly contributes to helping businesses, even small, to face up mass-customization, by establishing a flexible production process as 3D printing is.

To make an example we can look at the Normal company case. Normal company is an earphone producer that makes customized 3D printed earphones. In order to customize the product, the users can download the app, take a picture of their ears, upload it to the app which then creates the customized earphones based on the user’s preferences. From the picture to the production it takes only 48 hours.

Figure 2.3 *- Normal earphones.*

2.2.4 - Design Efficiency

Another one advantage of 3D printing technology is the product creation in one single step, with no operator's intervention during the process. Then after the design is ultimate, it is uploaded to the printer. So, there isn't the dependence on a number of different processes step that result in a major supervision over the final product.

In designing and manufacturing models, it has to be taken into account efficiency. In traditional methods of production there are many steps to manufacture a product. This, in turn, lead to a high probability of errors at each step, that can affect the whole manufacturing process and forcing the process coming back to the beginning.

In the design step of an AM technology process we can identify three main features: Quality, Risk Reduction and Complex Geometries manufacturing.

2.2.4.1 – Quality

Regarding the quality and finish of models obtained by traditional manufacturing methods, this can occur in poor designs therefore in lower quality prototypes.

On the other hand, with the AM manufacturing process the parts are printed step-by-step, enabling the constant and instantaneous monitoring of errors to reduce defective parts and wastes, while the whole quality of the parts increase.

The 3D printing technique guarantee great improvement of the design process and better quality of parts.

2.2.4.2 – Risk Reduction

As a consequence of how the design step is carried out during the traditional manufacturing process, many defective prototypes are created and discarded, that results in waste, time, and money increase.

Indeed, for each wrong prototype, the design process restart, going back to the drawing board, without assurance about the success the second time.

With the 3D printing process this risk can be removed since designs can be monitored through creating a production-ready prototype before going directly to the final model and moreover the CAD file of the model can be easily modified if needed without additional costs and wastes.

2.2.4.3 – Complex Geometries

Products which have complex geometries, such as three-dimensional structures with cavities, are very difficult to manufacture with traditional technologies like casting, milling, or turning and consequently they have enormous high costs of production.

Instead, the model that can be transformed in a 3D CAD program, can be produced with additive manufacturing technology. This technology didn't impose restrictions at any structure. Indeed, in the AM technology process the material is only added where it is necessary and must go. The additive manufacturing permits producers high design freedom while complexity isn't a barrier anymore, in the production costs too. Moreover the costs is often decreased due to the lower material consumption.

Real examples are jewellery creation which have complex design or watches that have many small and complex parts, with limited manufacturing tolerance. The 3D printing technology can make this complex geometry and at a lower cost too. The final product will have good quality as required by the design step.

Figure 2.6 *- A 3D-printed brake caliper. Source: Bugatti*

2.2.5 – Sustainability

An advantage of 3D printing is that it builds the product producing very little waste, thanks to the additive manufacturing technique. Although the traditional process produces wastes that can be re-used or recycled, it still requires time and cost efforts to determine the wastes destination. This in turn, makes large volume 3D printer a very sustainable option.

The traditional manufacturing process is typically a subtractive process, where the raw material is wasted and reused over again, so with high costs and volume of wastes.

In traditional process there is more waste material since the part is carved out of a solid block as it is in subtractive manufacturing. In the 3D printing process, instead, the model is built layer by layer of material so reducing and limiting the wastes and moreover does not require additional tooling.

Indeed the additive manufacturing technique, as the name suggests, adds the material during the manufacturing step and not remove traditional subtractive manufacturing method. As a result, with the AM process the material wastage is reduced to 70%. Furthermore, if there is any failure during the manufacturing step, in the 3d process only the printed material is wasted but in traditional method the entire block of material is wasted, increasing cost.

So, the 3D printing creates very less waste of material for a single part plus the materials used in 3D printing generally are re-usable and recyclable.

As an example, the thermoplastic materials can be melted, cured (in order to become solid), melted again, cured again, and so on. Thus, manufacturing material waste can be reused (instead of becoming waste at first time).

Moreover, using 3D printing, fewer parts need outsourcing for manufacturing. This means less environmental impact because fewer things need to be shipped across the globe and there is no need to operate and maintain an energy consumption plant.

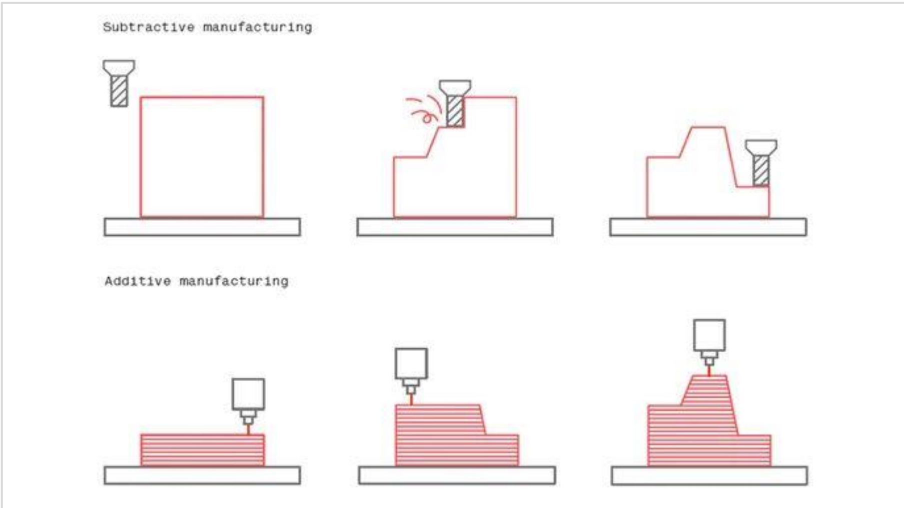


Figure 2.5 *- AM vs SM. Source: core77.com.*

2.3 – Drawbacks

On the other hand, as per each process, there are some limitations linked to the Additive Manufacturing technologies that have to be considered when adopting 3D printing technologies.

Below we describe some of the main relevant disadvantages that could be faced, that are: Energy Consumption, Materials Restrictions, Limited build size, Post Processing, Design Defects, Cost of printers.

2.3.1 – Energy Consumption

One of the drawbacks of adopting the 3D printing as manufacturing process is the energy consumption cost. Indeed, according to some studies made about this technique, the energy used with 3D printing is estimated to be 100 times more than the energy consumed by traditional manufacturing process.

However 3d printing from a side is eco-friendly using reusable and recyclable materials, it has to be taken into consideration that at the same time the process consumes non-renewable energy for its operations. A possible solution could be to use the 3D printing process for small batches of production.

2.3.2 – Material Restrictions

The biggest limitation related to the adoption of AM manufacturing process maybe is the material restriction that appear when a desired material is not available for the printing process. Indeed this material scarcity can limit the use of 3D printing for a major number of applications. This limitation is firstly due to the melted temperature of the chosen materials that cannot be always controlled.

Nowadays the material most used and spread is the plastic as it is the cheapest and easiest to adopt for the 3D printing process due to its lower melting point.

Indeed, the amount of materials to be chosen for AM technology is increasing as the technology become more known but they are still lower compared to the ones at disposal for traditional manufacturing.

2.3.3 – Limited build size

This limitation is linked to the printer size. In fact, 3D printers have usually restricted size print chambers that allows to print only small parts. In case of a bigger model to be printed, it has to be splitted in small parts to be printed separately.

After, the different parts are linked together manually by operators. It is clear that this limitation increases a lot both costs and time.

2.3.4 – Post processing

Most of 3D printing models need some post processing steps to perfectly manufacture the surface in order to obtain the required finish. The main post processing steps are cleaning, fixing, curing, or hardening, surface finishing and colouring.

The need for post processing operations depends on various elements such as the size of the model to be manufactured, the application and the technology used to manufacture the model.

The post processing operations can reflect on the speed of production, limiting and slowing it and moreover as additional costs for production. Indeed, it has been seen that the cost of post-processing operations can amount to one third of the production cost of a 3D printed object. According to the 2018 Wohler's report, 27% of the total costs of producing a model can be attributed to post-processing related costs, which include the cost of part breakage.

2.3.5 – Design defects

One other potential problem with 3D printing manufacturing is concerned with the surface finish of the final object depending on the type of machine or process used, since some printers have lower tolerances, leading to final models that differ from the original design.

Indeed Additive Manufacturing objects are likely to have various internal defects, like as powder agglomeration, balling, porosity, internal cracks, and thermal/internal stress, that can really affect the quality, the mechanical properties, and the safety of final models. The overall finish quality of the additive manufacturing powder is very rough compared to traditional powder metal materials. Moreover there is the 'layering effect' when using the AM technology, that creates a distinct layering effect.

In this case defect inspection methods are of strategic importance to reduce the defects and to improve the surface quality and mechanical properties of AM components.

The actions that can be taken to solve this limitation can be post-processing operations, that on the other hand will increase the time and cost of production and outsourcing of defective parts. Typically the parts can be outsourced for tumbling or electropolishing to increase the whole quality, however those operations can allow to dimensional accuracy problems.

2.3.6 – Cost of printers

However there are factors for which additive manufacturing is cost-effective, there are others where it isn't. In addition to the ones described above, maybe, the main relevant barrier of the adoption of the AM for an enterprise is the important high cost associated with the 3D printers that can cost hundreds of thousands of euros each, being a significant high initial investment. Moreover, there are associated implementation and extra costs such as software, material requirements, set-up, certification, post-processing, and training costs.

However, the continuous and rising spread of the AM technology in businesses in addition to a more competitive markets could allow the increasing production of 3D printers and consequently the decline of its prices.

2.4 – Materials

In traditional manufacturing process material is a precise quantity as a block of material. Its form changes in the process, but the material properties are already established.

In the additive manufacturing process the material properties depends on the geometry of the part. The raw material has an impact, but the manufacturing process also play a main role in properties of the final part, in elements such as strength, ductility, porosity and surface finish.

Nowadays, the main classes of materials used in the application of the Additive Manufacturing technology: polymers, composites, ceramics, powders, metals.

2.4.1 – Polymers

Polymers are classified into two groups based on their behaviour at high temperatures. Thermoplastics can be repeatedly melted, cooled, and hardened, and melted again, largely retaining their properties, although some degradation can occur. Thermoset polymers (also known as thermosets) are permanently "set" once they are formed and cannot be re- melted. Photopolymers are thermosets. "The polymer materials used in material extrusion systems are almost exclusively thermoplastics, such as acrylonitrile butadiene styrene (ABS), polycarbonate, polyvinyl alcohol and polylactic acid (PLA)". [20]

The PLA, polyastic acid, is the more sustainable option for 3D printers, since it is sourced from natural products, and it is biodegradable too. It is present in soft and hard forms, the objects made from polyastic acid are expected to dominate the 3D printing industry.

The ABS is relevant for its strength and safety, it is a popular option for home-based 3D printers. Moreover it is used for jewellery and vases production.

The PVA instead, is used in low-end home printers and it is useful for support materials of the dissolvable variety. Although not useful for products that require high strength, the PVA materials.

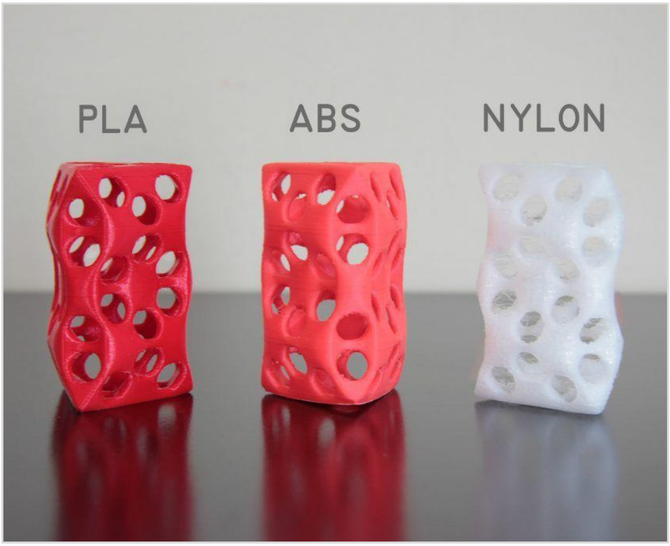


Figure 2.6 *- 3D printed parts with different materials*

2.4.2 – Composites

They are created by adding an additional material to a base material. This category that combines different types of materials are also gaining relevance in the market of 3D printing. The composite material can be formed during the 3D printing process, or that process can begin with a material that already includes an additive one.

The most common base materials are polymers reinforced with carbon or glass fibres, used for everything injection moulds to end-use parts, offering a solution in between plastics and more costly metals. These additional materials are added in order to improve the properties of the final object such as the strength, the rigidity, and the hardness.

2.4.3 – Ceramics

Ceramics have lower absorption with respect to other categories and are difficult to print with laser-based systems. They show high strength and hardness and good temperature resistance.

Mostly, the 3D printing process uses a ceramic slurry or blend of material to build parts that can then be sintered.

2.4.4 – Powders

The mostly common printers today use powdered materials to manufacture objects. The printer process melts and distributes the powder layer by layer until the required thickness and texture are achieved. The main powder source used is Polyamide (Nylon) giving its properties.

Indeed, Nylon is common for its strength and flexibility, allowing high levels of detail and accuracy on the final model. The material is especially suited for linking pieces together and dividing parts in a 3D-printed model.

Moreover, it is possible to find metals in powder form, like steel, copper, and others, in order to simplify the transport and mould into the desired shapes. Metal powder must be heated to the temperature point where it can be distributed layer-by-layer during the process to create the model.

2.4.5 – Metals

This is the second most important category of materials in the 3D printing industry. The range of metals that a 3D printer designer can choose from is huge, and it is growing in time. For the metals category, the most commonly 3D printed materials are aluminium, titanium, stainless steel, Inconel, and cobalt chrome. Copper has been difficult to 3D print with laser-based systems, but with innovations such as blue-light lasers it can be possible.

Metals for 3D printing are usually provided in wire or powder forms but can also be mixed with other materials.

Those materials are mostly used in the direct metal laser sintering (DMLS) processes; particularly in jewellery industry where products can be produced much faster and in larger quantities, gaining on costs and time.

2.5 – Applications

The Additive Manufacturing technologies are gaining more and more attention from a wide variety of sectors. Indeed, the 3d printing is not a R&D investment only anymore, but it is a manufacturing process established on the production line. Moreover, objects and models that are impossible to believe are now manufactured with this technology.

Biggest OEMs adopted the 3D printing in order to meet their performance and quality requirements; furthermore, companies used the AM approach in contemporary with the traditional one, giving birth to new possibilities.

The three main industry sectors of AM application are listed below.

2.5.1 – Aerospace

The Aerospace companies were the first to adopt additive manufacturing. Indeed, this industry is characterized by the toughest industry performance standard that exist, requiring the parts to bear every condition. Engineers and producers for both commercial and military aerospace require components made with high-performance materials.

Less material and consolidated designs result in overall weight reduction, The 3D printing technology is perfectly matched with aerospace industry, since with this technology it is possible to respect the strict standards of the sector and moreover produce parts with less material (so reducing costs and wastes), with consolidated design and with lower weight, always guaranteeing resistance.

The main notice applications include environmental control systems (ECS) ducting, custom cosmetic aircraft interior components, rocket engines components, combustor liners, tooling for composites, oil and fuel tanks and UAV components.

Figure 2.7 *- Wing brackets for Airbus A350 XWB jets. Source: ge.com*

2.5.2 – Medical

The medical sector innovation is approaching to additive manufacturing solutions to deliver a quicker and quality manufactured product to customers. Moreover, medical manufacturers can choose from a wide range of strength materials to use, such as transparent, flexible but rigid too, customizing it if required.

In this sector the additive manufacturing has achieved great advancements for life-saving device, thanks to the production of functional protypes, surgical components and real-life anatomical models.

Some of the main applications in the medical industry are pre-surgery models, orthopaedic implant devices, enclosures and specialized instrumentation, dental devices, and custom saw and drill guides.

Figure 2.8 *- Titanium hip implant. Source: EOS*

2.5.3 – Consumer products

The retail sector is one of the industry sectors that mostly exploited all the AM technology advantages. Indeed, in this industry the customers are of ventral importance. Thanks to the AM technology, the mass customization isn't anymore a utopia. Moreover, for producers the time-to-market is everything; this is why designers and producers adopted the AM technology, that helps them to develop iterations and adjust design quicker and at a lower cost with respect to traditional manufacturing.

Between the different sectors, the goldsmith industry sector is one of the sectors that main benefited from this adoption, requiring high quality and a quicker manufacturing process. As we will see in detail in the following chapters, the AM applied to the goldsmith industry allows a process smoothness that in turn lead to several benefits.

Chapter 3 – Additive Manufacturing applied to the goldsmith industry

3.1 – Introduction

"Additive Manufacturing (AM) or 3D printing has the potential to be the next industrial revolution". [21]

Historically the jewellery making industry has been defined by two major techniques: handcrafting and lost-wax casting. These both techniques involve significant technical requirements, high levels of time-consumption and defectives in the manufacture that can lead to expensive process. Today, the digital design and the 3D printing innovations disrupted these old techniques in a major way. Indeed, this new technology, supplementing traditional processes with digital innovations and techniques allows to new possibilities in designing and production to jewellers, moreover new customization possibilities for customers. The 3D printing technology applied in the jewellery production improves the principles of investment casting, or lost wax casting bringing the advantages of a digital design and manufacturing process. Using digital techniques the need for time-consuming manual labour has declined and the design is better preserved, modifiable, and duplicated when needed.

"Utilizing this technology, different kinds of products with a wide range of complexity can be manufactured on a massive scale with high accuracy. Rapid prototyping is a critical demand in most industries, and additive manufacturing can effectively fulfil this requirement". [22]

For a long time, customized jewellery was considered a privilege of a few, due to its complex geometries design and long manufacturing process. Thanks to the 3D printing technology, it is easier and faster to produce prototype of a jewel then creating custom jewels. Indeed, due to the spread of digital tools, today jewellers offer personalized creations, discussing directly with the customer, to customize a unique design as a basic service or as an additional one. In this way the models created fully meets the customers' requirements.

The prototypes can be 3D printed again in order to tailor it to the customer need and then manufactured with lost-wax casting to reduce the cost of realization of customized 3D printed jewellery. Using the full advantages of the 3D printing technology it is possible to create different jewels at the same time. Moreover with this technology the jewel is as accurate as possible, already from the prototyping model.

The Additive Manufacturing technology main quality is that it allows both unique pieces production but large-scale production too, reducing most of process steps and costs of tooling.

Currently, the traditional technique combined with high-definition 3D printing is widely used in the goldsmith, dental, mechanical, and generically artistic fields.

Thus, the 3D printing technology will not replace the art of craftmanship goldsmithing instead the combination of traditional processes with innovation technologies will offer new challenges in the design step and in cost savings.

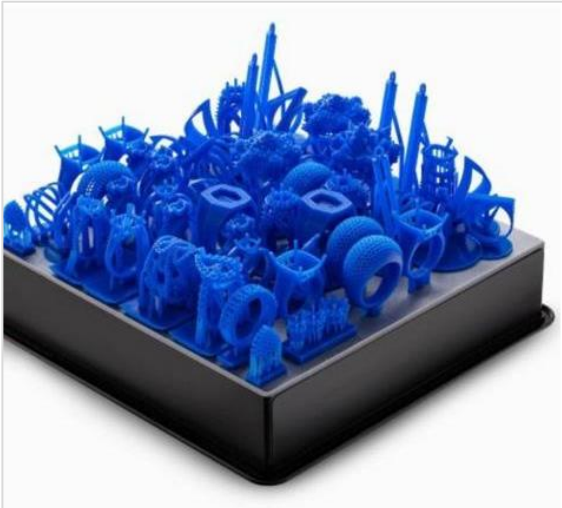


Figure 3.1 *- Jewellery prototypes 3D printed. Source: manufat.com*

Below, in the following paragraphs an overview of the three traditional and innovation techniques is presented: the Classic Microfusion, the Direct Microfusion and the Selective Laser Melting will be discussed in detail.

3.2 – Lost-Wax Casting (Classic Microfusion)

Lost-wax casting is a process for creating objects, from simple to complex, in a variety of metals (such as gold, silver, brass, or bronze) by casting an original model or pattern.

“It is one of the oldest known metal-forming techniques dating back 6,000 years, but it is still widely used for producing jewellery, dentistry, and art. Its industrial form, investment casting, is a common way to create precision metal parts in engineering and manufacturing”. [23]

Lost-wax moulding is also known as precision moulding or investment casting, since a non-permanent model usually made by wax is used for each casting.

The lost-wax casting process applied in goldsmith industry involve the jeweller to build and work on a wax model.

The process procedures prevent making a model that has to be reproduced using a ductile and malleable material such as wax, after which a mould is made around it. The structure of the mould is created to contain several objects to be melted, in a cluster arrangement around a central pillar, for costs and processing times optimization. Thus, A cylindrical mould is obtained, ready to receive the casting of molten metal.

In fact, the chosen metal (gold, silver, or bronze) is poured inside, once cooled the support is broken and the jewel is finally created. Implicit in its nature this technique gives life to unique pieces since each wax model gives life to only one piece. Once the melting of the metal has started at the appropriate temperature, it is injected into the mould by means of a centrifuge. Then there are a series of following steps which are the tempering, the breaking of the support, the acid cleaning, and the final cut of the individual jewels with shears.

From the lost wax casting process the objects come out rough and imperfect, for this reason each piece is then finished and polished by hand through post-processing activities.

Lost wax casting is a conceptually simple craftmanship method that requires great skills in order to obtain surprising results. This type of workmanship is very ancient, in fact there are many well-known sculptures created with a similar methodology, such as the Riace Bronzes or Donatello's David.

Therefore, the process is known as lost-wax moulding. Lost-wax moulding is used when casting with intricate shapes, good dimensional accuracy, and very smooth surface finishes are required.

Today, the lost-wax moulding process is used in manufacturing of large objects like cylinder heads and crank shafts. It is best suitable method when castings with intricate shapes and good dimensional accuracy are required.

3.2.1 - Process steps

The lost-wax casting process can be different depending on the sector and on the application, but it generally consists of the same technical main steps, that we listed below.

1. *Model-making:*

The starting poi is a wax matrix that is carved and shaped by the craftsman or artist through the use of spatulas, files, hacksaw, and other small tools. The size and complexity of the wax model depends on the artist's skill and the capacity of his casting equipment.

2. *Creation of a mould:*

The artisan casts the model and then polishes the casting to produce a master-pattern. The master model is used to make a wax mould out of rubber, which can be heated and vulcanized around the master casting to obtain a flexible wax mould.

3. *Production of wax patterns:*

Molten wax is injected or sometimes poured into the rubber mould. This can be done over and over to make copies of the original design. Injecting the wax into the cavity brings to the preparation of a heat disposable-wax pattern.

4. Assembling the wax pattern:

A number of identical patterns are joint together to compose a pattern assembly: patterns are attached to a central bar made of wax or plastic, the same as the leaves attached to the branches of a tree.

This tree-like structure, which provides paths for the molten wax to flow out and molten metal to later fill the cavity.

5. Application of investment materials:

The wax pattern tree is then dipped into a slurry of silica or ceramic or another refractory material. Typical slurries are made of silica flour suspended in a solution of ethyl silicate.

After dipping, the assembly is coated by sprinkling it with very fine silica sand. A support ceramic shell mould of about 6mm thickness is formed all around the wax assembly.

6. Burnout:

After the investment material dries, the pattern assembly is placed upside down into an oven to melts out the wax leaving a negative cavity in the shape of the original model.

7. Pouring:

The resulting investment mould is further heated in an oven at a temperature of about 900°C to 1000°C to eliminate all traces of wax, to gain sufficient strength and to reduce the temperature difference with the molten metal.

8. Devesting:

Once the molten metal has cooled, the investment mould is quenched in water to dissolve the refractory plaster and release the rough casting. The sprues often are cut off and recycled, while the casted parts are cleaned up to remove signs of the casting process.

9. Finishing:

In the final step the casted parts need to undergo by a several post-processing activities to guarantee a higher finishing. These activities provide the part, depending on the need, are filed, ground, polished, cleaned, and machined, or sandblasted to achieve final geometry and surface finish. Where necessary, the cast parts are also heat-treated to improve the mechanical properties of the material.

3.3 – Direct Microfusion

Moving from the Lost-Wax Casting technique into the 21st Century with Digital Design and 3D Printing, we have the Direct Microfusion technique, between the two extremes.

This technique differs little from the Classic lost-wax casting and at the same time involves the use of new technique such as the Additive Manufacturing one. Indeed, the only differences is in the initial's design steps.

Nowadays, the digital software tools and 3D printing increases lost-wax casting with the advantages of a digital design and manufacturing process.

With the digital workflow, the designers use CAD software tools to create and designs digitally and a high-resolution 3D printer to produce 3D printed patterns that can then be cast in the mould.

Then after the burnout of the positive pattern, the process follows the identical path as traditional investment casting.

Thanks to the digital techniques, the need for time-intensive manual labour is greatly reduced and the design itself is easy to preserve, modify, and recreate when needed.

"Jewellery designers can use jewellery CAD software tools to design jewellery pieces, making it easier to produce and fit complicated geometries that once required hours of meticulous labour to carve from wax".[23]

3.3.1 – Process steps

Figure 3.2 *- Direct Microfusion steps. Source: formlabs.com*

1. Creation of a digital model:

This first step involves the main revolution with respect to traditional microfusion. Indeed, in this case the model is created starting from a Computer Aided Designing software. After having decide how has to be the desired model, then it is constructed and designed with a CAD software as a 3D model, bringing the objects from the idea to a 3D printed model.

This technology allows the creation of model more precise and more accurate and allows a more flexible production too.

2. Creation of a model:

After having prepared the CAD design file, it is transformed in order to be printed. Then the file is transferred to the printer chosen and will start the selected Additive Manufacturing process based on the choice made. The jewellery models can be printed individually or in batches.

3. Creation of the wax tree:

As per the traditional microfusion process, in this step the cured prints are attached to the wax sprue to allow for a tree structure. It is better to attach the thicker parts on the bottom and the thinner parts on the top of the structure. Differently from the traditional tree structure, in this case the 3D printed parts require more space between them. The use of a wax pen facilitates the union of the resin models to the wax sprues. [24] Then the following steps are the same that follows the classical Microfusion technique.

4. Application of investment materials:

The wax pattern tree is then dipped into a slurry of silica or ceramic or another refractory material. Typical slurries are made of silica flour suspended in a solution of ethyl silicate.

After dipping, the assembly is coated by sprinkling it with very fine silica sand. A support ceramic shell mould of about 6mm thickness is formed all around the wax assembly.

5. Burnout:

After the investment material dries, the pattern assembly is placed upside down into an oven to melts out the wax leaving a negative cavity in the shape of the original model.

6. Pouring:

The resulting investment mould is further heated in an oven at a temperature of about 900°C to 1000°C to eliminate all traces of wax, to gain sufficient strength and to reduce the temperature difference with the molten metal.

7. Devesting:

Once the molten metal has cooled, the investment mould is quenched in water to dissolve the refractory plaster and release the rough casting. The sprues often are cut off and recycled, while the casted parts are cleaned up to remove signs of the casting process.

8. Finishing:

In the final step the casted parts need to undergo by a several post-processing activities to guarantee a higher finishing. These activities provide the part, depending on the need, are filed, ground, polished, cleaned, and machined, or sandblasted to achieve final geometry and surface finish. Where necessary, the cast parts are also heat-treated to improve the mechanical properties of the material.

3.4 – Selective Laser Melting

The Selective Laser Melting is an advanced additive manufacturing (AM) technique for the 3D printing of metals, That uses a high-power density laser to melt metal particles together. This technique is a revolution that completely redefines the traditional process methods that has been used for years.

Indeed, in this case, with the respect to Casting process, there is a completely change in process not only on the initial steps. The totality of the process change, in fact, the middle steps is substituted by a unique step of the SLM machine. Instead, the design steps remain unchanged.

The SLM technique, as an AM technology, builds models layer by layer allowing to create complex geometries, internal details that otherwise couldn't be made with casting process. Indeed, in this process metal parts are subjected to a lower stress that in turn reduce the need for post-processing activities. Moreover this technique produces more resistant and during in time models, that are prototype and jewels too. This is only one of the multitudes of AM printing technology, that is mostly used in the goldsmith industry for jewellery production.

3.4.1 – Process steps

1. ***Creation of a digital model:***

This first step involves the main revolution with respect to traditional microfusion. Indeed, in this case the model is created starting from a Computer Aided Designing software. After having decide how has to be the desired model, then it is constructed and designed with a CAD software as a 3D model, bringing the objects from the idea to a 3D printed model. This technology allows the creation of model more precise and more accurate and allows a more flexible production too.

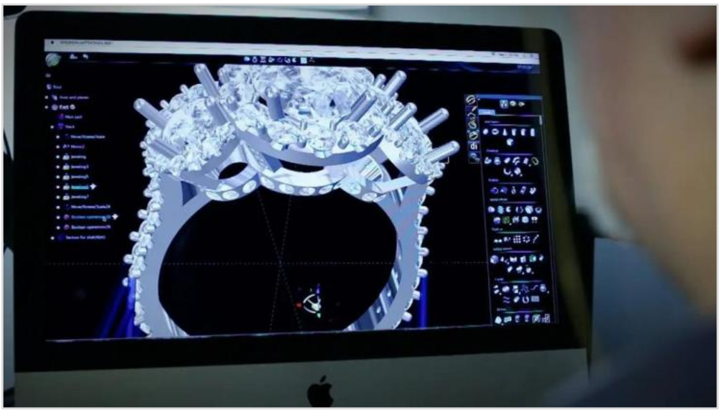


Figure 3.4 *- Digital creation of a model*

2. Creation of a model:

After having prepared the CAD design file, it is transformed in order to be printed. Then the file is transferred to the printer chosen and will start the selected Additive Manufacturing process based on the choice made. The jewellery models can be printed individually or in batches.

3. ***Printing process***

In this step, by using a SLM machine, there is the printing of the final product. The SLM printing process has been explained and illustrated in chapter 1.

The 3D file is transferred to the printing machine and the process start. First, the printer is charged with the precious powder and then the arm distributes it in layers on the platform.

Here, the laser goes on melting the metal particles together in a homogenous form. This operation is repeated as the platform continues to descend simultaneously.

This process goes on until the final object is completed and the process ended, then the exceeding powder is removed. The final object that is obtained needs, depending on the requirements, some post-processing activities, such as the polishing.

4. ***Cleaning***

The Cleaning activities is only one of the different post-processing activities available after a 3D printing. This is the most important since it is the first to be done. With cleaning activities we refer to the support structure removal, necessary for 3D printing. Then, in this specific technique, we refer to the powder removal, that can be removed manually but nowadays exist some automated solutions too. Finally there is the washing activities in order to clean the final object.

5. ***Polishing***

This 3D printing post-processing activity allows for a better-quality finishing and a smoothest possible surface. This activity can be carried out with plastic polishers and tools easily available, in addition to a microfiber cloth. Before the polishing of the part, it has to be checked that there are no particles left.

Figure 3.5 *- 3D prototype and printed model*

3.5 – Materials

As we already explained in the chapter 2.4, there is a wide, and in continuous evolution, range of materials for AM techniques. With the AM introduction in the production process, the prototype can directly be made by the printers in wax or resin. Indeed, the traditional microfusion prototypes are no more designed by hand in wax and then casted in metal.

The choice of materials to be used for the realization of a prototype is a very important step since it will affect the quality of this. Moreover, it depends too on the availability of the materials themselves and on the possibility or not of using that material for a given printer.

Among these, the main materials adopted for the 3D printing of jewellery are high performances resins. In particular, the *castable wax resin* is ideal for producing the master models of jewellery. Indeed, the formulation of this material is ideal for capturing even the smallest and most complex details, or to create perfectly smooth surfaces and finish. The castable resin burns without leaving any residue inside the mould, allowing jewellers to obtain perfect jewellery in precious metal when casting.

Additionally we have the *grey resin,* that has the particular "feature of matte finish that greatly brings out the details. This feature makes it ideal for rapid and economical prototyping of jewellery items. This material, which is sturdy enough to be handled, worn, or even shipped to a customer, is perfect for reducing customization costs and giving customers and designers peace of mind before casting." [25]

Furthermore, the *high temperature resin* has to be mentioned too. "The high temperature resin is strong enough to withstand the temperatures and pressures required for moulding medium temperature vulcanized rubber". [25]

However there is a wider range of waxes that are widely used too and still remains the favourite material chosen. Indeed this material guarantee high detailed and complexity geometry and a good quality finishing, good resistance without limiting in the use of additional materials.

3.6 – Comparison

The three technologies described above represents the main used and known technologies of jewellery production that have been and are still in use today.

As it is already clear from the description of the process steps, the differences between Microfusion technologies and SLM technology are substantial, and they result in better parameters and conditions of SLM if compared.

In recent years, Progold S.p.A., a specialized company in the production of master alloys for goldsmith's and silversmith's, has tried to integrate the SLM more and more into the goldsmith industry production, analysing and studying processes and materials, also through the creation of critical elements. This is why Progold S.p.A. then decided to carry out a comparison of the three techniques described above on the basis of a series of the optimal and most relevant printing parameters through which measure the different alternatives.

Taking the analysis carried out by Progold S.p.A. as a reference, we will go back to the main results obtained to make a comparison on the basis of four main parameters analysed, which are: limit geometries, productive lead time, production capacity and market price. [26]

3.6.1 – Limit Geometries

Geometric limitations are one of the main critical elements of comparison for the three techniques. In this case the analysis is carried out by considering the possibility to have hollow objects and the thickness as parameters.

Indeed," the presence of the refractory mould in the investment casting process with the entire chain of operations necessary for its realization and filling by the metal, is a source of geometric limitations of the jewel, which can be overcome with selective laser melting" [26]. A striking example is the fact that it is not feasible the production of an internal cable jewellery, with the internal part isolated from the outside in the Microfusion processes.

This is more emphasized in the Classic Microfusion process where this limitation is already present during the production phase of the wax model. In order to overcome this limitation, a possible solution consist in the separation of the object in two parts and in the separate fusion of the parts that will be then fused together. Unfortunately, this will lead in turn to an additional process step and to the possible presence of defects.

These problems disappear when using the SLM technique, that allows for the production of cable objects. In this case in the object production there is the need to make a limited number of tiny holes in order the powder can get out of the object without creating additional problems, while creating hollow shapes object totally closed as the one below in Figure 3.6.

Figure 3.6 *- Example of hollow wedding ring made using SLM in white gold: model 3D and printed object.*

Regarding the thickness parameter, in this case the limitation concerns with the thin thickness. Indeed, with Classic Microfusion process it is hard to obtain the desired objects with thin thickness. Indeed, “filling thin thickness often requires conditions of high wax compression, so rubber tends to swell and produce thicker or deformed models. Rubber moulds can certainly be optimized to facilitate filling, reducing pressure drops and cooling speed of waxes with a feeder structure, together with the use of waxes with better filling properties”. [27]

Moreover, creating thin thickness objects involves difficult in the extraction of the models from the moulds, causing deformity and dimensional defects.

In case of Direct Microfusion, “the use of additive manufacturing makes the production step of the model much less critical, even if an appropriate choice of polymer materials, the waxing cycle, the printing technique and the parameters will be fundamental to obtain excellent quality castings without resin residues that can clog the thin cavities to be filled”.[28]

In both the Microfusion processes, it is difficult to obtain thin thickness due to the critical step of the metallic casting in the mould. Finally, the lower limit of achievable material thickness is 0.4-0.6 mm for priests for Classic Microfusion, while it is 0.2-0.4 mm for priests for Direct microfusion.

Differently, using the SLM technique, obtaining thon thickness it is absolutely not a problem, since there is no need to fill the moulds and no need for a wax model too. The lower limit in this case is the minimum thin of the laser melting trace, that depends on materials used, printer used and process. It is around 0.1-0.2 mm.

3.6.2 – Productive Lead Time

The lead time of production of a piece is a main element for companies’ performance and competitive advantage. This parameter is different for the three different processes and also depends on the type of production, if in batches or pieces.

Progold S.p.A. carried out the analysis on lead time taking high jewellery as a reference sample, since in this market segment the SLM innovative technique is totally coherent. In the Figure 3.7 below there is a summary of the data obtained from the analysis carried out.

Production technique	**1 piece (hours)**	**10 pieces (hours)**	**100 pieces (hours)**
CLASSIC MICROFUSION	34.0	34.5	37.5
DIRECT MICROFUSION	18.5	18.5	28.5
SLM	2.0	8.0	78.5

Figure 3.*7 - Estimation of production times in classic microfusion, direct microfusion and SLM [26]*

It is clear from the Figure that in case of limited production (of the order of ten), the SLM lead time is really lower with respect to microfusion processes. In fact, in classic Microfusion producing a few pieces is not convenient due to the high impact on lead time of the prototype creation.

However, the situation completely changes if the production rate increase, with a number of pieces around 100. In this situation, the SLM lead time's is bigger than the ones required for the Microfusion processes. Again, due to prototype production time, the Classic Microfusion lead time is still higher than the one for the direct microfusion.

We can therefore affirm that the SLM technique offers a time advantage for a low number of pieces that represents an advantageous opportunity nowadays, when mass customization is the main company's strength point. Therefore, to produce limited edition pieces or unique pieces or niche pieces, the SLM is needed. In the same way, in case of series production, the most convenient technique is the Microfusion which, however, will be replaced by the SLM in case of objects with complex geometries or critical materials.

3.6.3 – Production capacity

The production capacity is an additional parameter that the study analyse. Indeed, it is one of the main elements to make a relevant comparison among the three techniques. "With production capacity it is meant that the quantity of jewellery produced every day, and it has been defined equal to the mass of pieces produced daily, as established by traditional industrial canons. The instruments made available are once again considered unitary by type and medium production capacity, while the daily working hours have been set at eight, without taking advantage of night shifts by human resources. It was also considered a single operator for each production department". [26]

In the case of classic microfusion, a baking oven can complete only one cycle in a day, due to the dewaxing process which takes a long time. However, a single oven can contain 15 cylinders. Then are added 30 seconds for the injection of a single wax and 10 minutes of assembly for each tree. In the case of direct microfusion the limit to the capacity is given by the printing of the waxes with the printer. In the case of SLM, it completely depends on the printing times of the printer. The Figure 3.8 below, summarize the data resulting from the study.

Production technique	**Classic Microfusion (Kg/day)**	**Direct Microfusion (kg/day)**	**SLM (kg/day)**
Daily productivity	3.75	2.2	0.35

Figure 3.8 *- Production capacities of the three techniques examined.[26]*

The Figure 3.8 underlines how the traditional production technologies are better in terms of production capacity compared to the selective laser melting. "However, it should be emphasized that this high potential production capacity is not always necessary and fully exploited in the field of high jewellery, where investment casting plants are often underused. In any case, the production of large batches of articles in hundreds and thousands of pieces is not convenient if you only look at the pure economic side in terms of costs using laser printing, but for series with a medium-low production volume. To date, unique pieces and niche collections remain the undisputed protagonists of SLM technology, except for particular shapes that can only be created with this technology." [26]

3.6.4 – Market price

As the previous one, this term of comparison, it is relevant in order to understand the benefits of a new innovative technology. Indeed, understanding and analysing the market price, helps to understand the economic impact and convenience of introducing a new innovative technology replacing the old one.

In the study to make a coherent evaluation since the cost of operators and the energy costs vary based on the geographical position. In this case it has been take into consideration the Italian market.

The results of the analysis are showed in the Figure 3.9 below:

Production technique	Market price (€/d)
Classic microfusion	0.2-1
Direct microfusion	2-6
SLM	4-12

Figure 3.9 *- Market prices for jewellery produced with the three techniques examined. [26]*

From the table above it is clear that the Classic Microfusion is the cheaper technique since the cost of single machine and tools used is lower than the laser printer. Moreover classic microfusion it can gain on series production lowering costs. Instead, direct microfusion and SLM shows similar prices in the market.

3.6.5 - Conclusion

Finally, we can say that, in general, the SLM technique is actually the more versatile with the respect of the microfusion ones and the one that has more potential. Moreover, it is important to choose the technique in relation to the single case necessity.

To conclude we report the final consideration of the study analysed, saying that "if at the moment the SLM technique is still seen as experimental and limited to big names, in our vision of the future the goldsmith world will use classic microfusion and SLM in equal measure. In fact, the higher cost of the jewel and the average longer production time can often be overcome by the greater geometric possibilities of SLM compared to classic microfusion. With regard to microfusion, its versatility in terms of geometries compared to the classic technique is already exceeded by the potential of SLM. Furthermore, SLM does not have negative implications compared to direct microfusion such as to be disadvantageous compared to the latter, so it is not utopian to think that in the near future it will gradually replace it."[26]

In conclusion, the classic microfusion and the SLM will start to integrate each other and coexist in the very near future, increasing the possibilities offered to jewellery manufacturers in terms of economic savings and technical solutions.

Chapter 4 – The Italian goldsmith sector

4.1 – Introduction to the goldsmith industry

“The goldsmith sector is defined as a set of activities which transform precious metals (i.e., gold, silver, platinum) and gemstones into products such as rings, necklaces, bracelets, brooches, earrings, cutlery, trays, etc.” [29].

“The piece of jewellery can be produced in an industrial and/or artisan way—goldsmith production. The difference between the goldsmith and industrial jewellery lies in the production techniques, which determine its quality and uniqueness. Furthermore, due to the high flexibility of the artisan sector, different types of products can be obtained from the goldsmith’s workmanship given the multiple techniques of material processing and the use of precious stones that make it possible to create products that are different from one another”. [30]

In the craftsmanship sector, the differentiation and flexibility of production are strategic elements for the enterprises that operate there. “Goldsmithing has been for long time an important sector within the European Union (EU) economy. The EU is an essential supplier of precious jewellery in international trade, and it is also considered to be the 2nd or 3rd largest market for the consumption of jewellery”. [31] The refined jewellery sector is defined as “driven by a growing demand for custom-made, personalised, individually designed and innovative designs of high-quality and high-value jewellery as high precious metal prices have resulted in many consumers now considering the design and innovation within a jewellery item as equal to if not more important than its base intrinsic value”. [32]

“Despite the economic crisis, the European jewellery market has consistently shown great opportunities for importers from Developing Countries. While countries like France and Italy have an established reputation for both classical and trendy jewellery, and numerous fine jewellery brands, Europe needs imports from Developing Countries mainly in the fields of costume jewellery, bridge jewellery (affordable gold and silver jewellery), special jewellery designs and jewellery components”. [33]

Over the years the EU jewellery industry has earned the esteem and reputation globally, as a manufactured of certified quality and design jewellery, moreover, produced with careful and respectful processes of environmental issues.

4.2 – AM effects on the sector

“A key opportunity is presented to the EU jewellery manufacturing sector through the harnessing of the emergent and rapidly maturing DMLM technologies and processes, which will facilitate the manufacture of uniquely designed, high-value-added, often custom-made, personalised, jewellery products that will be inherently resistant to being copied”. [34]

The innovative nature on a jewellery product can be achieved once the early stages of concept and design. The transformation of the idea into reality, so into a model, is provided nowadays by digital software like CAD and then by newly processes, from the am family.

The consumers need and requests changed the way jewellery were made. Their requirement for flexibility and customization imposed a change in the manufacturing process and impact the core of the traditional jewel production.

The AM introduction involve a new radical process that helps meet and achieve this new requirement, indeed, the AM technologies or rapid manufacturing and printing are nowadays becoming routines.

The Additive Manufacturing provides essential benefits, that has been already assessed. These benefits mainly come from the AM ability to the traditional supply chain and reduce working capital requirements and to improve the economic performance. Moreover there is a decreasing in the time to market that allows companies to achieve the final customers’ needs rapidly.

“In the long run, such shifts in supply chain structure may represent a key growth vector, as firms large and small try to capitalise on the ability to deliver faster, cheaper, and more precisely than their competitors”. [34]

Companies can begin to be highly innovative by adjusting their way to do businesses to the rules of the Additive Manufacturing by creating unique products that cannot be more produced with the traditional processes.

So, new frontiers in customized jewellery, design freedom, easier mass production, are only the main relevant 3D printing benefits of adopting this technology that will continue to attract new entrants, such as competitive independent jewellers.

4.3 – The Italian industry

4.3.1 - Overview

The Italian goldsmithing is an excellence recognized all over the world. The Made in Italy goldsmith tradition is one of the main strengths of the country: a production sector that owes its success to Italian skill, perfection, creativity, and innovation. Italian artisan jewellery has a long history that began in the shops to get to the big Italian luxury boutiques around the world today.

"The goldsmith sector is usually defined as a set of assets and undertakings processing gold, silver and platinum, coral, and precious stones for the production of items such as rings, necklaces, earrings, trays, cutlery, and other decorative objects. They excluded from this definition of gold and silver processing activities for industrial and medical uses, as well as those governing the production of coins". [35]

The companies that are part of this sector to date are approximately 11.000, with a turnover of approximately 7.4 billion euros and a workforce of approximately 40.000 employees. [36]

The recognition of the Italian goldsmith sector quality and originality of productions is all over the world. The European market is one of the main supporters for Italian products. Thus, the jewellery production also represents an important role for the Italian manufacturing itself and for foreign trades: "in 2018, 75 tons of gold were processed in Italy. A value that places us in third place in the world after China (690 T) and India (630 T). The trade surplus of the sector vis-à-vis foreign countries in 2018 was 4.5 billion euros, while the percentage of companies in the sector that export is over 75%". [37]

The Italian gold-silver-jewellery sector counts, according to the estimates from the Confindustria Moda Study Center on ISTAT- Movimprese and Eurostat data, 7,500 companies able to employ over 31,300 people. During 2018 while the active companies are overall decreased (-1.5%), the employees were affected by a significant trend positive (+ 0.7%). Sectoral turnover, specifically to companies more closely manufacturing / processing, is equal to just under 7.4 billion, as a result of a decrease on an annual basis of -2.7% experienced in 2018. [38]

Finally, it is necessary to outline how the crisis situation of these lasts two years, really affects the Italian goldsmith industry. Indeed, in 2020, the Italian goldsmith sector, as the entire world, was hit by the crisis, resulting in the worst data ever within the Italian manufacturing sector with production contracting by 27.6% (against -11.7% for manufacturing) and turnover in the 23.6% (against -11% for manufacturing). The fall in world demand for gold jewellery weights a lot (-33.5% on average in

2020 according to WGC data in tons) and led to a contraction in the Italian exports of comparable size (-31.2% in value and -29% in quantity).[39]

4.3.2 – Distribution area

The distribution on the geographic area is an important intrinsic aspect of the goldsmith industry that has to be taken into consideration.

In Italy there are three goldsmith headquarters, placed in the three main important districts: Valenza, Arezzo and Vicenza. According to the Intesa San Paolo data, 31.5% of the local units and 55% of the Italian workers involved in the manufacture of jewellery, are concentrated in these three provinces (code Ateco 32.1). Reporting data from Intesa, the province of Alessandria employs 5,494 workers (equal to 17.5% of the total Italy) and 802 local units operate in the area (representing 10% of the local Italian goldsmith units). The province of Valenza is the crib of the Alexandrian goldsmith district, presenting the highest number of employees (4,963 to be exact, equal to 90% of the employees in the province of Alessandria) and most of the local units (693, equal to 86% of the total). Valenza, compared to Arezzo and Vicenza, has traditionally specialized in high-end jewellery, thanks to the presence of n highly numerous specialized artisan industry. [39]

Below, in Figure 4.1, there are the Italian provinces with the highest number of employees and local units dedicated to jewellery, costume jewellery and precious stone processing.

	N.employees	Weight of the employees of the local units on the total Italy	Index of specialization of employees	N. local units	Weight of local units on the total of Italy
Italia	**31.393**	**100,0**		**7.903**	**100,0**
Arezzo	7.673	24,4	24,5	1.119	14,2
Alessandria	**5.494**	**17,5**	**19,9**	**802**	**10,1**
Vicenza	4.127	13,1	3,5	565	7,1
Milano	1.893	6,0	1,1	561	7,1
Firenze	1.619	5,2	2,1	398	5,0
Roma	1.094	3,5	1,7	497	6,3
Napoli	770	2,5	1,0	372	4,7
Varese	764	2,4	1,0	108	1,4
Torino	622	2,0	0,4	138	1,7
Padova	493	1,6	0,6	132	1,7

Figure 4.1 *- Italian provinces numbers (2018 data). Source: elaboration of Intesa Sanpaolo (data 2018).*

These companies developed into productive districts territorial, sharing the same values, tradition, and cultural background. There are different features that characterized districts, such as:

- the essential relationship with the market, based on the production of the specific district.

- between them, the presence of both cooperation and competition, to enhance the innovation process, under the control of local institutions.

- always ready to recognize and develop innovative mechanism, through constant flexibility to keep up with the reality.

- the principles and the feeling among each district, among the entrepreneurs itself, taking inspirations each other's.

- the main important element, from the economic side, the agglomeration economies; the presence of a mass of specialized industry in the same territory, enhancing creation of laboratory and of network infrastructures and the growth of additional services.

- the presence of tacit knowledge, such as know-how, procedures, relationships professional and personal, images.

- "social psychology" elements, such as the degree of competitiveness between industries, the trust and the social capital, the belonging to the community and the sense of identification that it gives to the people. [37]

4.3.3 – Economic aspects

In this paragraph we focus on the economic side of the Italian goldsmith industry, underlying the main remarkable and significant data about exports and indexes of economic performance.

About 75% of Italian exports in the sector is owned by the three goldsmith districts. Reporting Intesa San Paolo and Istat data, the Valenza goldsmiths showed the significant growth in exports over the last decade: between 2009 and 2019 exports increased by 1.7 billion, going from less than 400 million to 2.1 billion. In the years 2017 and 2018 the Valenza district was the largest exporter in Italy, surpassing Arezzo. The 2019 year saw substantial parity in terms of exports between the two districts. [39]

Despite the crisis, the Italian exports took advantage of the increasing demand for jewels, and, thanks to the strong recovery, they tried to come back the pre-covid levels.

The Italian gold sector is making all that it can, to seize the opportunity of recovery represented by a growing turnover of 80% compared to the lows of the 1st half of last year but which, above all, is already the 8% higher than in the same period of 2019. Always reporting Intesa data, Italian exports of gold jewels have already return to pre-crisis levels both in quantity (+ 3.6%) and in value (+ 0.4%), thanks to the United States, once again being one of the engines of the growth of the sector.

The world demand for gold jewellery consolidated in the 2nd quarter of 2021 (+ 60%) the increase already showed in the first three months of 2021 (+ 54%).

Moreover, the signs of recovery are also present in the production and turnover indexes: on average in the 1st half year, industrial production and turnover grew by about 80%, mainly due to the comparison with the data of the 2nd quarter of 2020, highly influenced by the containment measures of the pandemic; the comparison with the first half of 2019 shows however a positive evolution with an increase in turnover of 8.2% and production of 5.1%, as illustrated in Figure 4.3. The latest evidence from July also confirms this trend with indexes in growth compared to 2019 both in terms of turnover (+ 33%) and production (+ 14%). [40].

Finally about future expectations, although they will still depend on the evolution of the pandemic situation, they are oriented towards the continuation of the good development trend. There is a widespread general agreement on the high potential of the jewellery market worldwide and on the of Made in Italy companies to seize these opportunities.

4.4 – AM future outlook in goldsmith sector

According to a new report from SmarTech Publishing, the market for 3D printers, materials, software, and services used by the jewellery industry will exceed $900 million by 2026.

However, due to the high cost of printers, of large-batches 3D printing and the perceived barrier-to-entry of digital jewellery with software for the design, the 3D printed jewellery, despite its potential, still represents a relatively small fraction of the market. By the way, with a spreading in the easy to use and a more accessible 3D printing technologies, the 3D printed jewellery market will disrupt the tradition.

“New, easy-to-use materials like castable wax resin are easing the learning curve, leading to greater adoption of the workflow and the subsequent expansion of the market. 3D printed jewellery is not just a matter of technology. The newer cohorts of jewellery designers entering the industry have started education with digital methods, including training on 3D printers, as opposed to the traditional ones”. [41]

Figure 4.4 *- 3D Printer [46]*

3D printing in jewellery has a great margin of growth. With the increasing industry adoption of techniques, the arrival of new generations of designers more flexible to digitalization, and the presence of new materials and hardware, there are all the elements for a major positive disruption.

Furthermore, according to SmarTech report [42], “the demand for photopolymer resins (including wax for material jetting and non-castable prototyping materials) is expected to reach to account for 968,000 Kgs of jewellery-oriented materials consumption for AM processes as of 2022. These data reflect the steady growth in the use of photopolymer resins for direct casting in production”.

A great momentum in the increase in the use of 3D printed models for direct casting is given by the growing demand for fast fashion and mass customization phenomena that require fewer production pieces and shorter time to market. So far, the trend by creators has been that 3D printing still tends to be used only for prototype creation or model creation in the first part of the direct investment casting process. However, to date, the long and laborious manufacturing process of the craftsmen is gradually being replaced by 3D printing both in production companies and by external producers. As the SmarTech study [42] explains, this substitution is driving yearly sales of professional photopolymer-based 3D printers to reach 2,266 units by 2022, of which 70% are expected to be vat photopolymerization based systems. Moreover, the study underlines the great opportunity coming from the jewellery production with precious metal, between all, the most important is Gold, that account for over 86% of all precious metal AM powders in 2022 and remains the most commonly used in directly 3D printed jewellery. Therefore new 3D printing technologies are expected to introduce the possibility of creating new gold alloys and gold colours that are difficult to work with classic manufacturing processes.

Chapter 5 – The sustainability issues

5.1 – Introduction

Sustainability centres on global conditions of ecology (i.e. environment), economic development (i.e., by technologies), and societal equity. Sustainability, sustainable development, and sustainable manufacturing are three concepts very popular nowadays, for which there is not a punctual definition but instead there are several ones, to better interpret and explain their meaning.

In this study, some of the latter will be reported below. The sustainable development is, according to the World Commission on environment and development [43], "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The sustainable manufacturing is seen by Rachuri et al. [44] as a "system approach for the creation and distribution (supply chain) of innovative products and services that: minimizes resources (inputs such as materials, energy, water, and land); eliminates toxic substances; and produces zero waste that in effect reduces greenhouse gases, e.g., carbon intensity, across the entire life cycle of products and services". In general, sustainable manufacturing is assessed as "the essence of business, whose main purpose should be the creation of wealth throughout its whole system" [45].

When speaking in terms of sustainability, the challenge is the sustainability of the entire supply chain through traceability and a strengthening of protocols and certifications. Indeed, it is important to outline how the sustainability theme is not only respect for the environment, but for sure respect for human rights and ethics of governance too, analysing it based on a triple bottom line approach. The issue of sustainability along the entire supply chain of precious metals and jewels is indeed felt as urgent and relevant by the institutions and different society organizations, both internationally and nationally. It focuses in particular on aspects related to the management of ethical and environmental risks within the supply chain, such as the failure to protect human and labour rights in the procurement processes of raw materials, or the environmental impact of the processing of materials. precious, but not only.

Nowadays ethical responsibility and environmental impacts must still be kept in mind. The time needed to create a print can pollute but on a much smaller scale than subtractive manufacturing. It has been studied that 3D printing's waste is lower with respect to the waste produced by subtractive technologies and much of 3D printing waste is recyclable.

"Members must respect the rights of indigenous peoples and have their permission before starting or continuing mining activities in the territories where they live": the rule is the number 32 of the new

Code of Conduct of the Responsible Jewellery Council, the ong that since 2005, it has been providing sustainability certifications in the jewellery industry. An industry very committed to reduce its impact on the planet and its inhabitants, but which still needs to comply with strict and precise rules: just consider what is happening in the Amazon, where the "garimpeiros" are also setting the fires, illegal gold, and diamond prospectors. Sustainability is not a topic that affects only the origin of the precious chain, but also its final part, the consumers. Global brands such as Tiffany or Chopard know this well and also challenge each other with new initiatives and products that demonstrate their environmental and social responsibility. [46]

Engineering processes generally occupy the economic development portion of the spectrum. With respect to a manufacturing process, the driving factors of economic development include material, energy consumption, use of environmentally damaging process enablers (e.g., cutting fluids and lubricants) and water consumption. [47] In general, Additive Manufacturing (AM) processes presents relatively well environmental characteristics. Indeed, this technology uses only the amount of material needed for the whole model, so the additive manufacturing technologies have the potential to reduce the life cycle material mass and energy consumed with respect to conventional subtractive techniques by eliminating scrap, eliminating the use of harmful process enablers too. Differently AM technologies also own the capability to completely eliminate the supply chain operations associated with the production of new tooling, by having the capacity to repair and remanufacture obsolete or failed tooling. [48]

Different industrial sectors have found remanufacturing of existing products, in lieu of original production, a beneficial approach to simultaneously reduce costs, increase productivity, and reduce environmental impacts. AM technologies have made it possible to eliminate environmentally polluting process enablers in the tooling industry and to repair and remanufacture valuable tools and dies [49]. In the following paragraphs we go more in detail into the sustainability theme in the goldsmith industry, making an overview of the current status situation and deepened reviewing the AM techniques sustainability imprint.

5.2 - Sustainability of the goldsmith sector

Focusing on the Italian goldsmith sector, this is one of the main sponsors of the 'Made in Italy' among the worlds. However, as we already explain in the previous chapter, the sector has entered a phase in which its leadership is compromised due to the globalization, which has caused the unification of world markets and increasing of competition from new emerging East Asian countries. Although, the concepts of sustainability and the enterprises Social Responsibility must be kept in mind and new strategies must be implemented to develop and practice plans and actions coherent.

Below, in Figure 5.1, a schematic representation of the driving factors for sustainability in the goldsmith sector.

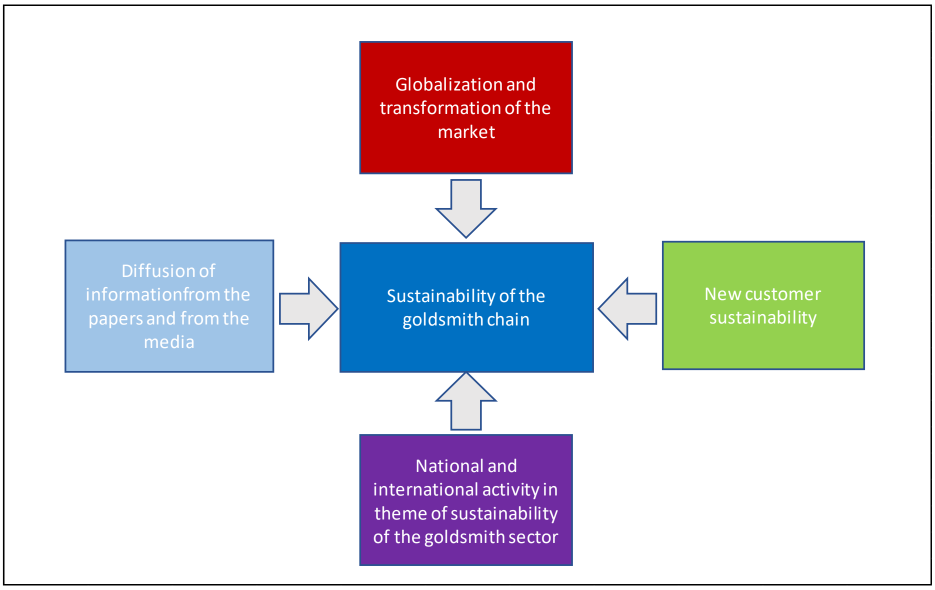


Figure 5.1 *- Driving factors for sustainability [37]*

Thus, according to the research of Bilanciarsi [37], we can affirm that these factors have to be considered when implementing a sustainability strategy. Analysing deeper these factors, first of all the globalization phenomenon mainly influenced this strategy. Indeed, globalization completely change supply chain and the way in which production processes works. This allows increasing of import and export and moreover the outsourcing. The latter permits the externalization of labour-intensive activities in developing countries to lowering costs.

As a consequence, the consumers sensibility changes too since they are more selective and informed. Nowadays consumers not only make choice on different and new criteria but want to be correctly confident and informed about the modalities.

"The new preferences of the market indicate how the awareness of the origin of the products goldsmiths and how they were produced becomes as important to the consumer as it is the product itself. According to this new trend line, gold and luxury companies have the possibility of re-establishing its business model on a more sustainable and integrated basis in their corporate philosophy (monitoring and control of ethical, social, and environmental aspects in their production and in the supply chain) and at the same time respond in a manner adapted to the demands of more informed, sensitive, and responsible consumers”. [37]

It is precisely for this reason that various actions have been undertaken in terms of sustainability of the precious metals supply chain, nationals, and internationals from governments too. Firstly there is the Responsible Jewellery Council (RJC).

The RJC is the leading standards authority in the global watch and jewellery industry and works with members worldwide to create a sustainable supply chain. It is the global membership and standards body for responsible jewellery throughout the entire supply chain, from mine to retail. [52] The RJC has developed a common platform of standards for the precious industry supply chain and some reliable mechanisms to attest to responsible business practices, using third-party auditing. This mission is also carried out by the Associazione Federorafi italiana, that adheres to the RJC system. The certification released by the RJC ensures that member organizations and operating in the goldsmith sector develop their activities in a responsible way, carefully not to harm the human and social rights of the workers involved in the supply chain of gold (extraction, transport, transformation, and processing) and to enhance the environmental performance.

Furthermore, projects with the Organization for Economic Cooperation and Development (OECD), for the promotion of responsible investment through improved due diligence in the mining industry. The International Council on Mining and Metals (ICMM) which also developed an interesting analysis of current standards in the mining sector, placing them in correlation with the international guidelines, including the OECD Guidelines. Finally, the Ministry of Economic Development (MISE), Confindustria Federorafi and the Responsible Jewellery Council (RJC) signed a Memorandum of Understanding, in order to cooperate in the development of joint projects aimed at improving social, environmental, and labour practices in the jewellery Italian sector.

Among the activities carried out by the MISE, in addition to training and awareness-raising seminars and research to investigate the level of knowledge of the subject, it has defined a first set of indicators for the management of the ethical and environmental impacts of goldsmith companies.

Regarding indicators, the set of these proposed takes as a reference, by reworking them, different KPIs developed by multiple national and international reference standards. However, the set of indicators has been enriched with further customized KPIs in function of the reference supply chain and elaborated again following the indications of various documents such as: OECD guidelines, GRI-G3 guidelines, with particular reference to the sector supplement relating to mining and quarrying. [37]

As a reference we report two of these indicators proposed: in the section of the environmental approach, we have the indicator "management of activities from the point of view of impact on the environment", in order to describe the overall strategic approach of the company to minimize its impact; another one on “materials and raw materials”, used to describe the policies and programs implemented to reduce consumption and for recycling and reuse; “energy management and consumption”, to describe the policies to increase energy efficiency, renewable supplies, consumption reduction, indication of direct consumption and indirect. Finally, one on “management of waste discharges and emissions”, indicating the total waste disposed, the management of disposal, the losses of harmful materials and the actions to reduce them.

Regarding the awareness-raising seminars and research to investigate the level of knowledge, according to the study these are the data: the business managers interviewed are familiar with the issues related to Responsibility Corporate Social in 76% of cases. 67% of the interviewees are familiar with the OECD Guidelines; while, only 7% of companies are aware of the Italian National Contact Point (NCP) as an organization promoting OCS principles and guidelines on the territory. [50]

5.3 - The materials supply chain

The impact of materials on sustainability is one of the main factors influencing the latter. In this paragraph we underline the importance of managing the precious metals supply chain. The main actions to be implemented are the traceability of raw materials, the guarantee of precious metals and responsible sourcing. As we already said in the previous paragraph, the selection of materials to guarantee a responsible sourcing has to be based on the RJC guidelines. Moreover, the advent of a European legislation (EU Regulation 821/2017) imposed the obligation of control of sources of supply for precious metals of extra-EU origin.

The goldsmith supply chain, along which the supply and demand of industries and companies which operate in the jewellery sector, it is very complex and fragmented. The complexity comes from the fact that raw materials can come from different types of mines and from different countries. To better understand the nature and essential characteristics of the goldsmith supply chain two explanatory tables are presented below in Figure 5.2 and 5.3. The gold chain (representing the "precious metals") and diamonds chain (representing the “precious stones”).

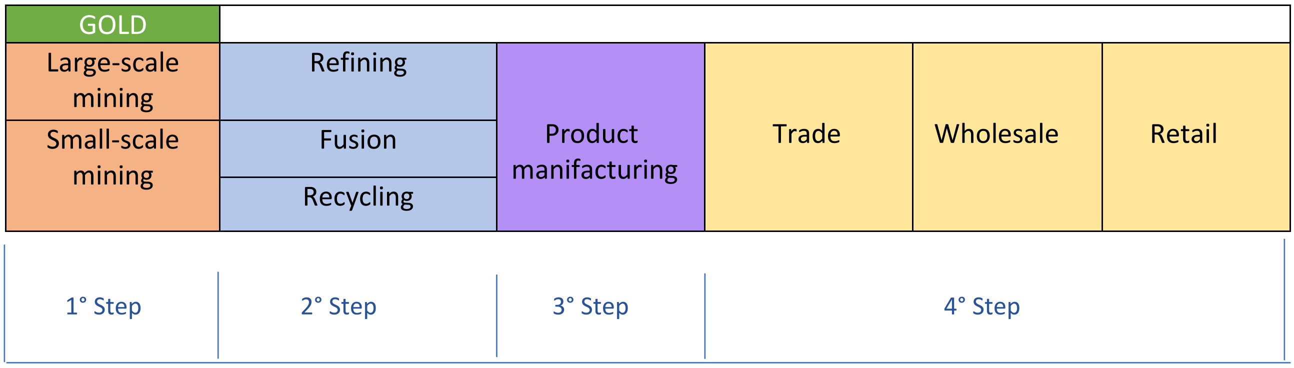


Figure 5.2 *- Gold supply chain. [37]*

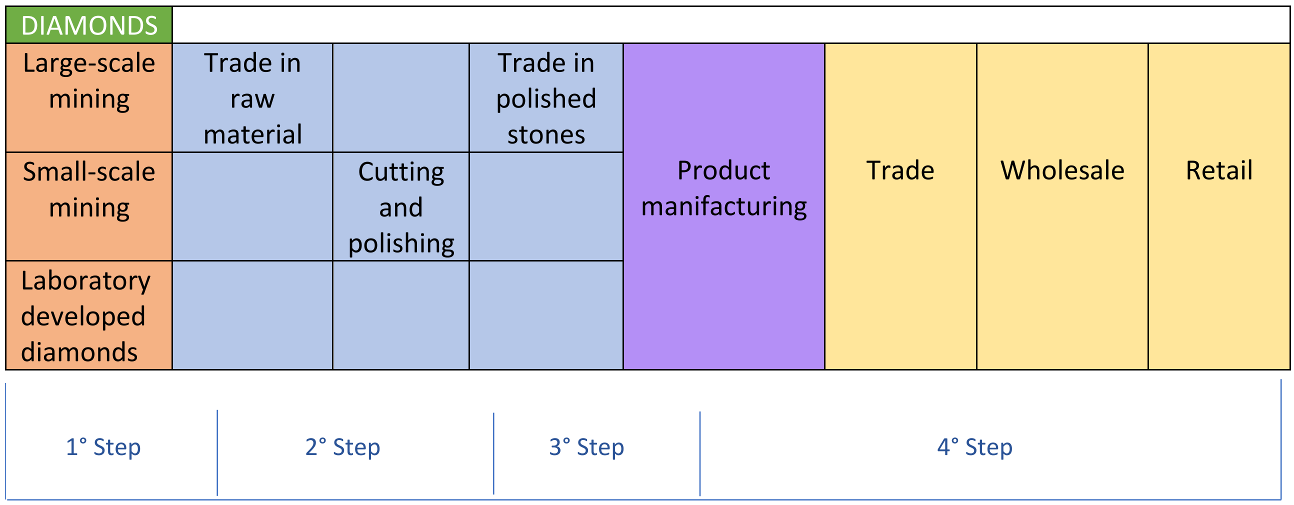


Figure 5.3 *- Diamonds supply chain. [37]*

In general, the life cycle of a jewel is characterized by the following phases, indicated in Figure 5.4:

Figure 5.4 *- Lifecycle of a jewel. [51]*

The whole production process inevitably generates both scraps than waste. It is a particular feature of the goldsmith sector that of the process of "recovery" of precious metals, allowing for economic opportunity even earlier than ethics, following the principles of the circular economy for the aim to minimize losses from processing, since those quantities in the manufacturing process otherwise would be dispersed. The scraps processing and blanking scraps are recovered and sent for remelting, in order to get the precious metal back in its natural state. In most cases, all waste or cleaning residues that they may contain, even minimally precious metals undergo the refining process, or to the merger of the waste and the decomposition into its chemical elements.

Regarding precious materials, we now make an excursus about these materials, in particular about gold and silver, reporting data and characteristics and assessing environmental impact values. The paper [58] report the annual production and reserves, the embodied energy, the process energies, and the carbon footprints associated. It is important to underline as the mechanical, thermal, and electrical properties, influence the environmental impact of the use-phase of life. Moreover there are additional information about recycling at end of life. The data are presented as ranges values of the property. When a single value is needed for projects, it has to be used the mean of the two values showed on the list. The measurement is made according to international standards and databases. They are not exact, but their precision is reported, with a standard deviation of 6-10% at best. Comparing precious metals with other classes of materials, metals are heavier but stronger, tougher, and stiffer. They present high melting points, allowing some metals alloy being used at temperatures as high as 2,200 °C. Furthermore, only gold is chemically stable as a metal itself, while all others need reacting with oxygen or carbon to form more stable materials than the metal itself. Regarding metals characteristic, they are first of all ductile, permitting them to be shaped by rolling, forging, drawing, and extruding; moreover they are easy to work with precision and they can be connected in many different ways. This permits a flexibility of design with metals that is only now being challenged by polymers. [58] Evaluating the primary production of metals this is high energy intensive. Many of these needs, at least, twice as much energy per unit weight than polymers. However, mostly metals can be recycled efficiently, and the energy required to recycle is lower than that required for primary production.

The gold is considered and estimated as the mainly important metal present in the world; its peculiarity is the rich color, its malleability, its resistance to almost all corrosion, and its scarcity that determine it as the most desirable of metals. Around the 90% of the global production of gold is transformed as bullion and jewellery. The remaining 10% used in the electronics industry as interconnectors and as surface parts on connectors. Moreover, gold owns high electrical conductivity and resistance. [58] Below, in Figure 5.5, we report the eco properties from the paper [58], of material, of processing, and of the end of life, for Gold, with a particular focus on energy and CO2 footprint:

Gold bullion and gold in electronics, from which it can be recycled

Eco properties: material				
Global production, main component	2,4000			metric ton/yr
Reserves	50,000			metric ton
Embodied energy, primary production	240,000	–	265,000	MJ/kg
CO_2 footprint, primary production	25,000	–	28,000	kg/kg
Water usage	126,000	–	378,000	L/kg
Eco properties: processing				
Casting energy	6.0	–	6.6	MJ/kg
Casting CO_2 footprint	0.45	–	0.5	kg/kg
Deformation processing energy	1.0	–	1.7	MJ/kg
Deformation processing CO_2 footprint	0.11	–	0.14	kg/kg
End of life				
Embodied energy, recycling	650	–	719	MJ/kg
CO_2 footprint, recycling	41	–	45	kg/kg
Recycle fraction in current supply	40	–	44	%

Figure 5.5 *- Eco properties of gold. [58]*

Silver is a soft white metal that owns the highest electrical and thermal conductivities with respect to all other metals. It is presented as a by-product of copper, lead, and zinc refining. However, it is valued as a precious metal, used for jewellery, tableware, musical instruments. Moreover it has many industrial applications as electrical conductor, in photographic film and photovoltaics, pharmaceuticals. Silver is a non-toxic material and has good antibacterial properties. [58]

Below, in Figure 5.6, we report the eco properties from the paper [58], of material, of processing, and of the end of life, for Gold, with a particular focus on energy and CO2 footprint:

Silver bullion and solid silver conductors

Eco properties: material

Global production, main component	21,800			metric ton/yr
Reserves	495,000			metric ton
Embodied energy, primary production	1,400	–	1,550	MJ/kg
CO_2 footprint, primary production	95	–	105	kg/kg
Water usage	1,150	–	3,460	L/kg

Eco properties: processing

Casting energy	6.8	–	7.3	MJ/kg
Casting CO_2 footprint	0.5	–	0.56	kg/kg
Deformation processing energy	1.7	–	3.5	MJ/kg
Deformation processing CO_2 footprint	0.13	–	0.26	kg/kg

End of life

Embodied energy, recycling	140	–	170	MJ/kg
CO_2 footprint, recycling	8.4	–	10.2	kg/kg
Recycle fraction in current supply	65	–	67	%

Figure 5.6 *- Eco properties of silver. [58]*

As an example, we report the Unoaerre company case. [51] Unoaerre is a goldsmith industry of the Arezzo district, that own business activity as a deeply connected production organization to the social, environmental, and cultural reality that surrounds it. The company released an annual sustainability report where it collected data and improvements already carried out and future inside. In the 2020 financial year, the overall energy consumption was equal to 22,563.6 GJ (a decrease compared to 2019), 90% of which are related to the purchase of electricity for offices and production departments. The table 5.1 below shows the quantities of pure gold and silver that entered the company:

Used materials (Kg)	2020		2019		2018	
	Amount	From which from certified source (RJC-LBMA)	Amount	From which from certified source (RJC-LBMA)	Amount	From which from certified source (RJC-LBMA)
Gold	9.529,48	8.793,95	13.988,20	12.381,62	14.498,06	12.746,20
Silver	24.010,81	12.428,02	31.877,99	-	31.841,56	-
Aluminium	18.000	-	32.100	-	53.000	-
Brass	53.700	-	93.700	-	126.100	-

***Table 5.1** – Amount of material used by Unoaerre. [51]*

The table below shows the quantity of precious raw material used deriving from the refining process:

Raw material used for refining (Kg)	2020		2019		2018	
	Amount	Percentage	Amount	Percentage	Amount	Percentage
Gold	4.980,94	52%	7.397,25	53%	7.220,77	50%
Silver	5.001,10	21%	6.827,29	21%	6.743,89	21%

***Table 5.2** – Amount of raw material from refining used by Unoaerre. [51]*

Finally, we report the waste management they declared, in order to have a complete analysis, under all main aspects, with data from a real case.

		2020			2019			2018		
Tons of product waste	Activity code	Hazardous waste	Non-Hazardous waste	Total	Hazardous waste	Non-Hazardous waste	Total	Hazardous waste	Non-Hazardous waste	Total
Recycling HCl*		220	-	**220**	680	-	**680**	580	-	**580**
Composting	D8	5	12	**17**	19	27	**46**	-	30	**30**
Recovery, including energy recovery	R3; R4; R5; R6	31	316	**347**	56	442	**498**	81	507	**588**
Incineration	D10	2	-	**2**	1	-	**1**	2	-	**2**
On-site storage	R13; D15	29	58	**87**	18	76	**94**	57	72	**129**
Disposal	D9	10	93	**103**	52	206	**258**	86	104	**190**
Total		77	479	556	826	751	1577	806	713	1519

***Table 5.3** – Tons of waste produced by Unoaerre. [51]*

During the year, the company produced a total of 556 tons of waste, 89% of which was hazardous waste. Furthermore, during 2020 UNOAERRE emitted a total of 2,511 tons of CO2 equivalent into the atmosphere, divided as follows:

CO2 equivalent emissions	2020	2019	2018
Scope 1 **Direct emissions produced by fuels for heating, incineration processes and for the company fleet**	580	716	671
Scope 2 **Indirect emissions from energy consumption, associated with the use of electricity**	1.931	2.429	2.369
Total	2.511	3.145	3.040

***Table 5.4** – Emissions of CO2 equivalent by Unoaerre. [51]*

During the year, the company produced a total of 556 tons of waste, 89% of which are dangerous waste, consisting mainly (about 30%) of sludge from the treatment of effluents and from acids exhausted from the production cycle (about 44%).

Analysing, comparing, and searching for data about sustainability input in the sector is not so easy, since there ae still a great margin of improvement and disclosure of sustainability theme. Clearly, regulations and certifications are a good way and an assurance on which evaluate the company policy.

5.4 – Additive Manufacturing impact on sustainability

In this paragraph we centralized the attention on the Additive Manufacturing processes' sustainability. As we already analyse, AM processes only use the raw material required to create the final model, and in some cases a lower amount for the support structure, thus, they are highly material resource efficient, reducing the raw material-to-product ratio (the weight ratio between the raw material used for a component and the weight of the component itself) significantly. Sustainability is a complex theme, in manufacturing, there are different issues along with the waste generation, the energy consumption, the water usage, the sustainability of feedstock, the supply chain related energy costs, the product usage impacts and the end-of-life considerations such as disposal and recycling, and the environmental impact of the model created.

According to the "Sustainability issues in laser-based additive manufacturing" [47] research, in terms of carbon footprint reduction, there are five main environmental and sustainability advantages to the adoption of additive manufacturing:

1. Lower amount of raw material, and related extraction and mine, required in the manufacture.

2. Reduction in energy consumption due to process with low energy-consumption with respect to CNC.

3. Potentiality and capacity of designing, thanks to digitalization, parts with efficient and highly performance geometries.

4. Lower weight of transport-related products that allow for carbon footprint improvement.

5. Parts could be processed closer to the point of consumption.

However relatively few AM processes have been directly analysed for energy and environmental impact. The need for research in this area was identified in the 2009 Roadmap for Additive Manufacturing Workshop [53], that has been summarized and reported in the paper cited above [47]. The main part of interest is here reported to have a complete view of the AM impact, stating that “the Additive manufacturing processes as compared to traditional manufacturing processes (casting, machining, moulding) offer the potential to positively impact sustainability. The materials usage is optimal and in many cases AM scrap rate is negligible”. Furthermore, they declare that “the energy footprint of AM can be low, particularly for processes which do not involve lengthy processing at elevated temperature. There is no requirement in AM for ancillary, sustainability-impacting cutting fluids, casting release compounds, or forging lubricants. Some AM processes, particularly those based on metallic powder deposition methods (i.e., LENS, LAMP, DMD, etc.) are particularly well suited for automated part repair. A large amount of energy is saved when a part is repaired or refurbished and placed back in service rather than being replaced and disposed. The entire production chain of tooling is eliminated. Since AM manufacturing tends to be regional and delocalized, there is a reduction in transportation which impacts carbon emissions and overall energy consumption. Finally, the design freedom of AM allows parts to be produced with superior energy consumption in service. Examples include incorporation of conformal cooling channels, gas flow paths, streamlined geometry, lightweight cellular parts, etc.”

Particularly, in the paper [52], they present an energy assessment, that we report below, for a 3D Selective Laser Sintering (SLS) process, using the Systems Vanguard HiQ+HS Selective Laser Sintering (SLS) machine. In the study the power consumption was measured for various energy consuming SLS components.

The parameters based on which the machine worked, were: the laser scan speed was 10 m/s; the powder layer thickness was 0.15 mm; the laser power was 50 W. The warmup height was 12.7 mm;

the build height was 340 mm; the cool down height was 2.5 mm. All the four heater zones were initiated at 100°C. The part heater had a build zone temperature of 186 °C, and the right feed heater and left feed heater were set to 142 °C. The part cylinder heater zone had the lowest build zone temperature of 138°C. The cool down zone temperature of both the feed heaters was 45 °C, whereas the part heaters had a temperature of 60 °C.

The power was revealed to be 19.6 kW. This was an average power value obtained during the entire build. The original power values were found to vary from 12 kW to 24 kW. The variations were attributed to individual components of the system that switch on and off at various stages during the build process. The approximate values of power consumed by the individual components are given in Figure 5.7 below. [52]

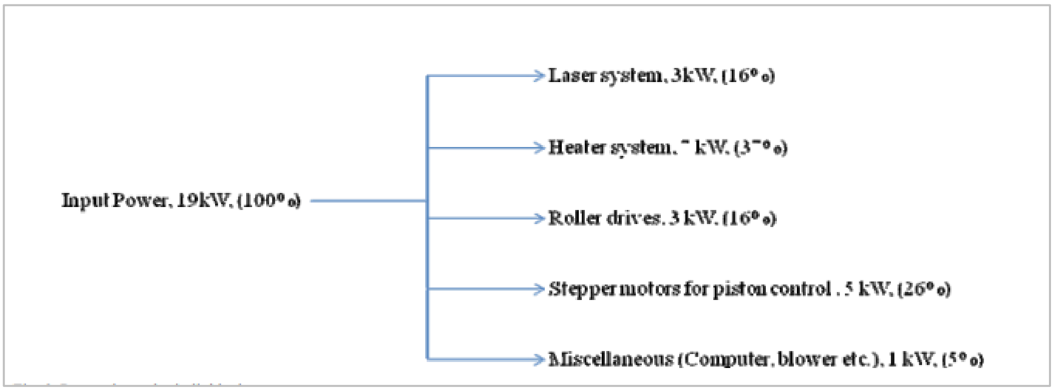


Figure 5.7 *- Power drawn by individual components. [52]*

Analysing results, about 40% of the energy was used by powder feed and partbed heaters. Around 25% of the energy was consumed by feed and build piston stepper motors, with 16% consumed by the laser system. Energy consumption may be reduced by better thermal management or elimination of the need to heat the powder. Use of high-efficiency lasers is another way to produce significant energy savings. The associated eco-indicator for SLS was 8.3 which was comparable to other AM processes.

Furthermore, to perform a sustainability analysis to determine the total energy factor, there was the need to use an Eco-indicator. The Environmental and Resource Management Data (ERMD) define what the environment actually is and how to quantify the consequences of impairment of the environment. In this study, they use the ERMD data, Eco-indicator 95. The higher the indicator, the higher is the environmental impact. It resulted to be approximately 8 which compared competitively with that of others two AM processes, the Stereo Lithography (SLA) and the Fused Deposition Modeling (FDM), which were 12 and 13, respectively. Then, from research at Loughborough

University that study energy consumption patterns for a polymer laser sintering machine and direct laser melting machine (SLM) [54]. The polymer process takes only 3 kW, due to better thermal insulation and more efficient laser system. The SLM was found to consume even less power (approximately 600 W). The power consumption decrease is mainly due to the laser type and the absence of heater systems.

However, there are some other researchers have estimated the environmental impacts related to the powder production phase based on theoretical process performance evaluations as well as datasets collected in laboratory environments. [55] The results are reported below in Figure 5.8:

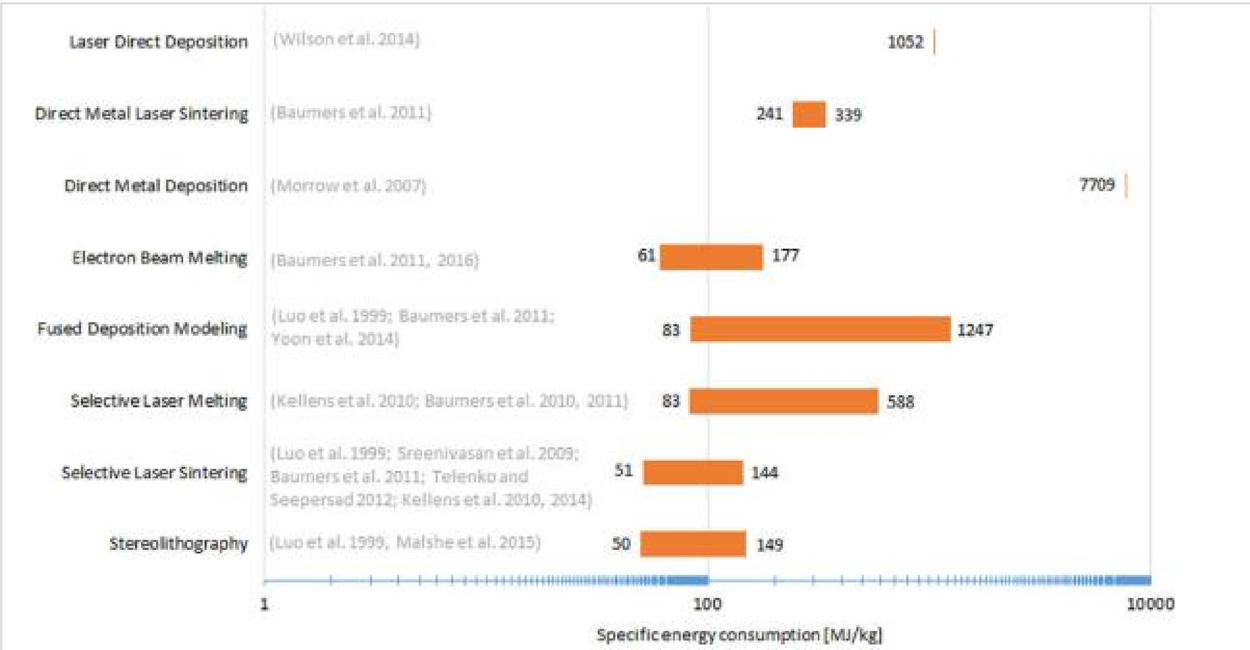


Figure 5.8- *Specific energy consumption (logarithmic scale) for AM systems. The energy values represent the electrical energy demand of the AM systems. AM = additive manufacturing; MJ/kg = megajoules per kilogram. [55]*

Among the potential Life Cycle Benefits of Additive Manufacturing processes for the model manufacturing, there are the environmental improvement in terms of weight reduction and the efficiency improvement.

The research literature presents different "design for AM" case studies in which elements have been redesigned to reduce weight meanwhile the original functional design requirements (i.e., strength, stiffness) are still achieved. From an environmental perspective, the weight reduction in transport can in turn lead to significant reductions in energy consumption and carbon emissions over the life of the transport system. "One of the most well-known examples of lightweight components is the fuel nozzle implemented in the LEAP jet engine by GE Aviation (GE Aviation 2016). The AM manufactured nozzle is 25% lighter, offers a cost reduction of 75%, and contributes to the aircraft's fuel efficiency.

Furthermore, the nozzle has a simpler design (one component instead of 18 beforehand) and more intricate cooling pathways and support ligaments result in a 5 times higher durability”. [55]

5.4.1 – Comparison between AM and traditional processes sustainability

In this sub-paragraph it is presented a general overview of comparisons between the environmental performance of CM traditional process and the AM processes. Firstly, it is important to underline that the new AM technologies parts presents lower dimensional tolerances and surface quality, and often need postprocessing, usually undertaken by CM processes. In consequence, AM is not an independent technology, as it is often presumed in case studies, indeed the AM is not a substitute for CM technologies, but, instead, an adjunct. Moreover, the design constraints (cost versus performance, and minimum weight) can differentiate alternative AM and conventional part designs. [55]

In literatures, Morrow, and colleagues (2007) provided a quantitative analysis of the energy consumption and process emissions associated with the production of mould by DMD and by CNC milling processes. The authors summed up that DMD provided important savings in energy consumption and related environmental emissions and economic costs over the life, being adaptable for updating, repairing, and remanufacturing of tooling.

Benatmane (2010) made a comparison between the environmental impact of a Delphi diesel pump housing manufactured by die casting and SLM. The SLM manufacturing permitted the absence of a major number of manufacturing steps, such as machining, drilling, and chemical deburring. It founded that the buy-to-fly ratios, were 2:1 and 1.4:1 for the casting and SLM routes, respectively.,

Among literature papers about 3D printing and sustainability, an interesting study is presented in the “A global sustainability perspective on 3D printing technologies” [56] one, which performed sustainability evaluation to identify implications of 3DP on the three sustainability dimensions: economic, environmental, and corporate.

The paper report, as we have already explicated, that 3DP has the potential to significantly reduce life cycle energy and CO2 emissions. Energy and CO2 emissions for manufacturing are lowered through shortened processes and more direct manufacturing with AM. In turn there are no need for tooling, handling, and decreased materials energy. Moreover 3D printing reduces resource inputs as it only needs the amount of material related to the printed model without too many losses. Many AM techniques needs support structure, but support materials can usually be reused. In aerospace manufacturing buy-to-fly ratios are generally high at about 20:1. 3D printing enables a buy-to-fly ratio of almost 1:1.

Then, the paper [56] give some interesting results about sustainability implications of energy and implications of CO2 emissions, that we report and analyse below in Figure 5.9 and 5.10:

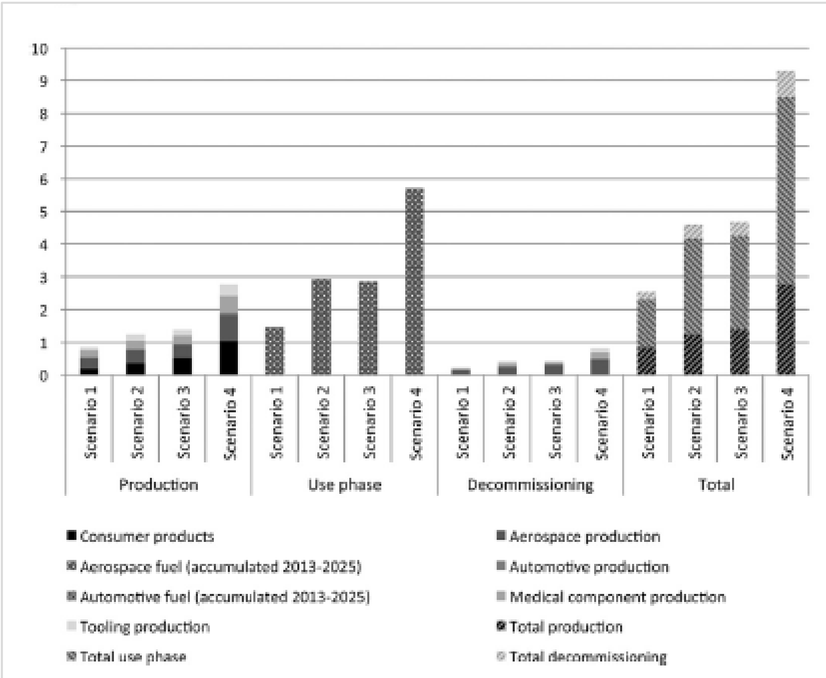


Figure 5.9 *- Annual avoided TPES use through 3DP in industry in 2025 in EJ. [56]*

The sustainability consequences of energy are expressed as total primary energy supply (TPES). The Fig. 5.7 shows that energy savings through 3D printing can be obtained over the entire life cycle of a product. TPES savings related to production phase account to 0.85–2.77 EJ, usage savings to 1.46–5.72 EJ and decommissioning to 0.22–0.81 EJ depending on the scenario in 2025. In total, TPES can be reduced through 3DP by the range 2.54–9.30 EJ over the entire life cycle. About one third of the TPES savings owns to the production phase, 55–60% of the total savings can be achieved during the use phase and 8% are obtainable during decommissioning. [56]

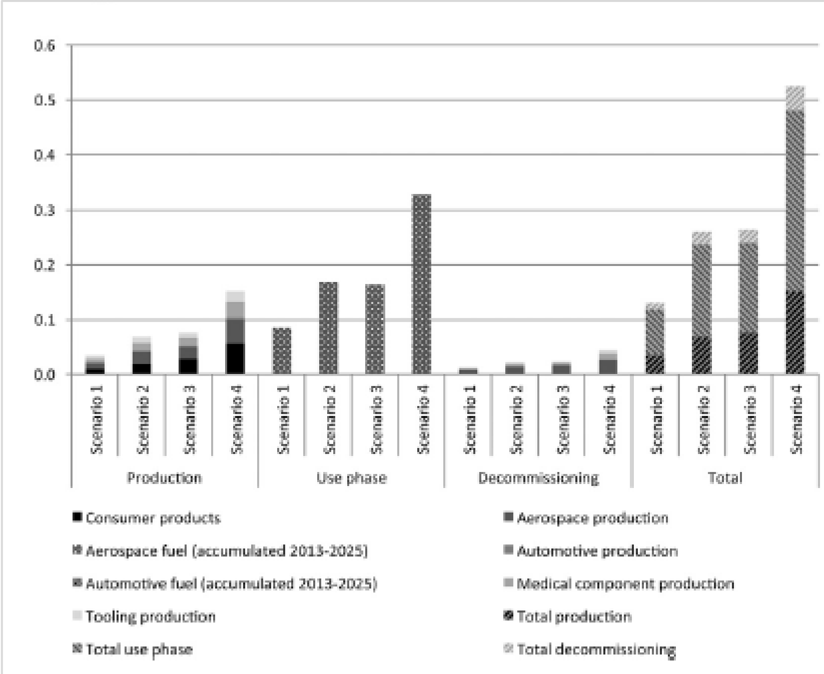


Figure 5.10 *- Avoided life-cycle CO2 emissions through 3DP in industry in GDP. [56]*

The consequences of 3DP of CO2 emissions are in line with the ones of TPES. Indeed, CO2 emissions are directly related to the TPES. 3D printing permits CO2 emission reduction over the entire life cycle of a product. The potential decrease is assessed to be 34.3–151.1 Mt (production), 84.1–328.5 Mt (use phase) and 12.1–44.5 Mt (decommissioning) in 2025 depending on the scenario. The total life cycle savings account for 130.5–525.5 Mt in 2025. Production savings related to CO2 emissions represent about one quarter of the total potential. About 67% of the total saving potentials are achievable during usage due to the high energy saving potentials. Decommissioning accounts for 8%.

Finally, after having analysed the literature research and described the differences and the advantages of the AM with respect to CM process, now the focus is shifted to the interesting comparison for the jewellery production between traditional manufacturing processes, Classic and Direct microfusion and the innovative 3D printing one, the Selective Laser Melting. To this aim, and to analyse a real case with analytics data, we report the Progold case study and results.

The parameters used in the study for assessing the environmental impact of a production process is the so-called Carbon Footprint (CF), which refers to the quantity of greenhouse gases (GHG) emitted during the process in question expressed in terms of equivalent CO2 mass.

The comparison of the GHGs emitted by the three techniques under analysis was carried out considering all the phases and materials present in the company necessary to complete the production of 1 Kg of jewels. For the calculation of the emission caused by the production and disposal of the materials used, the data were taken from the EcoInvent 2.2 database, while for electricity the data used comes from the Italian electricity grid (Higher Institute for Environmental Protection and Defense, 2015). In the comparison, the melting of the master alloy for investment casting and the pre-melting of materials before atomization for selective laser melting were not considered since it is common to the different techniques. Moreover, the emissions caused by the production of metal raw materials and the emissions caused by the construction and maintenance of machinery and collateral systems were not calculated, instead only the emissions caused by their productive use. In the case of classical and direct investment casting, the emissions have been estimated in the best-case scenario, i.e. considering the full furnace, and rescaling the emission of the phase by the number of cylinders necessary to make 1 kg of product, that means four cylinders out of fifteen. [26]

Below, in Figures 5.11, 5.12 and 5.13, the total estimations for the three different techniques coming from the study results.

Carbon footprint of classic microfusion	
Production phase	Kg CO2/kg
Prototype realization	7.39
Rubber mold preparation	1.62
Injection of waxes	0.31
Spindle assembly	0.07
Preparation of the cylinder	0.72
Firing cylinder	15.90
Alloy pre-casting	0.44
Fusion and casting	1.85
Pickling	0.42
Flattening	0.06
TOTAL (approx)	**28.8**

Figure 5.11 *- Carbon Footprint of classic microfusion [26]*

Carbon footprint of direct microfusion	
Production phase	Kg CO2/kg
Wax print	3.70
Media removal	0.64
Spindle assembly	0.07
Preparation of the cylinder	0.72
Firing cylinder	15.90
Alloy pre-casting	0.44
Fusion and casting	1.85
Pickling	0.42
Flattening	0.06
TOTAL (approx)	**23.80**

Figure 5.12 *- Carbon Footprint of direct microfusion [26]*

Carbon footprint of selective laser melting	
Production phase	Kg CO2/kg
Atomization	1.64
Press	13.2
Removal of pieces and supports	0.03
Total (approx)	14.70

Figure 5.13 *- Carbon Footprint of SLM [26]*

The estimation of CFC produced, coming from the use of the three different techniques, shows how the emissions caused by SLM are significantly lower than those caused by the other two techniques. It is also clear that most of the greenhouse gas emissions for all three techniques are caused by the production steps that use electricity for a longer time: the annealing of coatings in the classic and direct investment casting while the printing phase for selective laser melting. If the furnace is not used completely full, the impact of the annealing step of the investment casting cause higher production of greenhouse gases. More, the data presented in the Figures corresponding to 100% efficiency of the oven. In the case of SLM, the emission varies with the variation of the printing speed, which in turn depends on the complex geometry of the pieces and the printing parameters used. The emissions of the case studied in Figure 5.13, corresponds to a printing speed of 14 g / h. [26]

Only in the presence of very low printing speeds and high production efficiency, the investment casting techniques, classic and direct, show lower greenhouse gas emission and so are preferable. Generally, in fact, the CO_2 equivalent produced in SLM is much lower, reaching to be more than half decreased compared to classic and direct investment casting if these have poor production efficiency, that is usual with highly underused furnaces. To conclude, it can be said that the SLM technique is advantageous compared to Microfusion as regards the production environmental impact. [26]

Finally, significant savings in energy and resource consumption can firstly be achieved by an appropriate process and AM system selection. Most of the reported study focus mainly on energy consumption. In order to assess the full environmental impact of manufacturing, also the material resource consumption and direct as well as indirect process emissions should be documented and analysed.

Chapter 6 – Case study: diffusion in Arezzo district

6.1 – Introduction

After having outlined in the previous chapters the AM technology state of art, its diffusion and application in the goldsmith industry, in this chapter a case study based on real data will be analysed.

The case study purpose is to study the diffusion of the technology in one of the main Italian districts: the Arezzo one. In order to study the adoption, a survey to collect and analyse answers and comments from a sample of goldsmith companies was created.

In the following paragraphs, we present the survey created, the sample to which it was submitted and a final analysis to get out conclusions.

6.2 - Sample composition

The analysis is carried out on the goldsmith companies of the Arezzo district, one of the 3 main important Italian districts in the goldsmith sector. In the first phase of the analysis there is the definition of a sample and the creation of a database to which submit the survey and to be analysed.
The creation of the list is carried out by consulting the exhibitor's area of the official website of Gold Italy [57], the international workshop that brings together the demand of the best Made in Italy goldsmiths from selected manufacturing companies in the Italian gold districts and international demand from the main markets for Made in Italy production.
After having collected all the company the database was created with the available information, likewise the name of the company, the address, the phone number, and the online e-mail.
Then, before the submission of the survey, the sample target chosen has been contacted with an introductory call to present the research study and preventively ask for the availability to participate to the survey. Moreover, to those who answer positively to the call, an e-mail address was requested to be sure to proceed with a more targeted sending of the questionnaire. This decision was taken to the purpose of getting a higher response rate, dealing with rather reticent small businesses.
To those who accept the submission, a link to the survey, created by Google form, was sent in order to collect the needed responses and to successively analyse them.
Below, in the table, there is an overview of the sample composition, including the calls feedback and responses.

	Absolute frequency	*Relative frequency (%)*
Invalid phone number	2	2.6 %
Not interested	21	26.9 %
No production	6	7.7 %
Email collected	49	62.8 %
Total sample	**78**	**100 %**
Total companies contacted	70	89.7 %
Survey responses	19	27.1 %
Adjusted response rate	**27.1 %**	

Among the 78 numbers that were collected, 2 telephone numbers were invalid and 21 declared to be not interested to participate. Moreover, 6 numbers declared to not being producers but only carrying out commercial activity, so not in line with the sample chosen.

The companies that manifested interest and provided an e-mail address were 49. However, only 19 complete the survey, while 30 didn't do it, despite having made several attempts on different days and times. The adjusted response rate, computed on the basis of the 70 goldsmith companies actually contacted, was 27.1 %. Moreover in the table are indicated the absolute frequency and relative frequency (%).

6.3 – The survey

The survey created and submitted to the Arezzo goldsmith companies is attached in Appendix A. The survey structure involve is three main sections: a first part composed by 5 questions with the aim to gather “demographic” information and characteristics about the sample analysed. Firstly, there is a mandatory question to indicate the company email address, in this way it is possible to keep track and understand the company that actually participate. The subsequent questions related to the companies whether family-run or not and to the size of the company particularly the number of employees, in order to understand if there is a correlation based on this parameter. Then a final question, to discriminate companies and then move on to section two, that is whether or not they use the additive technologies (3d printing) for the production of jewels. In this way only those who actually use this technology will answer the most specific questions in the second section.

The second part focused on the additive manufacturing adoption, with specific questions prepared to understand the companies' actions. So, in order to assess the investments made, the adoption of the 3d printing with respect to traditional technique and moreover the goals to achieve with the technology and the hopes.

Finally, in the last section, that is submitted to the all sample, there are general question in order to understand future behaviours and diffusion, and to particularly understand the general thinking about the innovative SLM technique in the production of jewels.

6.4 – Analysis of responses

After demanding a mandatory email address, for the reasons explained above, getting to know more deeply the companies, one of the first questions of the survey regard the dimension, asking for the number of employees owned. In this sector indeed, the size of the company, measured by the number of employees, may be the most important aspect as it has a predominant impact on the companies' choices. Analysing the data, the sample is composed of 47% of micro-enterprises, 43% of small-medium enterprises and 11% large.

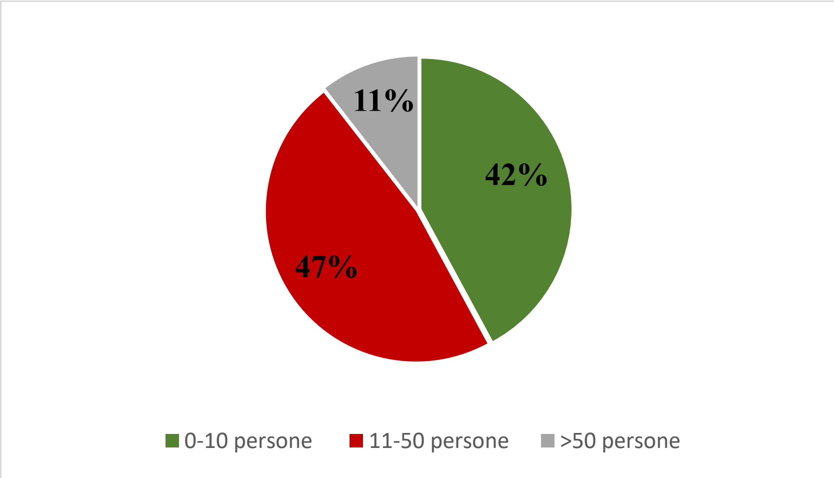


Figure 6.1 *- Question 3: How many employees does your company have?*

In fact, as it is possible to observe from the Figure 6.1 above, the district is made up almost half of micro and small enterprises. Therefore the sample perfectly represents the district from the point of view of the size of the company through the number of employees.

Then, the market has been deeper analysed, collecting data about the rate of adoption of the 3D printing in the jewellery production. In this case, the market is divided by the majority, the 74% of non-adoption of 3D, and a minority of adoption represented by the 26%. It seems that, being composed for the majority by micro and small enterprises, they may be loath to adopt alternative productions techniques such as Additive Manufacturing. Moreover, the classic method of lost wax casting, still represent a valuable and highly competitive choice. This, furthermore, is justified by the costs of this new technology and the fact that has not yet reached a maturity state.

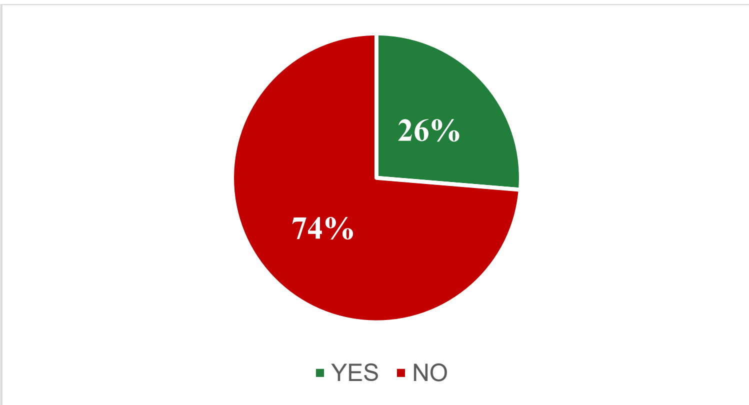


Figure 6.2 *– Question 5: In your company, do you use additive technologies (3D printing) in the production of your jewellery?*

Trying to analyse data more in detail, the correlation between the company dimension factor expressed in the number of employees, and the adoption rate of 3D printing, didn't result interesting, there being no correlation. Indeed, from a hand the propensity to invest of SMEs, and on the other hand, the potentiality of large enterprises, should be remembered.

The answers collected will help in understanding the trend of innovation and the optimization of processes with a view of development 4.0. Moreover, the propensity to adopt a new technology and to study the motivation at the base of non-adoption and reticence.

The second section is indeed only dedicated to those who adopted 3D printing in the manufacturing, trying to bring out more details. All those who answered "no" to the adoption of 3D printing, skipped this section and were redirected to the third and last section, the same for all the sample.
Firstly, questions 6, 7 and 8 are asked to get an overview of the relationship between 3D printing and company. The questions are: if the company uses 3D printers, they are company-owned or they rely on other companies? How many 3D printers are there in your company? How often is used the 3D printer?
The 75% of company affirm to own 3D printers, declaring to have 1, 2, 3 and more than 4 printers. Among them there is an isolated case of a company that didn't own a printer relying on third-party companies. Regarding the rate of use, we can underline three companies that use printers daily or more than 3 times a week and a company that declared to own 1 printer but without using it. All of these data are related with the following relevant questions:

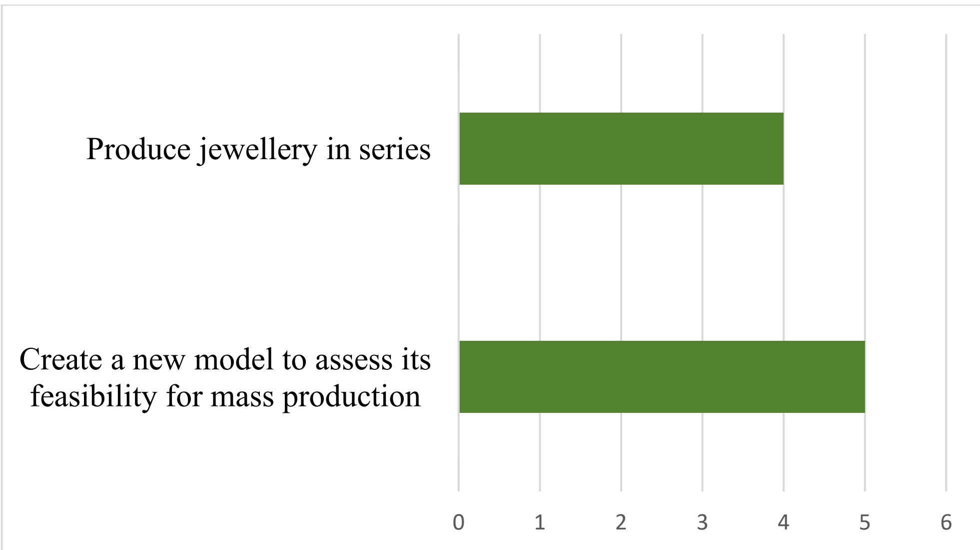


Figure 6.3 - *Question 10: 3D technologies in your company are used to?*

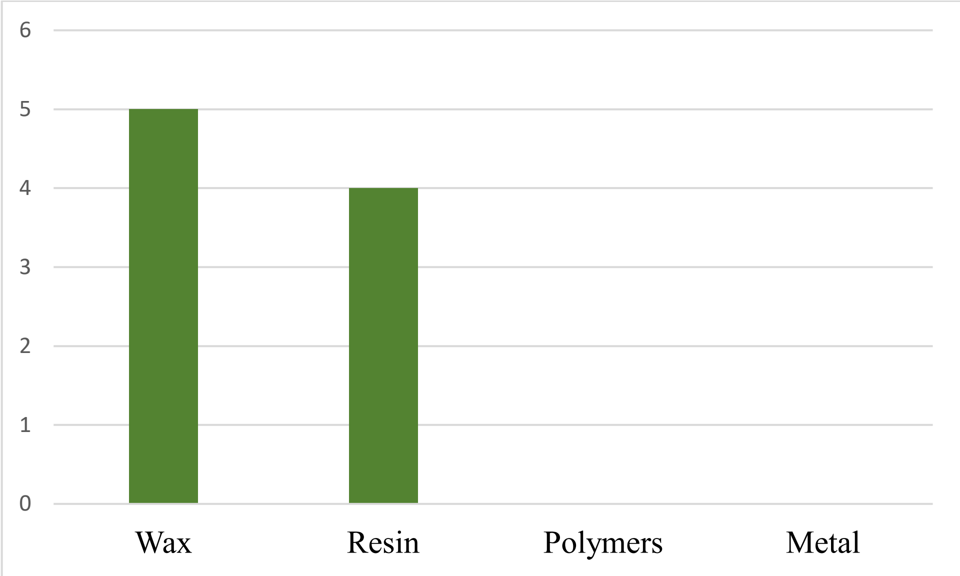


Figure 6.4 *- Question 11: Within your company, 3D printers use materials in?*

First of all, it has to be noticed the flexibility that 3D printing technique demonstrated to own. Among 5 respondents, almost all of them declare to use 3d printing technology for both purposes: in the creation of a prototype and in the following production of it with the printers. Amon these, only one use the printer for the prototype creation and evaluation only, and it is the company that coherently declared to own one printer without using it for the production. Beyond this, there is no real correlation between the number of printers and the purposes for which it is used, as per definition printers can be multi-functional.

Regarding the materials choice, the most reliable and used in parallel, at equal level, are founded to be the resins and the waxes, while not surprising at all, metals and polymers are not taken into consideration by the sample. This underlines that companies are still very bounded to traditional waxes, with all of them (100%) still using it. However, nowadays, in 3D printing, resins represent the best material in terms of performance and quality, and this is clear to the companies.

While this is not true for its actual adoption, the number of printers and the materials used are correlated in some way. This can be seen in the fact that all of the companies that declared to use both the waxes and the resins, at least own two printers, in order to produce product with both materials at the same time, with different processes.

Then, going straight to questions 12 and 13, the focus is shifted to the assessment of the economic side. In this study, the cost of 3D printers and the relative market has not been taken into account. For this reason, the survey directly asks for the investments made by the companies, in different years, with differentiated price ranges. Considering the price-ranges declared in the answers, it is clear that

3D printers and associated materials investments can be imposing. Moreover, it has to be considered that, as the market composed by micro and small enterprises for the majority, this can represent a barrier.

Focusing on the survey responses analysis, question 12 regard the very first year of investment in 3D printing. The answers were different, going from the early one in 2001, passing through 2005, 2013 and then the last in 2014. Question 13 is still more detailed, asking for the amount of investments made in additive technology, each year, from the 2014 to the 2020. The price-ranges in the survey were 0-15.000, 15.000-40.000, 40.000-70.000, 70.000-100.000, 100.000-200.000. To make a preliminary, general analysis, below the two graphs representing investments made by the five companies in the years 2014 and 2020.

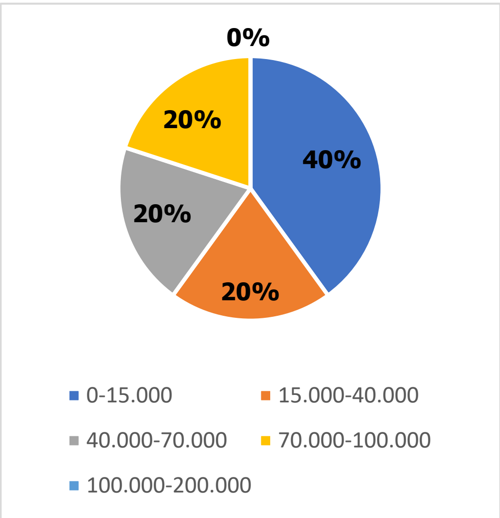


Figure 6.5 *- Question 13: What is the amount investment in additive technologies in 2014?*

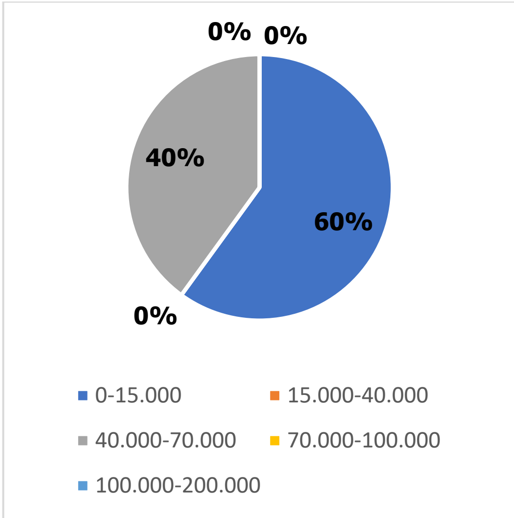


Figure 6.6 *- Question 13: What is the amount of investment in additive technologies in 2020?*

However, correlating the answers obtained in question 12 and 13, three different behaviours has been spotted. Indeed, the amount of investment made in the year 2014, strictly depends on the year of first investment. The one with the first investment in 2014, made an initial high investment on this first year, then the trend of investment amount is lower and constant. While the one who first invested in 2013, maintain a constant high level of investment for the all-period range considered. Lastly, the two companies, “early adopters”, that made the first investment respectively in 2001 and 2003, after about 10 years from that, continues with medium amount of investments. Instead, searching for a correlation on the amount of investment made in the year 2020, this depends on the world situation from that year now. The advent of the pandemic due to the Coronavirus at the early 2020, initiated a crisis from which the world is still emerging. Due to that, the different amount of all the companies, in 2020, are lower and decreased with respect to previous years.

Finally, it has to be noticed that, only one company, in 2019, invested an amount greater or equal to 100.000 euros. Furthermore, grouping the amount of investments in two price ranges, 0-70.000 and >70.000, grouping years and excluding the 2020 for the above explanation, we can track the following graphs:

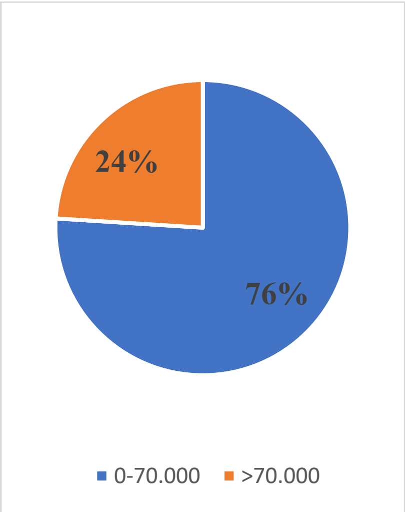


Figure 6.7 *– Cumulated amount of investments made between 2014-2018.*

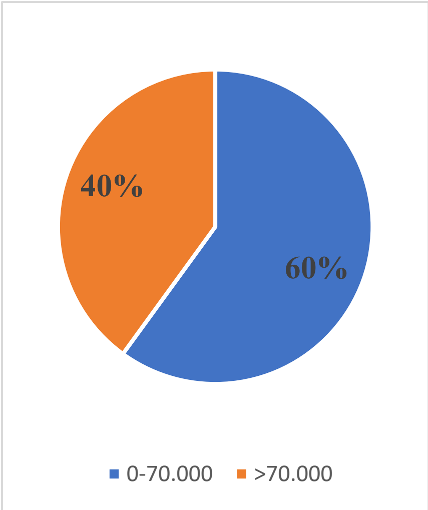


Figure 6.8 *- Amount of investments made in 2019.*

As it can be seen, the amount of investment higher than 70.000 almost doubled in 2019, showing a positive trend. Although the situation of crisis, this date can be hopefully interpreted as a promising trend, as it attested the interest about the innovation of additive techniques and digitalization of processes. Therefore the diffusion of this technology is still in place.

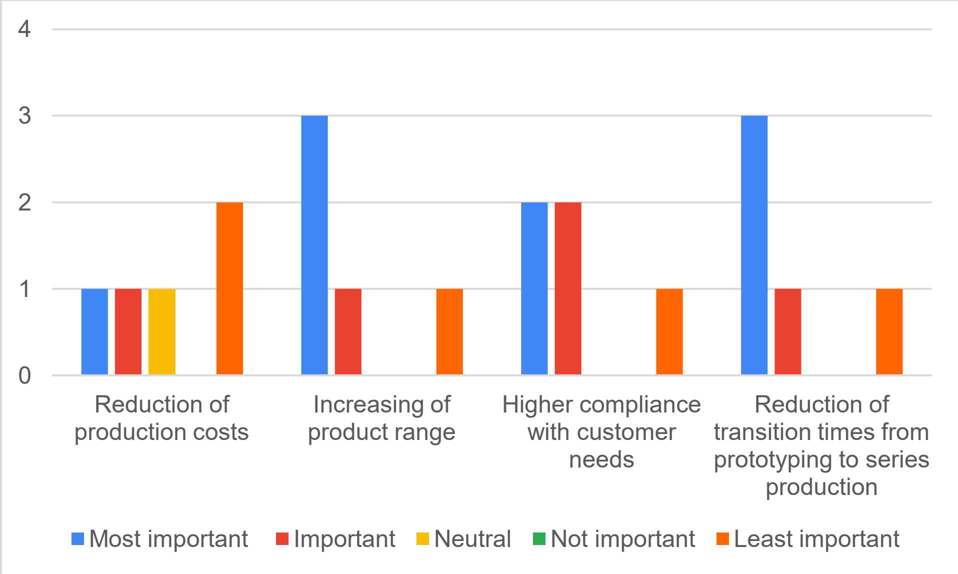


Figure 6.9 - *Question 14: What were the main objectives that the company set out to achieve with the investments in additive technologies made in the 2014-2020 period?*

The above Figure 6.9, regarding question 14, asked companies what were the final purposes they wanted to achieve, with the amount of investments made declared in the previous answers, based on four possible objectives choice. The reduction of transition times between the prototyping and the production in series and a wider product range, were the two main goals that the company wanted to achieve investing on 3d printing technology innovation. This is perfectly in line with those who are the primary benefits that the additive manufacturing technology, particularly in the goldsmith industry, can bring. Furthermore, important as well, is the goal of a greater correspondence with the customer needs. This is fully satisfied by the additive technology too, which, as we explained in the previous chapters, allows complex geometries that were previously unthinkable, mass-customization and shorter times. While, the reduction of production costs, is not perceived as one of the main objectives of the additive manufacturing introduction.

Additional information comes from question 15, where the companies were asked to indicate the production processes of the jewels they adopted, among the classic microfusion, the direct microfusion and the SLM. The results shows that 100% of them still use the classic microfusion process, the 60% of them use in addition the direct microfusion too, while none of them, who already adopted AM from years, use the SLM technique. Indeed, not surprisingly at all, the sector is still anchored to the traditional production technique, that is well consolidated and still provide great results. So there is no real need to give up with this old process. Meanwhile, they invested in 3D printing, in order to give a chance to this new technique, and due to this the companies have also adopted the direct microfusion method, that allows for a more rapid prototyping in the first steps of the process, digitalizing it.

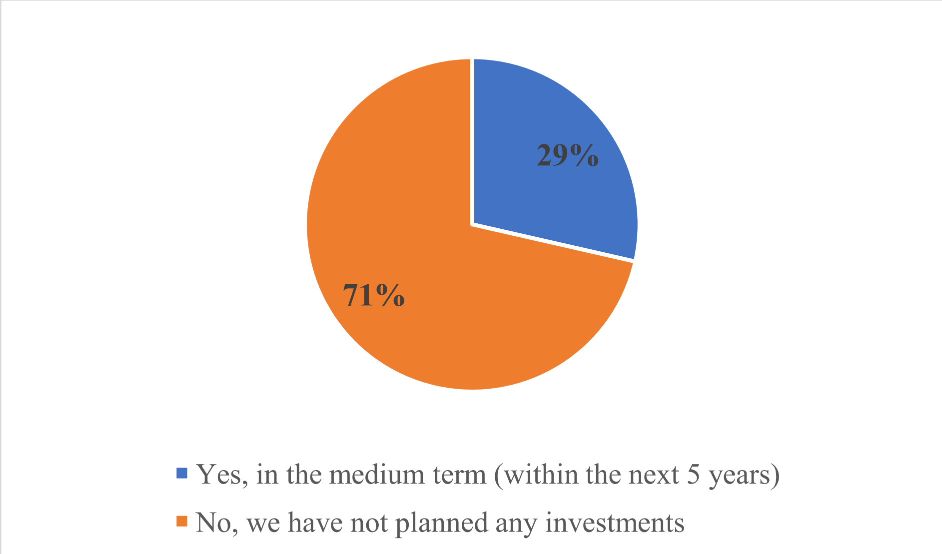


Figure 6.10 - *Question 20: Have you already planned future investments in additive technologies?*

Future investments and adoption data on the 3D printing diffusion in the goldsmith companies are provided by Figure 6.10, which indicates that only the 29% of enterprises have planned a medium-term investment, within the next 5 years. On the other hand, the 71% of them appear to have no intention to adopt the additive technology in the next years. The ones who answered positively, probably are a representation of the laggards, the more reticent ones. These people come last and have a real aversion to thee change. Therefore, the late majority, which is the first to be a rather sceptical category, already adopted the technology. Therefore, the 71% that declared that haven't planned an investment, with high probability will never adopt this innovation. This is due firstly to a radical culture and a traditional attitude that links producers to the classical techniques that are today still valid and competitively.

Therefore, from the results obtained, the SLM technique, is not yet well known. For this reason, in the last part of the questionnaire, the knowledge about the presence of this technology, that permits the creation of jewels directly through the printing machine, on the market is investigated along with the impression behind the adoption. So, the cause for non-conformity with the technology are examined in question 6.10, where non-adopters (the totality of respondents) are asked to express their degree of agreement or not, based on a series of sentences, proposed to underline what could be the main disadvantages regarding the adoption.

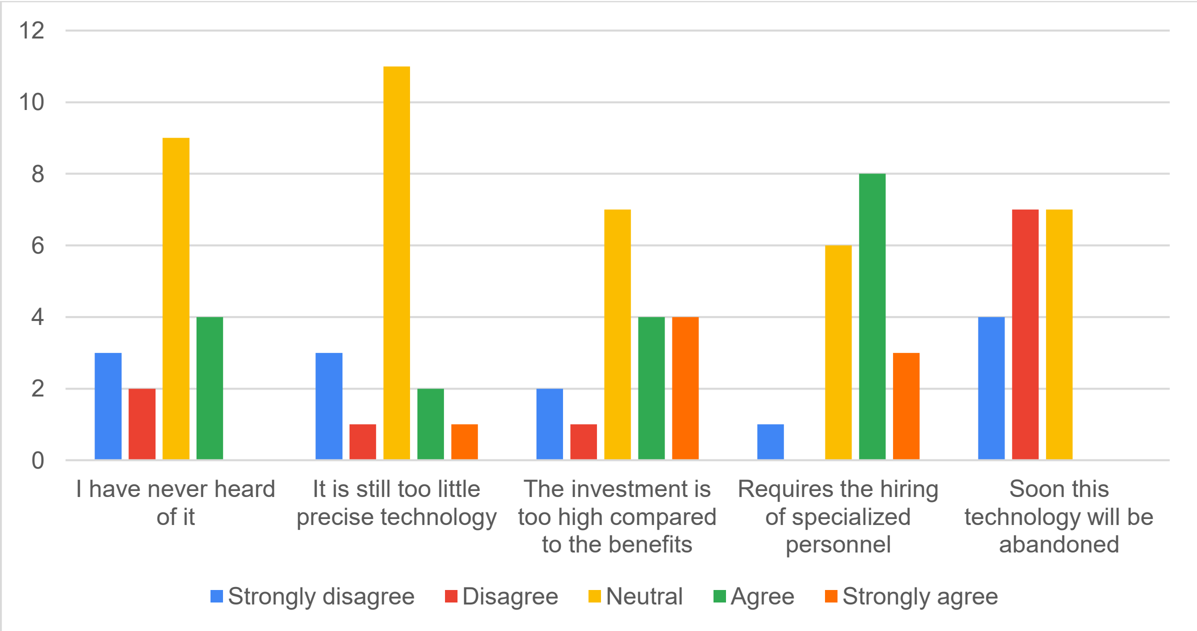


Figure 6.11 - *Question 21: Please indicate your impressions regarding the adoption of Selective Laser Melting (SLM) technology in jewellery manufacturing.*

First of all, in Figure 6.11, it has to be noticed that many of the neutral responses hide a low level of knowledge of the SLM technique along with a low interest for it, that has already stated why. There are two mainly reasons to which many producers seem to agree and are the high price in relation to the benefits and the requirement of hiring specialized personnel. Indeed, purchasing an SLM printer, or more generally a 3D printer, require a high initial investment, and in turn a proper strategy production plan in order to efficiently use it. Furthermore, additionally to thinking that the investment is greater than the benefits it can provides, they believe in the needing of specialized personnel who must own the know-how to profitable use the machine, increasing more the initial investment. This common thought, linked to the still efficient and rooted classic process, has lead to a greater lack of interest towards the SLM. It can be seen from the data on Figure 6.11, where the 61% declared to have a neutral opinion regarding the accuracy of the SLM technology, while only 17% believe it is not yet a mature technology. However, the sentence “Soon this technology will be abandoned” caused a general disagreement that can be seen positively as underlining a sort of trust in the future development of the innovation.

In conclusion, the non-adoption factors can be primarily found on the common think of high investment necessity, disinterest with a sense of immaturity and a rooted traditional craftmanship art. However, an increasing spread in the adoption of the technology would significant lower these factors.

6.4.1 – Cross-analysis by company size

The cross analysis has been used to analyse more in detail the responses and to search for interesting correlations of the data. The sample has been divided by two company dimension ranges: companies with 0-10 employees, and company with >10 employees. The decision to cluster companies by size has been taken since as it has already been discussed above, the dimension represents an important factor of the sample, especially the micro and small dimension companies, in order to coherently represent the district.

In particular it has been decided to study for correlation between company size and the rate of adoption of 3D printing.

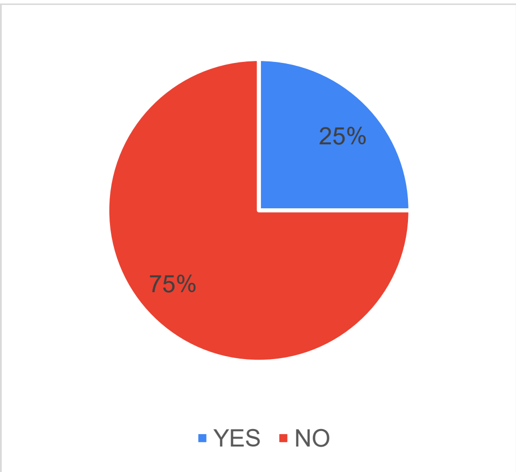


Figure 6.12 *- Rate of adoption of AM in companies with 0-10 employees.*

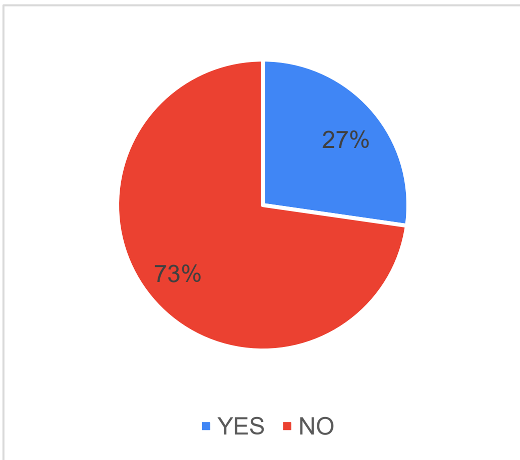


Figure 6.13 *- Rate of adoption in companies with >10 employees.*

The data analysed and reported in Figure 6.12 and 6.13, did not provide an interesting and expected result, since there is not a correlation between the company size and the actual adoption of the additive manufacturing technology. Indeed, independently from the dimension of the company, in both the cases, more than the half of the companies, have not yet assumed the 3D printing as production technique, underlying again the high cost and the disrupting nature of the innovation itself in the sector. However, small, and large-sized enterprises should display different behaviours towards innovation, given that the latter have greater economic power and reliability with which sustain innovation.

Trying to go deeper in the analysis, the focus is shifted on the companies that adopt the AM technology. Among these, two company belongs to the 0-10 employees cluster, while three company to the one of >10 employees.

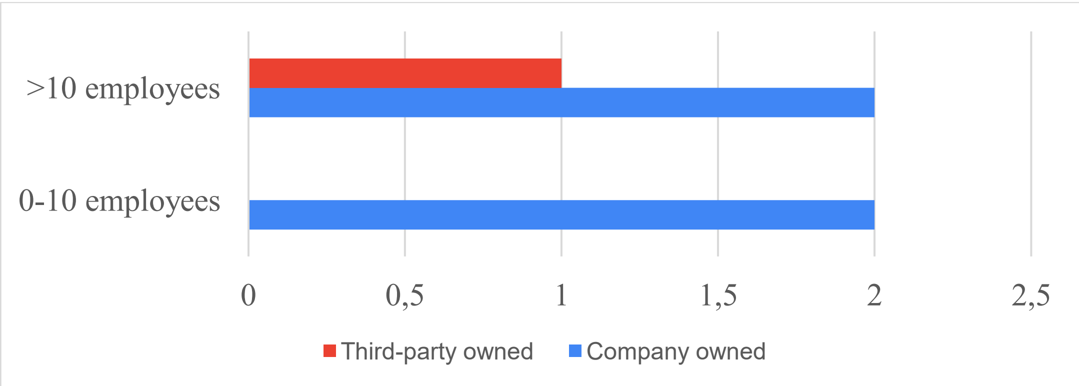


Figure 6.14 *- Q6: If your company uses 3D printers, they are?*

All of the two micro company owns at least two machineries of property. Instead, two of the medium companies that adopted the AM technology, has their own machineries, respectively 3 and 1 machines, while only one company declare to outsource to third-party the 3D printing production.

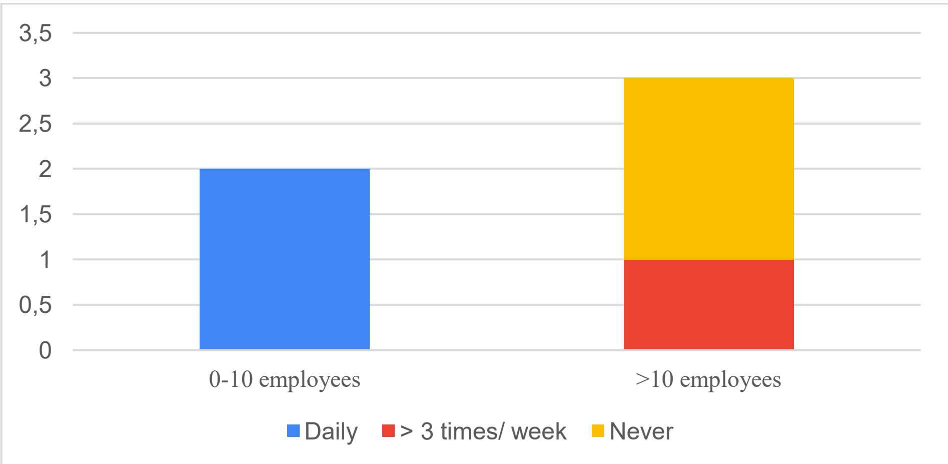


Figure 6.15 *– Q8: How often do you use the 3D printer?*

Finally, we can combine the analysis with the results showed in Figure 6.15, as responses of questions 8. First of all, the two medium companies that never use the 3D printer, has to be separately analysed.

Indeed, one of the two company, the one who outsource the AM, didn’t own a printer; the second company, who firstly adopted the AM in 2005, declared to adopt it only for prototyping purposes, not production.

Instead, the interesting outcomes, are from the two small companies, and the one from the medium cluster too, that declared to use the 3D printers, so the AM processes, daily or at least three times per week. This result is coherent with the choice of adopting 3D printing they made, directly investing the technology. Using it frequently will allow them to recuperate more rapidly the investment they made, moreover, increasing process speed with a more balanced organization of the work.

In conclusion, it can be supposed that this lower number of companies, being less reluctant, understood that in order to maintain the competitive advantage, though in a traditional sector, they need to optimize and innovate their production process.

Conclusion

In this study we tried to analyse the additive manufacturing technology applied to the goldsmith industry in all major aspects, from the economic to the sustainability. After introducing the additive manufacturing technology family, we depict its advantages and disadvantages that can be founded in the goldsmith application too. Indeed, the focus was on the goldsmith sector. As it was explained, the Italian sector is composed of three main district that make the difference and exported the craftmanship goldsmith art all over the world, making the Made in Italy one of the main recognised poles in all the industry.

In particular, the emphasis was placed on the techniques most used in the goldsmith's art, which, as already mentioned, are classical and direct investment casting and SLM. What emerged in the first place was a strong traditional and cultural attitude factor that leads the districts and in general the other goldsmith’s artisans to be reticent, as the lost wax casting still represents a performing and problem-free solution.

Then, analysing the situation deeper, we carried out an analysis on a sample of goldsmith companies of the Arezzo district, aimed at verifying and drawing further conclusions with respect to what had been theoretically discussed in the chapters above. As it is expected, from the analysis the adoption rate of the 3D printing is still low and questioned by the companies in the sector. The additive technology has not yet reached the maturity, so it is expected a greater spread and diffusion of this innovation that due to the highly competition in the market, will in turn lower the costs in the coming years. So, the goldsmith industry could be rapidly changed in its product and process elements by the AM innovation potentiality.

Moreover, the case study analysis showed as the Arezzo district is mainly constituted by small and medium enterprises, still very anchored to the historical goldsmith art they own.
Craftsmanship as a quality of the model has to be expanded, through the use of innovative technologies that guarantee greater creativity and flexibility to the craftsman, a wider range of previously unthinkable geometers and the possibility of mass-customized production, as well as the rapid prototyping.
Indeed, looking to the future, although it is seen as limited and experimental, certain of the potential that SLM has showed as a production technique in jewellery, this will certainly be part of the near future. Clearly it will not be the only one, but once again the classical investment casting will continue to be present. What remains fundamental is the choice of the right technique in relation to the material and the model to be made, also considering times and costs, as we have already explained. As far as

concerned the direct investment casting, since it does not show any advantages over SLM technology, it will probably no longer be used. In the near future, therefore, production will probably be carried forward by the simultaneous presence in the market of the two production processes, the traditional classic microfusion and the innovative additive manufacturing (such as SLM).

Appendix A: The survey

-Additive Manufacturing (stampa 3D) nell'industria orafa

Sono l'Ing.Fioravanti e collaboro con il Dipartimento di Ingegneria Gestionale e della Produzione (DIGEP) del Politecnico di Torino per una ricerca sull'utilizzo dell'Additive Manufacturing nel settore orafo.
Le chiedo gentilmente di rispondere alle seguenti domande, la compilazione del questionario le richiederà 3/4 minuti.
I dati raccolti non saranno assolutamente forniti a terzi e avranno unicamente scopo scientifico e non commerciale.

*Campo obbligatorio

Informazioni sull'azienda/laboratorio orafo

1. Inserire l'email dell'azienda (il dato non sarà reso pubblico, serve solo per individuare quale delle aziende contattate ha risposto al sondaggio) *

2. E' un'azienda a conduzione familiare ? *
Contrassegna solo un ovale.

- Si
- No

3. Quanti dipendenti conta la sua azienda? *

Contrassegna solo un ovale.

- 0-10 persone
- 11-50 persone
- >50 persone

4. Qual è la strategia produttiva attualmente adottata? *

Contrassegna solo un ovale.

- Su un unico sito
- Su più siti produttivi

5. Nella sua azienda, fate utilizzo di tecnologie additive (stampa 3D) nella produzione dei vostri gioielli? *

Contrassegna solo un ovale.

- Si
- No *Passa alla domanda 19.*

6. Se la sua azienda fa utilizzo di stampanti 3D, esse sono:

Se avete scelto "No" nella domanda precedente salti questo quesito e selezioni "Avanti"

Contrassegna solo un ovale.

- Di proprietà dell'azienda
- Ci affidiamo a società terze

Stampanti 3D

7. Quante stampanti 3D sono presenti nella sua azienda? *

Contrassegna solo un ovale.

- nessuna
- 1
- 2
- 3
- ≥ 4

8. Con quale frequenza utilizzate la stampante 3D? (scelta multipla) *

Seleziona tutte le voci applicabili.

- [ ] mai
- [ ] giornalmente
- [ ] più di 3 volte a settimana
- [ ] più di 5 volte al mese

9. Se avete scelto più di un'opzione nella domanda precedente, si prega di giustificare la risposta

10. Le tecnologie 3D nella vostra azienda, vengono usate per: *

Seleziona tutte le voci applicabili.

- [ ] Creare un nuovo modello per valutarne la fattibilità per la produzione in serie
- [ ] Produrre i gioielli in serie

11. All'interno della vostra azienda, le stampanti 3D utilizzano materiali in: *

Seleziona tutte le voci applicabili.

- [ ] Resina
- [ ] Cera
- [ ] Polimeri
- [ ] Metallo

Altro: [ ] ____________________

12. Quando ha effettuato il primo investimento in tecnologie additive? *

Specificare anno

13. Qual è l'ammontare di investimento in tecnologie additive in ciascun anno dal 2014 al 2020? *

Contrassegna solo un cerchio per riga

Contrassegna solo un ovale per riga.

	0 - 15.000€	15.000€ - 40.000€	40.000€ - 70.000€	70.000€ - 100.000€	100.000€ - 200.000€	Oltre 200.000€
2014	◯	◯	◯	◯	◯	◯
2015	◯	◯	◯	◯	◯	◯
2016	◯	◯	◯	◯	◯	◯
2017	◯	◯	◯	◯	◯	◯
2018	◯	◯	◯	◯	◯	◯
2019	◯	◯	◯	◯	◯	◯
2020	◯	◯	◯	◯	◯	◯

14. Quali sono stati i principali obiettivi che l'azienda si è proposta di raggiungere con gli investimenti in tecnologie additive effettuate nel periodo 2014-2020? *

Indicare in ordine decrescente, 1 il più importante.

Seleziona tutte le voci applicabili.

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

Processo produttivo

15. Il processo produttivo dei vostri gioielli prevede: *

Seleziona tutte le voci applicabili.

- [ ] Microfusione classica - si intende il procedimento comprensivo di gommatura e realizzazione di un master
- [ ] Microfusione diretta - si intende il processo di gommatura diretta sul prototipo creato dalla stampante 3D
- [ ] Fusione laser selettiva (SLM) - si intende la sinterizzazione di polvere in oro da cui si ottiene direttamente il prodotto semifinito

16. Se la sua azienda utilizza la microfusione classica, ci conferma che il processo produttivo (dalla realizzazione del prototipo alla spiantonatura) per 1 pezzo (si consideri un anello a fascia) dura un intervallo di tempo compreso tra 30 e 40 ore?: *

Contrassegna solo un ovale.

- Confermo
- No, dura meno di 30 ore
- No, dura più di 40 ore
- Non utilizziamo questa tecnica

17. Se la sua azienda utilizza microfusione diretta, ci conferma che il processo produttivo (dalla stampa delle cere alla spiantonatura) per 1 pezzo (si consideri un anello a fascia) dura un intervallo di tempo compreso tra 20 e 30 ore?: *

Contrassegna solo un ovale.

- Confermo
- No, dura meno di 20 ore
- No, dura più di 30 ore
- Non utilizziamo questa tecnica

18. Se la sua azienda utilizza fusione laser selettiva (SLM), ci conferma che il processo produttivo (dall'inizio del percorso macchina al distacco del pezzo/supporti) per 1 pezzo (si consideri un anello cavo) dura un intervallo di tempo compreso tra 1 e 3 ore?: *

Contrassegna solo un ovale.

- Confermo
- No, dura meno di un'ora
- No, dura più di 3 ore
- Non utilizziamo questa tecnica

Passa alla domanda 21.

Additive Manufacturing: no

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

____

20. Avete già pianificato investimenti futuri in tecnologie additive ? *

Contrassegna solo un ovale.

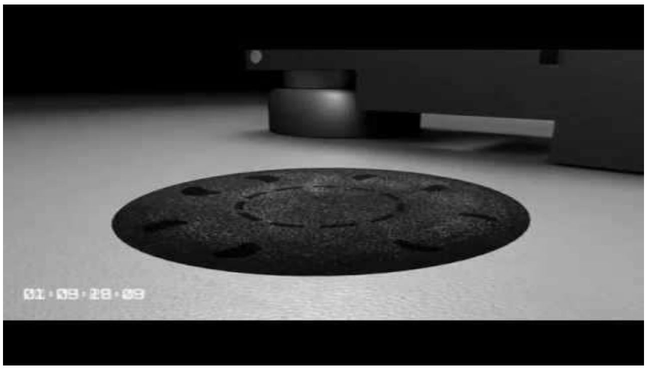
- No, non abbiamo pianificato nessun investimento
- Sì, a breve (entro 1 anno)
- Sì, a medio termine (entro i prossimi 5 anni)

Passa alla domanda 21.

Considerazioni finali - fusione laser selettiva (SLM)

Come forse già saprà, sul mercato è presente una nuova tecnologia per la

realizzazione di gioielli, si tratta della tecnologia fusione laser selettiva (SLM) che permette di creare un gioiello direttamente tramite il macchinario si stampa. Di seguito è fornito un video a titolo esemplificativo rappresentante la tecnologia fusione laser selettiva (SLM) in funzione. Il video è una pubblicità del produttore della stampante, si consiglia la disattivazione dell'audio.



http://youtube.com/watch?

v=jTUp810yOiQ

21. Si prega di indicare le proprie impressioni in merito all'adozione della tecnologia fusione laser selettiva (SLM) nella produzione di gioielli

Contrassegna solo un ovale per riga.

	Molto in disaccordo	In disaccordo	Neutrale	D'accordo	Molto d'accordo
Non ne ho mai sentito parlare	◯	◯	◯	◯	◯
È una tecnologia ancora troppo poco precisa	◯	◯	◯	◯	◯
L'investimento è troppo alto rispetto ai benefici	◯	◯	◯	◯	◯
Necessita l'assunzione di personale specializzato	◯	◯	◯	◯	◯
Presto questa tecnologia verrà abbandonata	◯	◯	◯	◯	◯

Commenti aggiuntivi

22. Il sondaggio è giunto al termine, se gradisce può fornire qui sotto dei commenti aggiuntivi in merito all'utilizzo dell'Additive Manufacturing nel campo dell'oreficeria.

Vai alla sezione 8 (Sondaggio concluso).

Sondaggio concluso

Il questionario è terminato.
La ringrazio per le risposte fornite e per il tempo dedicatovi. I dati forniti saranno utilizzati a soli fini di ricerca e senza nessuno scopo commerciale.

Rinnovo i miei ringraziamenti,
Ing. Fioravanti

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