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Towards a more efficient and sustainable goldsmith production

The current adoption of Additive Manufacturing technology in the Valenza district

Supervisor:
Luigi Benfratello

Candidate:
269055 Francesca Guido

Co-supervisor:
Paolo Claudio Priarone

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ABSTRACT

In the last decades technical innovations have come up at an incredibly fast pace. Although before it was difficult to imagine that new technologies might have disrupted the classical way of manufacturing things, now innovative techniques and tools have revolutionized the approach to the product development process as traditionally conceived. This paper focuses on investigating such change witnessed in the Italian goldsmith industry due to the adoption of Additive Manufacturing (AM) technologies. In fact, there is a rising, but slow, trend of switching from the traditional production process, mainly carried out by hand, to more efficient methods for designing and manufacturing pieces of jewellery.

A general overview of the main AM technologies developed is detailed in chapter 1. The classification of the techniques available according to the material form (liquid, solid or powder) is accompanied with a brief description of the fields where they have found a meaningful application. Likewise, chapter 2 introduces the Italian goldsmith industry in general terms. Some data about the National import and export of jewels are provided to give an idea of the principal market trends like sales volumes and revenue. In doing so, the pandemic and the lockdown periods which have damaged the global economy have been taken into consideration as well. Moreover, in the second half of chapter 2, the three largest goldsmith districts in Italy i.e. Arezzo, Valenza Po and Vicenza have been analysed both from an historical and an economic point of view.

Chapter 3 discusses the most popular production processes diffused among the goldsmith companies. The Direct Investment Casting and the Selective Laser Melting have spread beside the ancient Lost Wax Casting because they exploit, partially or fully, the benefits of 3D techniques and digital tools since the design phase of jewels development process. A comparison among them is also made to highlight the strengths and the weaknesses of each.

Then, chapter 4 goes through the advantages of AM technologies in greater detail. “Complexity for free”, iterative design and easy product customization are just few from the list of benefits that enterprises can achieve. The choice to take these opportunities may also result in the acceleration of the time-to-market allowing companies to gain a better competitive position. Nonetheless, there are still different challenges to tackle. The capital investment in equipment, materials and employees training is the first critical point; the

production rate is not fast enough; post-processing operations are usually necessary to ensure the desired surface quality.

Furthermore, in order to assess the attitude of Italian goldsmith firms towards these technologies, a survey has been carried out in the province of Alessandria as representative of the whole sector. A sample of 140 enterprises were reached by phone and asked to fill a questionnaire. The aim of the survey was trying to investigate whether companies are reacting in an active or passive manner; if they think that benefits overweight costs or vice versa; what is their sensitivity to sustainable manufacturing topic. The analysis of the responses collected is explained in chapter 5.

In the light of the data obtained from the questionnaire about enterprises responsiveness to sustainability issues, it has been added in chapter 6 a final discussion on this recent hot topic. Going for AM technologies opens up several possibilities of reducing the environmental impact of production activities. Materials savings, reduction of scrap, lightweight products and improved recyclability of printed objects are acknowledged as the best contributors to the attempts by firms of lowering their environmental impact. However, there is still a diffused scepticism among goldsmith companies. They fear most the uprise of energy consumed by printers, the costs for machinery maintenance and disposal of scrap produced, though in smaller quantities, but several possible solutions are already under investigation. In fact, design and manufacturing stages can be driven by sustainability. Eco-materials and circular processes can be introduced to reduce the carbon footprint of goldsmith supply chain. Finally, despite these limits to be still overcome, AM technologies represent solid grounds for going on exploring their full potential to find out how to further optimize materials efficiency and design to make the goldsmith production processes more sustainable in the future.

CHAPTER 1: INTRODUCTION TO ADDITIVE MANUFACTURING TECHNOLOGIES

1. INTRODUCTION

The AM technologies have been spreading in the last decades as alternative to the traditional subtractive production processes such as turning, milling, and drilling. Innovation has played a fundamental role into exploring new products and how to manufacture them. Innovations can be classified into *product* and *process innovations* and AM technology can be considered as a mixture of the two. The cutting-edge tools and the modern techniques developed to manufacture objects are examples of process innovations since they are new operational methods that change how companies operate their business processes (Cantamessa & Montagna, 2016); new materials employed and geometries achievable are, indeed, product innovations because companies can sell new products and services. Bringing innovation into goldsmith processes allows to optimize the production activities so that efficiency and productivity are improved affecting positively companies' competitiveness; new machines and material blends open up the possibility of customizing jewels, building even the most complex and detailed shapes and achieving a higher quality level of products.

2. HISTORY

There are different terms to define the AM processes. According to ISO/ASTM 52900:2015, *Additive Manufacturing* is defined as "the process of joining materials to make parts from 3D model data, layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies". The term *3D Printing* has been used in a non-technical context as a synonym of AM. It is "the fabrication of objects through the deposition of a material using a print head, nozzle or another printer technology" and it has been usually associated with machines of low-end price and/or overall capability. *Rapid Prototyping* was historically the first significant application for additive manufacturing from a commercial point of view and since then it has been also used as a general definition of this technology. Nowadays these words are used interchangeably although Additive Manufacturing is the official standard term and 3D Printing is more popular.

Bourell et al. (2009) explain that the origin of AM can be traced back to *Topography* and *Photosculpture* after looking at the US patents literature. These technologies date back to 150 years ago and they can be considered as "manual cut-and-stack approaches to build a free-formed object in a layer-wise fashion".

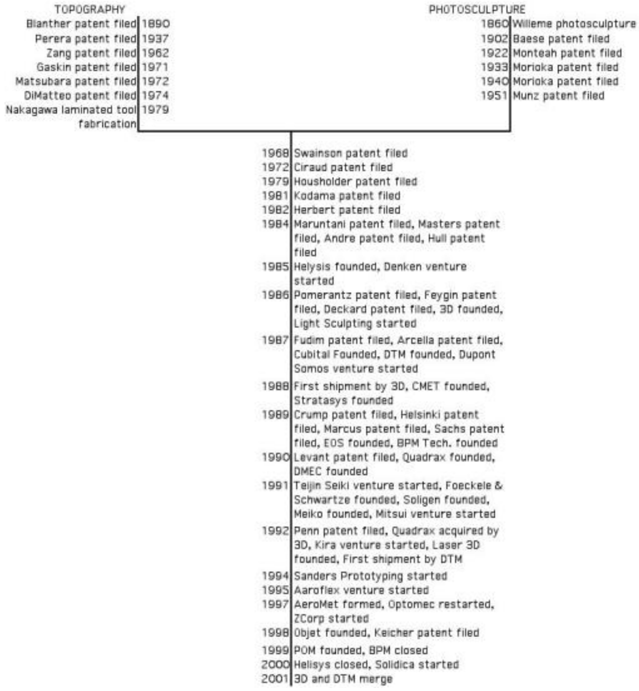


Figure 1: AM patents timeline
source: Bourell et al. (2009)

Regarding Topography, in 1890 Blather patented a technique to impress the contour lines in some wax plates and then cutting these plates on the contouring lines for making a 3D mould for topographical relief maps. Perera developed a similar method for making 3D maps by cutting contour lines on some sheets and then Matsubara from Mitsubishi Motors suggested to use a photopolymer resin of coated particles first spread into a layer and then selectively cured by the light of a projector to harden the portion of the layer scanned. Finally, DiMatteo and Nakagawa recognized the potential of these techniques and started applying them to produce several tools. In the 19th century, Photosculpture was adopted to replicate exactly three-dimensional objects. F. Willème designed a circular room where a subject or object was photographed by 24 cameras simultaneously and then an artisan carved the portions of the figure in each photograph. Bease tried to ease this process by using a graduated light to expose a photosensitive gelatine that expanded when in contact with water. Then a copy of the object was made of annular rings of treated gelatine fixed on a support. The Japanese Morioka patented a hybrid method where the contour lines of the object were photographically created thanks to a structured light and then cut or projected into materials for being carved. In the 20^{th} century, new AM technologies that are those still in use emerged because from the late 1980s their features and performance were improved, new materials were processed allowing to enlarge their application range (Priarone, 2020). In 1981 the Japanese Hideo Kodama used a photosensitive resin polymerized by UV light to manufacture parts layer by layer [1]. This system is considered as the first version of the modern Stereolithography. Then, an American furniture builder, Charles Hull, invented a system to easily manufacture small objects by curing layers of photosensitive resin. After patenting this technology, he cofounded in 1988 the 3D System Corporation that built the first SL 3D printer. Around the same time, Carl Deckard filed the patent for the Selective Laser Sintering technology that fuses powder rather than a liquid polymer while Scott Crump for the Fused Deposition Modelling, a system where a heated nozzle directly extrudes a filament [1].

Furthermore, starting from the '90s, new companies began to explore the AM technologies especially thanks to the support of CAD software packages. In 2005, Dr. Adrian Bowyer developed the RepRap Project, an open-source initiative to build a 3D printer for creating both 3D printers and objects. Then, in 2009, the technologies patented in the '80s became public giving companies and start-ups access to many more 3D printing techniques. Since then, new materials, printers and methods have been investigated to improve the quality of the components manufactured and lower the prices.

3. 3D PRINTING INDUSTRY

The 3D printing industry now includes products such as 3D systems, software packages, materials, and related services.

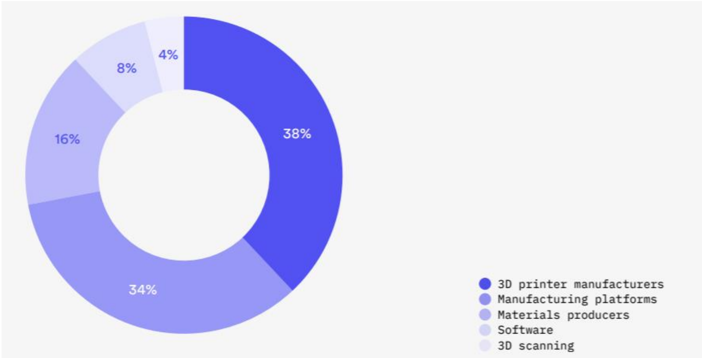
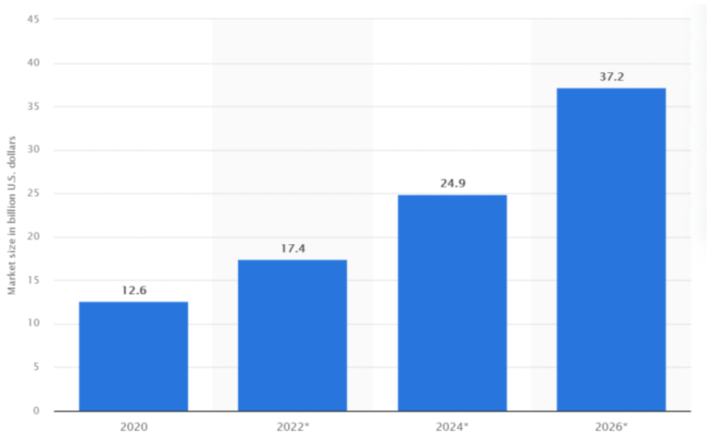


Figure 2: Market share of global AM players (2020)
Source: [2]

According to the report of 3D printing trends by [2], 3D Printers Manufacturing is the dominant sector of the industry. It can be further segmented into Industrial and Desktop 3D printers. Industrial printers are used for prototyping, tooling, and parts production in industries like aerospace, healthcare, automotive and electronics. Desktop printers were first used only by small enterprises and enthusiasts, but then they have been adopted also for domestic purpose by households and educational scope by Universities and research centres [3]. On the other hand, the services sector has been growing fast. Consulting, customer service, installation support, licensing and patenting are just few of the multitude of services provided by the firms. The reduction of production costs has allowed manufacturers to sell their printers at a more competitive prices so that the services demand have been driven by products one [3]. Moreover, despite the demand increase, some companies prefer not to rise their capacity and go instead for the so-called “online manufacturing”. The platforms that make the processes of searching and procurement automated account for the 34% of the overall industry [2]. However, both products and services market shares are expected to grow globally in the next 5 years as showed in the graph below. In fact, it has been foreseen that the whole industry will reach a compound annual growth rate (CAGR) of 17% between 2020 and 2023.



*Forecast

Figure 3: Global 3D printing products and services market size from 2020 to 2026 (in billion US dollar)
Source: [1]

4. PRODUCT DEVELOPMENT PROCESS

Although the AM processes have different characteristics, Gibson (2010) identified a set of common steps for the product development cycle. Calignano et al. (2019) have grouped all these steps into three main phases: digital, manufacturing, and post-process.

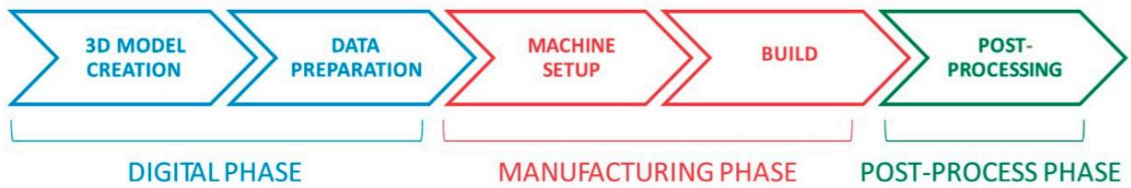


Figure 4: Main steps of AM product development process
source: Calignano et al. (2019)

The sequence of these steps is the following:

1. Conceptualization and CAD modelling

   The virtual model of part to be manufactured is first three-dimensionally designed on a CAD software or using a 3D scanner in order to represent every detail of the external geometry.

2. Generation of STL file

The 3D model is then converted in an STL file format. Initially developed for the Stereolithography by 3D Systems Inc. in 1987, the “Standard Tessellation Language” format allows to represent a surface as an assembly of planar triangles using a 3D Cartesian coordinate system. However, this conversion introduces the so-called “Curval error” that can be reduced by increasing the number of the triangles and so their density in the representation since the smaller the triangles the closer to the reality. Moreover, the surface is subject to the “Slicing” process that consists into fractioning it into cross-sectional layers to better improve the accuracy of the geometry represented. The slices can be uniform when of the same thickness or heterogeneous when they are adapted to the shape of the surface. After building-up the part, in some cases it is possible to observe the “stair-case effect” because of the Slicing step. The Stereolithography Contour (SLC) and SLI by 3D Systems and the Graphic Language (HPGL) by Hewlett-Packard are some of the other types of file formats available.

3. Transfer and manipulation of STL file on AM machine

   The part is transferred to a software where it is manipulated with respect to the AM technology restrictions and a machine code sequence is generated.

4. Machine setup and supports generation

   The machine parameters and tools are set up to build both the support structures in case of overhanging components and then the part.

5. Physical build-up of the part

   The part is built up layer by layer according to the type of AM technology.

6. Part removal and clean-up

   The part is removed from the machine platform and the support structures.

7. Post-processing of the part

   Additional operations such as heat treatment, cleaning, finishing could be necessary.

5. TAXONOMY

There are several classifications of AM processes depending on the criterion considered. According to Kruth (1991) and Wong & Hernandez (2012), AM processes can be classified into three groups with respect to the state of the raw materials: liquid, solid or powder.

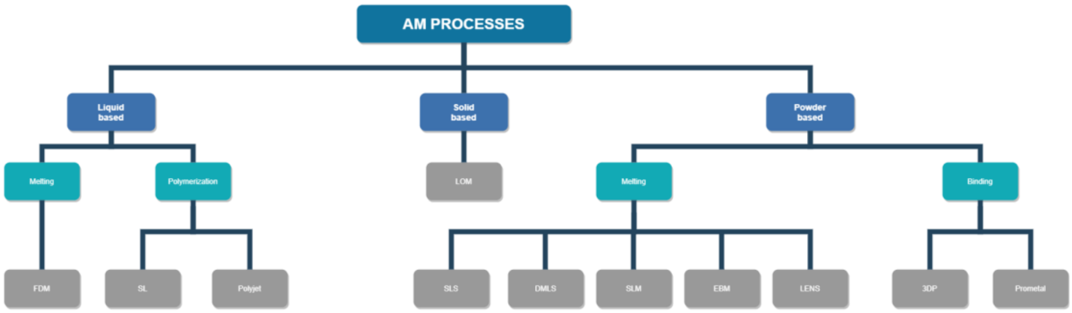


Figure 5: Classification of AM processes

The liquid-based processes include two technologies:

- a liquid photopolymer solidifies when scanned by a light beam from a lamp or a laser such as in Stereolithography (SL) and PolyJet.
- melted plastics or resins are deposited layer by layer on the machine bed where they become solid like in Fused Deposition Modelling (FDM).

In the solid-based processes as Laminated Object Manufacturing (LOM) many sheets are glued on top of each other and then this stack is cut into the desired shape. In the powder-based processes the grains binding can be obtained by

- melting together the grains of a component in powder form as in Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM) and Laser Engineered Net Shaping (LENS).
- gluing together the grains by adding a binder in a selective way like in 3D Printing (3DP) and Prometal technologies.

5.1 FUSED DEPOSITION MODELING

The part is built up by extruding a molten filament of thermoplastic material through a nozzle as the extrusion head or the base platform moves in the X-Y plane. Once a layer is completed, the platform moves down, or the extrusion head moves up, and a new layer is deposited and adhered to the already solidified material layers. After the loading of a thermoplastic filament spool into the printer, the solid material is fed into a XY extrusion head where it is brought slightly above its melting temperature (1 degree above) so that it solidifies rapidly by natural cooling. The flow rate of the molten filaments is controlled by precision volumetric pumps and the height of layers ranges from 50 to 400 microns. Larger pieces are quicker and less expensive to extrude while objects with small height are slower to manufacture, but the geometrical surfaces are more accurate and detailed.

This method was introduced by Stratasys in 1991 and their machines are now equipped with two separate nozzles that extrude two spools of material: one for the part and a second for the support structures. Post-processing operations might be needed when removing usually manually the support structures. However, this technology use is quite limited due to the poor quality of the parts realized and the narrow range of materials that can be extruded (mainly thermoplastic polymers), though now ceramics, concrete, composites, and organic materials have started to be processed as well. Other disadvantages are that the mechanical properties and the surface finishing are inferior in comparison with the conventional moulded parts. When the filament is deposited and pressed against the previous layers, the shape of the part might be deformed into an oval whereas uneven heating and cooling cycles distort the component causing weak bonding because of stress accumulation. In addition, the most common defect due to FDM is known as “warping” due to dimensional shrinkage after cooling and solidification. This phenomenon can be prevented by controlling the temperature parameter of the process and taking specific actions when designing the part such as avoiding sharp corners and large flat surfaces and using materials which are less prone to warping. On the other hand, FDM allows to realize functional prototypes cost-effectively and the lead time is so short that objects can be delivered very fast.

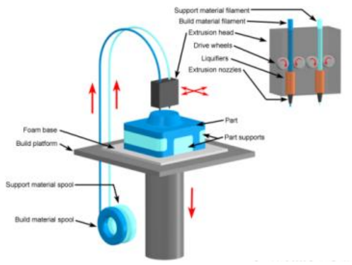


Figure 6: 3D printer based on FDM technology

5.2 STEREOLITHOGRAPHY

Stereolithography is a manufacturing process that exploits the vat photopolymerization technology. It was the first commercialized process in 1988 by 3D Systems Inc. and it is still the most popular. The part is built in a platform where a photosensitive monomer or polymer is cured when in contact with an ultraviolet laser. The UV laser selectively solidifies the resin layers. Once a layer is finished, the part is flooded with a new layer of the liquid polymer to be cured until the part is finally complete. The liquid absorbs the light to a few tenths of millimetres below the surface limiting the thickness of the layers while the illumination of the surface is constrained to a pattern that corresponds to the cross section of the part. After the removal of the support structures, the part is cleaned in a solvent solution to remove any residual resin left uncured and, if necessary, it might undergo a final polymerization using some post-curing systems such as a controlled furnace or an ultraviolet oven.

On one hand, many machines apply a "point-by-point" layer solidification: a laser beam scans the liquid resin so as to solidify a series of 3D vowels or points. The voxels must be large enough to connect with the neighbouring points and the layers underneath. The process is usually speeded up by scanning and solidifying only the outer and inner contours of the cross sections of the part that is eventually exposed to the light of a special post-curing oven. On the other hand, some machines avoid the post-curing operation thanks to the solidification of an entire layer at once. This technology is based on the use of a mask representing the cross sections of the part to manufacture. A new mask is created and deposited for each layer to be solidified.

After the final curing, the SLA pieces commonly go through some post-processing operations like sand blasting and vapor honing for improving surface finishing or electroplating to increase their strength and electricity-conductive properties. Despite the smoothness of surfaces, SLA parts achieve tolerances only up to 0.05 millimetres. Nonetheless, SLA is used to manufacture accurate casting patterns such as investment casting, injection moulding and vacuum casting. Moreover, functional prototypes to run tests, presentation models and highly detailed end-use pieces can be created as well.

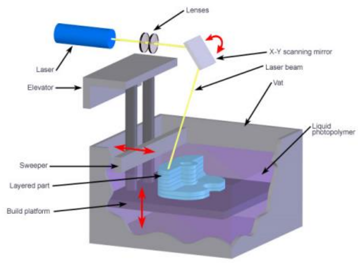


Figure 7: 3D printer based on SLA technology

5.3 POLYJET

Material Jetting was patented in 1999 under the name of PolyJet by Object Ltd., now merged with Stratasys. This process exploits inkjet technologies to build physical models by printing and curing photocurable resins. The inkjet head moves in X and Y directions depositing the photopolymer that is cured by UV lamps producing layer by layer fully solidified models without the need for any post-curing operations. Each layer is built accurately with resolution up to 16 microns. The overhanging features are supported by a gel-type polymer that is water jetted for being removed once the process is finished.

Balancing the proportions of the materials used, it is possible to realize parts or regions of parts with multiple material and different colours incorporated into a single piece. The other main advantages are the possibility of creating complex and detailed geometries, achieving smooth surfaces and accurate moulds, tools, and visual prototypes for aesthetic purpose.

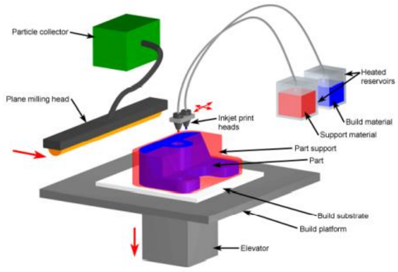


Figure 8: 3D printer based on PolyJet technology

5.4 LAMINATED OBJECT MANUFACTURING

This solid-based process combines additive with subtractive techniques. The part is realized by gluing together a stack of sheets and then cutting out the contour of the final object. Each adhesive coated layer of material is glued to the stack thanks to the pressure and heat of a roller and a laser traces on it the cross section of the part. After the completion of a layer, the build platform moves down, and a new layer of material is rolled on until the process is done. Since the material surrounding the contouring of the part remains on the machine bed until the printing process is not ended, it works as support structures for overhangs.

The materials used can be paper (cellulose), plastics, metals, composites, fabrics, and synthetic materials.

The advantages of this technology include low cost to manufacture parts fast and simply, the possibility of building large objects. However, some post-processing operations might be necessary such as machining, sand blasting, drilling and the so-called “de-cubing” process that consists in using some manual tools to remove any undesired material from the final product.

Furthermore, LOM application is limited because of dimensional inaccuracy, poor surface quality and heterogeneity of the mechanical and thermal properties of the material. Then, it is difficult to build complex undercuts and internal cavities because the material inside cannot be taken away unless the process is interrupted before the object is complete.

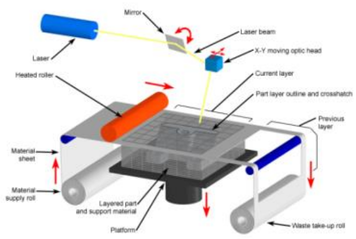


Figure 9: 3D printer based on LOM technology

5.5 SELECTIVE LASER SINTERING

Like the point-by-point Stereolithography, successive layers of the part are first scanned and then solidified by a CO2 laser beam. Instead of a liquid photopolymer, some bulk powder material preheated slightly below its melting temperature is spread homogeneously on the machine bed by a roller. The XY controlled pulsed laser beam selectively sinters the powder according to the desired design by further heating the layer up to the "sintering" temperature. The layer solidification happens when the grains viscosity drops with the temperature so that the surface tension is overcome creating an interfacial kitting of the grains without fully melting. The powder left un-fused is useful to give additional strength and support the next layer of powder and possible overhangs of the part. The unused powder is usually recycled especially if metal-based because metal powders preserve their properties integrity after the heating process more than polymers. The materials which could be used are plastics, metals, combinations of polymers and metals, combinations of metals and ceramics. Unlike plastics, metals and ceramics require binding materials and post-processing operations.

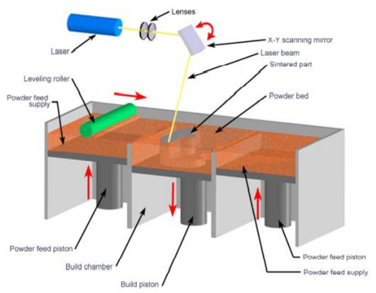


Figure 10: 3D printer based on SLS technology

5.6 DIRECT METAL LASER SINTERING

In 1995 EOS, the leader in the German market for DMLS technology, launched the EOSINT M250 machine. It was the first system processing metal powder to build functional prototypes. It is considered as one version of SLS technology since the manufacturing sequence is the same and the only difference is the type of materials used i.e. DMLS employs exclusively metals. Once the part has been 3D modelled on the CAD software, the information about its cross sections is transferred to the machine. First, the support structures are printed to anchor any overhanging sections which undergo high thermal stress. Then, a roller spreads a 20/40-micron thick layer of material on the platform where a highly powerful laser heats the powder until the grains fuse together. When a layer is completed, the machine bed goes down so that the roller can deposit a new layer of powder until the piece is fully printed. As soon as the process is done, the support structures are removed, and the piece taken away from the platform for a heat-treating process that makes it stronger. About materials, it is possible to use stainless steels, titanium alloys, cobalt- and nickel-based superalloys.

5.7 SELECTIVE LASER MELTING

Like DMLS, Selective Laser Melting belongs to the category of the so-called "Power Bed Fusion" (PBF) processes. Nevertheless, these two technologies are slightly different because the powder is fully melted reaching a higher level of homogeneity in the surface in case of SLM while it is just heated if directly sintered by a laser. Consequently, SLM is commonly used for building components made of only one material, so with a single melting point. When the printer has received the data from the CAD software, a layer of 20/100 micron thickness is swept by a roller. A high-power laser beam tracks the contouring of the part upon the powder bed in a controlled way. The metal particles melt and fuse together once their melting point is reached. A new powder layer is spread above the ones already cool and solid until the part is fully completed. Then, the powder left un-melted works as support structure before its removal and disposal. The main materials used are stainless steels because of their corrosion-resistance properties. Although SLM allows to realize detailed and precise functional prototypes and end-use parts with high resolution, the heat of the laser beam can cause defects and surface roughness due to excessive metal vaporization and spatters and the continuous cycle of material melting and solidification.

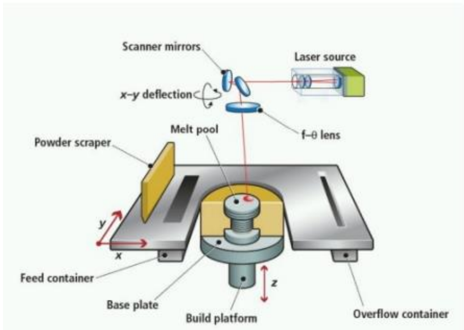


Figure 11: 3D printer based on SLM technology

5.8 ELECTRON BEAM MELTING

The Electron Beam Melting is a manufacturing process commercialized by the Swedish Arcam company for metal components. The powder is selectively melted through a thermionic emission gun with one 18 tungsten filament and powered by high voltage (typically 30 to 60 KV). Each layer is preheated because of the beam scanning at low power and high velocity to sinter lightly the powder and only after that the final contours of the part are designed. Once a layer is complete, the build platform moves down, and a new layer of material is automatically added up to be melted until the part is done. The printing process happens in a vacuum chamber to avoid any oxidation issues and when the process is finished, the build chamber with the both the part and the support structures inside are chilled down. The un-melted powder support the features of the part and it can be recovered to be reused. The EBM process reduces residual stress and distortion in the surface of the part thank to the high temperature, but the greatest advantage is represented by the vacuum chamber because it allows the optimal manufacturing environment for materials which are oxygen reactive used for medical implants and aerospace appliances where impurities are forbidden for safety reasons.

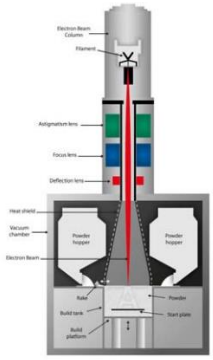


Figure 12: 3D printer based on EBM technology

5.9 LASER ENGINEERED NET SHAPING

In 1998 Optomec commercialized its LENS metal powder system that represents one of the Laser Powder Forming systems together with the Direct Metal Deposition (DMD) by Precision Optical Manufacturing and Laser Consolidation (LC) technologies. This process is manly used to add features to existing objects or to repair damaged parts. In a closed chamber with an argon atmosphere, a high-powered laser beam melts the target surface while the metal powder is injected into the same spot to create a melt pool so that the powder deposit is bonded to the substrate because it solidifies when it is cooled down. The deposition process is directed by a computer that also controls the melt pool for the deposition of the material strips and the development of the part layer by layer. Moreover, a multi-axis joint or a robotic arm combined with a rotary build platform can be used to avoid mono-directional deposition of material layers and allow different angles possible by manipulating the laser head. This manufacturing technique permits a huge variety of materials, but one of its main disadvantages is the residual stress caused by the uneven heating and cooling processes. So, depending on the application, some post-processing heat treatments might be exploited to improve the strength and the ductility properties of metals.

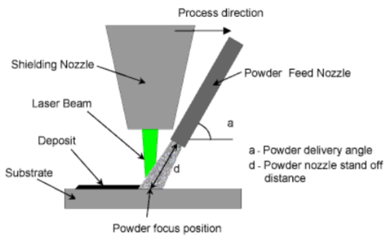


Figure 13: 3D printer based on LENS technology

5.10 3D PRINTING

The 3D Printing/Glueing technology has been developed and licensed by the Massachusetts Institute of Technology (MIT) to manufacture ceramic moulds, cores for metal casting and porous ceramic preforms. A water-based liquid binder is supplied by an inkjet printing head onto a starch-based powder bed. The printing head projects droplets of the binding material onto the powder deposited layer by layer according to the desired design. When the object is complete, the build platform contains the printed part surrounded by unbound powder, but the object is still considered as in its “green state” and it is fragile. To cure the loose powder, the component is usually put into an oven while the remaining still unbound powder is vacuumed out and eventually recycled. The next step is placing the part into a vacuum furnace for a cycle of sintering, infiltration and annealing since it is still fragile, and it is necessary to improve its strength. The sintering process allows to burn off the binder and bond the metal particles until the density reaches 60%. The infiltration allows to bring the part up to full density while the last process is to cool down gradually the furnace so that the part gets less brittle for post-machining operations (e. g. milling, drilling) by lowering the tensile and yield strength.

Finally, MIT explored two inkjet printing systems: the “drop-on-demand” for discontinuous solidification of layers point by point and the “continuous jet” where the nozzle spreads a continuous stream of the binder that breaks into a succession of droplets as it moves to the part. In order to speed up the process, some printheads with more than 100 jets have been commercialized.

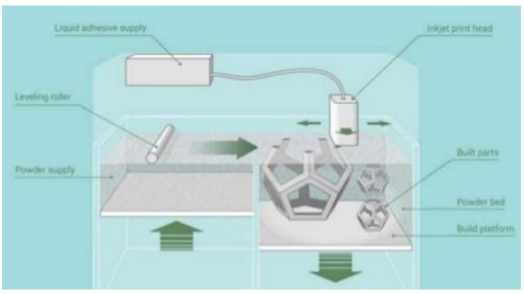


Figure 14: Printer based on 3DP technology

5.11 PROMETAL

This process is used to produce injection tools and dies by using materials such as stainless steel, copper and tungsten carbide. The metal power is deposited on the powder bed that is controlled by some pistons which lower the bed down each time a layer is completed while a feed piston supplies the powder of the new layer. A liquid binder is spurt out in jets to glue the powder. When manufacturing a mould, no post-processing operation is required. On the other hand, when realizing a functional part, it is necessary to perform the Sintering, Infiltration and Finishing processes. When using stainless steel, the part is first heated to 350°F for 24 hours during the Sintering phase to harden the binder thanks to the fusion with a steel specimen. Then, in the Infiltration stage, the part is infused with bronze powder creating at 2000°F an alloy of 60% steel and 40% bronze. If other materials are used, the process is the same, but the temperature and the alloys are different.

6. MATERIALS

3D objects are built using mainly polymers and metals. However, several companies have also made good use of ceramics, composite, and hybrid materials.

There is a wide variety of polymers available depending on their properties. They are usually classified into Thermoplastics and Thermosets with respect to their reaction to high temperatures. In fact, Thermoplastics can be melted many times without compromising their properties except for a possible little degradation. Thermosets cannot be remelted because they are permanently “set” once formed (Wohlers et al., 2017). Photopolymer processes such as PolyJet and Stereolithography use thermoset polymers whereas extrusion systems exclusively thermoplastic. Among Thermoplastics, there are ABS (Acrylonitrile Butadiene Styrene) and PLA (Polylactic Acid) [4]. ABS was one of the first plastics to be used and it still widely used because it is cheap and ideal for printing tough and durable objects. It can resist to high temperatures before deformation, but it also tends to shrink when it cools so that the part can might result dimensionally inaccurate. Derived from crops, PLA is a low-cost and biodegradable material used for extruding filaments even at low temperature. In 2012, the nylon copolymer filament by Taulman3D began to enlarge the number of low-cost materials available for 3D printing [4]. Now PET (Polyethylene Terephthalate) and PET-based materials like PETG, PETE and PETT are quite common because chemically and water resistant, easy to print and ensuring smooth surface finishing. The PVA (Polyvinyl Alcohol) is useful when printing complex geometries, maybe with enclosed cavities. Because it can dissolve when in contact with water, it is a good material for support structures. Then, TPU (polyurethane) and soft PLA are rubber-based materials known for their strength and flexibility while Mineral- and Wood Filled materials are available to reproduce stone and wood surfaces (Wohlers et al., 2017). Wood-based filaments are composites made of a PLA base material, cork, and other powdered wood derivatives. Other composite materials employed are a combination of Polyamide (Nylon) and fillers such as carbon fibres, glass and aluminium which improve the strength and rigidity of the base material. In this case, 3D printers usually have two nozzles: one for extruding the polymer and one for the filler like the machine designed by Markforged company [5]. Regarding photopolymerization, the most common resins used are Acrylics, Acrylates and Epoxies. Acrylic Thermosets have a great UV stability, and they are resistant to heat and water. They also present a wide range of base colours so that it is possible to build multicoloured parts [4]. In order to further improve their hardness, the photopolymers have been reinforced with ceramic particles and powders like the Accura CeraMAX developed by 3D Systems [6]. Finally, the other group of materials which 3D printers are fed into is represented by metal powders. They include Stainless Steel, Tool Steels, Titanium that are resistant to corrosion and abrasion, hard and good for several applications. Despite their great mechanical properties, metals have an important drawback that is the additional cost associated to the creation of the powder from the feedstock material. In fact, in the last years, different companies have attempted to introduce new metals and polymers too looking for better performances, lower costs and a higher degree of environmental sustainability. It is worth to highlight the contribution given by the partnership between 3Dom and c2Renew because of their proposal of a set of bio filament materials extracted from hemp, beer, and coffee (Wohlers et al., 2017).

7. APPLICATIONS

One of the main reasons why the diffusion of the AM processes has been so successful is the variety of the fields they can be applied across industries. Their first employment was to build prototypes and functional parts for the industrial/business machines sector and the Wohlers Report (2017) shows that it is still the leader with 18.8% of share. It includes computers, documents printers, robots, and other automated machines. The other dominant sectors are aerospace, automotive and consumer products/electronics.

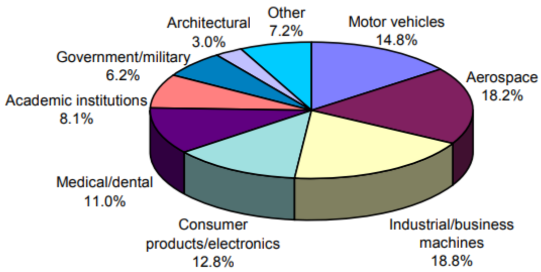


Figure 15: Industrial sectors of AM processes application source Wohlers et al. (2017)

3D printing technology allows to create complex shapes reducing the product development time and the material waste. In fact, design can be repeatedly iterated fast until the final approval and the functionalities of the parts printed can be intensively tested before the product launch to ensure the desired level of performance quality and surface accuracy. Injectors and combustion chambers are just some of the 3D-manufactured components for aircraft.

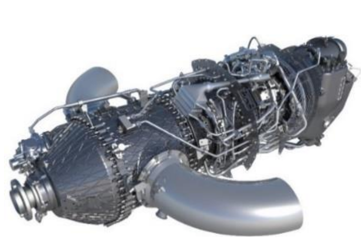


Figure 16: "The Advanced Turbprop (ATP)", the 3D-printed airplane engine by GE source: [7]

Consumer products include not only toys, mobile phones, household appliances, but also jewels, pieces of art and food because AM techniques enable the customization of these products (Wohlers et al., 2017). Another interesting field providing fertile ground for 3D printing growth is the healthcare sector. Bioengineering and tissue engineering studies have been put in practice for realizing organs and prostheses. The achievement of lower costs and extreme complex geometries printable have helped scale up the production of automated dental solutions quickly and in a very accurate way. It is possible to show the models to the client and try to reach the optimization of the products.

Figure 17: The "NextDent 5100" 3D printer commercialised by 3D Systems source: [6]

In addition, AM processes have proved to be satisfactory for producing moulds, tooling, and tooling inserts. The presence of conformal-cooling channels inside the tool or insert allows to cool down the die or the mould faster unlike straight-line channels so that the tool life is expanded, and the quality of the final product turns out to be higher. Then, the research field is another example of AM methods application for educational purpose. 3D printers and CAD software can be used to explore new technologies, experiment on innovative products according to a hand-on approach. All the major applications of 3D printing are summarized in the following graph.

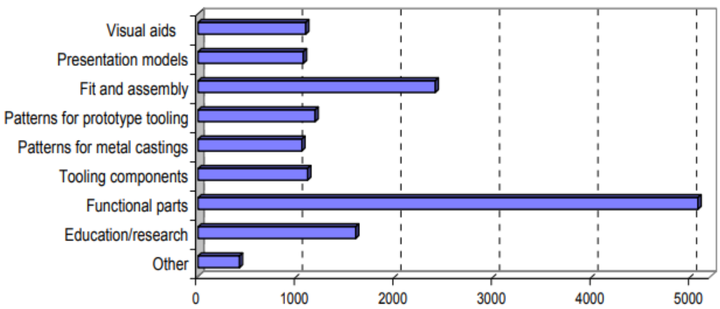


Figure 18: Answers of firms surveyed to the question "How do your customers use the parts built on your AM systems?" source: Wohlers et al. (2017)

CHAPTER 2: THE ITALIAN GOLDSMITH INDUSTRY

1. INTRODUCTION: THE GLOBAL GOLDSMITH INDUSTRY

Italy can be considered one of the flagship Countries contributing most to the global supply of high-end pieces of gold jewellery. Companies and local laboratories of artisans are spread along all the peninsula devoting their business to buy and process precious metals and stones for supplying fine jewels to their customers. It is worth to mention that, according to the ATECO 2007 classification, the code 32.1 is the one taken into consideration since it is referred to "the manufacturing of jewels, bijoux and other related articles and the processing of valuable stones". This code includes many subcategories, but only 32,12,1 is considered because representing "the manufacturing of pieces of jewellery and goldsmith jewels made of or coated with precious metals".

If thinking about the recent events, it is evident how much the pandemic together with the lockdown periods and the rising gold price have badly damaged the Italian goldsmith sector with -27.6% of production and -23.6% of sales. These negative results mirror what happened all over the world since, according to the World Gold Council [8], the annual jewellery demand fell to 1,411.6 tons globally while it was 2,122.7 tons in 2019.

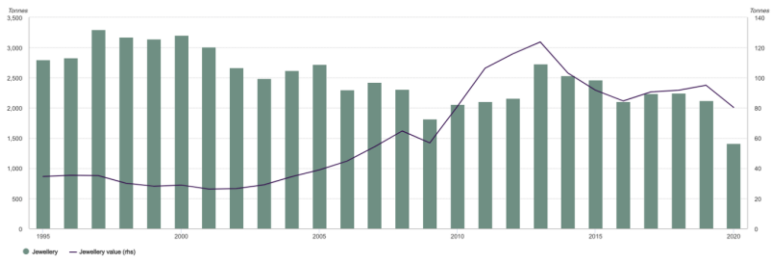


Figure 19: Annual gold jewellery demand
source: [8]

This annual drop can be attributed mainly to India and China with -42% and -35% of jewellery tons demanded in 2020 with respect to the previous year. Turkey and Middle East experienced -30%, not only due to the pandemic, but also to the inflation and the high gold price while in the USA the gold jewellery demand reached 118.2 tons yearly equal to 10% less than 2019.

The jewellery industry was not the only one to have undergone such a dramatic setback because other sectors were affected by the general slump of gold demand in 2020. The annual demand for gold decreased to 3,759.6 tons (-14%) while the last year when less than 4,000 tons were demanded was 2009. Technology sector used -7% of gold; central banks purchased annually only 272.9 tons of gold (-59%). On the other hand, bars and coins demand increased to 10% year-on-year in the last quarter of 2020 helping the retail investment sector achieve +3% to 896.1 tons. Regarding annual supply of gold, it had the worst drop since 2013. Only 4,633 tons were supplied, 4% lower year-on-year. Despite the negative trends of the last year, there are clear signals of improvement in the International markets that are driving the Italian goldsmith industry towards the full recovery as well. Among the markets where most Italian exportations are addressed, India, China and the USA have been witnessing a good economic growth, though still fragile. The seasonality and the gradual recovery from the crisis are pushing up the demand for gold jewels so that Italy can succeed again in foreign markets.

2. ITALIAN GEOGRAPHY OF GOLDSMITH PRODUCTION

The goldsmith industry is the typical expression of the "Made in Italy" concept in the world. The experience of the artisans and the products quality are globally well appreciated as symbols of expertise, originality, and luxury. The production and distribution centres are placed along the whole territory so that almost all regions caught up on the goldsmith production processes through time. Considering the first 30 provinces as shown in Figure 20, in the first semester of 2019 the provinces with more than 5% of the total units in Italy were 6 (Arezzo, Alessandria, Vicenza, Rome, Naples, Milan); those above 2% but below 5% only 2 (Florence, Caserta); those with local units below 2% were 22 (Padova, Bari, Turin, Palermo, Cagliari, Pavia, Varese, Venice, Sassari, Ancona, Macerata, Reggio Calabria, Bologna, Bolzano, Cosenza, Perugia, Genova, Treviso, Verona, Lecce, Bergamo, Pesaro & Urbino). Each province mainly includes an agglomeration of small-medium firms and few big companies which contribute to different stages of the same supply chain. In fact, the job specialization is their principal strength for manufacturing high-quality pieces of jewellery while achieving globally a good level of competitiveness.

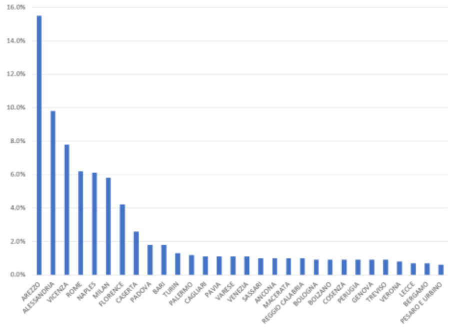


Figure 20: % of n. local units over the National total jewellery sector - first 30 provinces, I trimester of 2019
source: INFOCAMERE data processed by Camera di Commercio *Vicenza*

3. MARKET DEMAND

Changes in customers' needs and tastes have lately revolutionized the traditional demand for top-quality pieces of jewellery made by hand by Italian artisans. In the '80s the industrial production of jewels in big volumes challenged the perception of goldsmith jewellery as a symbol of uniqueness and luxury. Due to the rising price of gold and platinum, companies opted for cheaper materials like steel, stones, and metallic alloys. In addition, the trend of being always fashionable without spending too much money increased in the market. So, customers began to think of jewels as accessories for being cool and showing off the social group where they belonged rather than one-off pieces of art. This different concept of jewellery resulted into a new segment called "fashion jewellery" (Contrino, et al., 2012) as the expression of the need of making jewels accessible to any customer while the segment of the traditionally handcrafted jewellery continued to live despite its smaller size.

The market demand was affected by this phenomenon and other factors such as fierce competition due to globalization, seasonality since jewels sales boost in some periods of the year (Christmas, anniversary) and the fluctuations of gold quotations.

The demand for luxury goods is by definition rigid since large price variations induce only slight variations into the quantity demanded. Specifically, it is possible to identify two different behaviours of the demand depending on price variations. As shown in Figure 21, in an opposite way to the common norm, the quantity demanded by customers increases as the price rises up to a certain level that corresponds to the inflection point of the curve. Once the customer senses the presence of a disequilibrium between the price paid and the effective quality of the product, he/she is no longer willing to pay such a high price. So, a more traditional price-quantity relation is restored in the upper section of the curve so that the quantity demanded drops if the price increases. On the other hand, the diffusion of fashion jewellery contributed to make the market demand more elastic. Cheaper materials and mass production of jewels as accessories to complete the outfit took the place of precious metals, fine and rare pieces of jewellery. Because jewels began to be perceived as normal goods, the demand underwent a sort of “elasticization” process (Contrino, et al., 2012).

Considering the income available to customers per week instead of the price, the demand is more elastic. As the income customers have at their disposal increases, luxury goods have a minor impact on their purchasing choices so that they are more prone to buy expensive products.

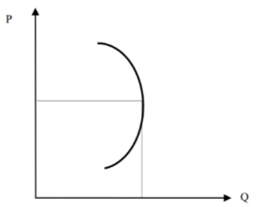


Figure 21: Rigid demand for luxury goods

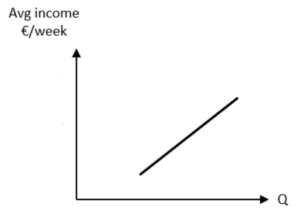


Figure 22: Demand elasticity w.r.t. average income per week

4. SUPPLY CHAIN

The supply chain is the system of activities that companies carry out to transform raw materials into final products. In the goldsmith industry, the metals extracted from mines are subject to different processes and, in the end, they are turned into more valuable objects ready for being delivered to the customer. The main stages of the supply chain of a goldsmith company can be summarized in mining, refining, manufacturing, logistics and distribution. Except for the large enterprises that may have a higher degree of vertical integration, the Italian SMEs are usually specialized just on few steps of the value chain such as design and manufacturing or retailing only.

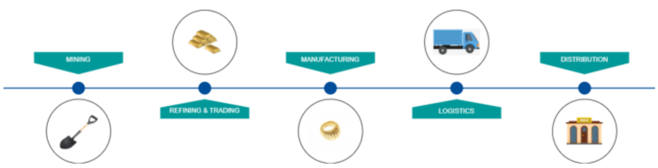


Figure 23: Supply chain of goldsmith industry

Mining

The very first step in the supply chain is the sourcing of raw materials. Gold, silver, and platinum belong to the category of precious metals, those mainly employed, together with stones, by goldsmiths. Considering gold ore, it can be extracted by "placer mining", separating the metal from the sand and the gravel in a waterway; by "vein mining", the most popular method; as by-product of other metals such as copper and zinc [9]. The mining activities are classified into artisanal and small-scale mining (ASM) and large-scale mining (LSM). ASM is spread mostly in the global South: sub-Saharan Africa, Central and South America, Asia, and Oceania (Fritz et al., 2018). The reason is that ASM represents an easy way to make up for a low income from agriculture since most of the populations living there suffer from poverty. In fact, low-skilled workforce and rudimentary equipment are the main characteristics of how ASM is carried out. Frequently, miners use mercury to separate gold from other minerals, but it is illegal, toxic, and polluting as well. Due to the uprise of precious metals prices, ASM operations have become more intense. For example, in 1993 only 6 M people were involved in ASM while in 2017 they boosted to 40.5 M (Fritz et al., 2018). In some regions, ASM coexists with LSM which are more formally regulated. Innovative techniques and tools are used for LSM by expert workers, especially to reduce the environmental impact of such operations of extraction. In addition, there is an alternative way to supply precious metals: instead of extracting the virgin materials from mines, they can be recovered from scrap. This kind of "scrap supply" of raw materials has become popular after the inflation of the market demand and the increase of gold price. Private individuals can sell their pieces of jewellery in exchange of cash while any business can decide to cash the value of their overstock or obsolete inventory [10]. Then, scrap is refined and transformed into pure gold that can re-enter the value chain.

Refining & Trading

Once they have been extracted, the impure alloys of metals can be refined on the mining site or sent to refineries. In case of secondary production processes, scrap is supplied to the refineries for being reprocessed. The largest companies refining metals from virgin sources are in China, South Africa, North America, Australia, and Switzerland. In Dubai, the Emirates Refinery is focused mainly on refining the scrap from India and Middle East [10]. After being refined, the metals are delivered in form of bars and ingots or leaves and wires depending on the customer needs. Especially for gold ingots, the first providers of precious metals to the market are Bullion banks where they are stored and secured as Unallocated Accounts (the client has general entitlement to the metals like a currency bank account) or Allocated Accounts (the client has full entitlement to the metals, and he/she is charged a fee for storage and insurance by the bank).

Manufacturing

The metals supplied by Bullion banks are, then, employed by manufacturers to realize jewellery artworks. The manufacturing phase includes, first, the design of the final product by hand or by using a CAD software; after the model building, the effective production of the piece through the assembling and galvanic plating of metals and/or punching and mounting stones; post-processing operations to improve the quality of the part and correct eventually any defects. Finally, the products which have gone successfully through the quality control are ready for being delivered.

Logistics & Distribution

The next step in the supply chain is the delivery of the final product to the distribution centres and then, to the final consumers. Depending on their degree of vertical integration, some companies may be responsible for both the production and the distribution of the pieces whereas others may be specialized in only one of the two. In fact, some firms with suitable manufacturing centres and logistics produce and autonomously sell their jewels under their proprietary or licensed brand; some focus on manufacturing processes only because working for a third-party; others just buy the jewels collections for reselling them to the customers when a capillary logistic system is what their core business is based on. In addition, distribution can be intended as both wholesale and retailing. The products by SMEs are usually intended for small segments or niches of local markets because their aim is to compete on quality, luxury, expertise following a differentiation strategy. Larger companies, instead, exploits their bigger capacity to expand their portfolio and serve the segments of both local and global markets.

5. EXPORT AND IMPORT

As one of the features of this sector is the concentration of the National production in the hands of SMEs, Italy is indeed the European Country with the largest export-import balance in the industries of SMEs with 39.1 B€ reached in 2020 [11]. Between 2019 and 2020, the export from the sectors of SMEs accounted for 7.5% of National added value. Referring to the first 9 months of 2020, export showed a negative trend in almost all the major sectors having a high concentration of SMEs. Among the manufacturing ones, the jewellery industry experienced -34.5% while only food & beverage reached a positive value (+1.8%). This trend is in line with the events of the last years since, due to the pandemic, several companies have been forced to reduce their production volumes with negative effects on their sales.

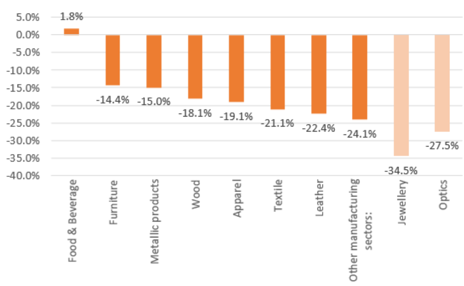


Figure 24: % var. of export trend in sector with high concentration of SMEs in Italy (Jan-Oct 2020) source: elab. of Istat data by the Research Office of Confartigianato

Looking at the last stages of the value chain, the export represents the main income source for goldsmith companies. The total exportations have boosted from 6,988 M€ to 7,425 M€ in the triennium 2017-2019. However, in 2020 the pandemic and the lockdown measures have forced many firms, wholesalers, and retailers to slow down (or shut down, in the worst case) their activities damaging their sales revenue. Moreover, the decreasing trend of the global demand and the higher quotations of precious metals also have contributed to a drop in the exportations that have reached only 5,351 M€ corresponding to -27.9% (in M€) with respect to the previous year. The total revenue has shown the same trend of export. In 2019, revenue raised up to 9,230 M€ while it was only 7,981M€ in 2017, but it decreased to 7,052 M€ in 2020.

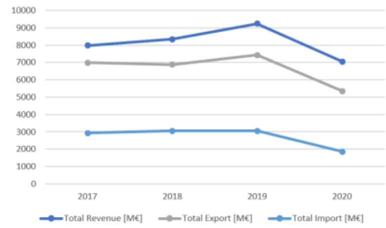


Figure 25: Trend of total revenue, export and import in the Italian goldsmith industry in M€, 2017-2020
source: elab. of data from "Sintesi quantitativa del settore orafo italiano" by Club Degli Orafi Italia and Intesa Sanpaolo Direzione Studi e Ricerche

Looking at the foreign markets singularly, their export shares have changed comparing the data from 2010 to those from 2020. In ten years, exportations towards the USA, Switzerland and France had some fluctuations, but they remained almost stable. In fact, their shares were 15.3%, 16.40% and 10.3% in 2010 and they have been the top players respectively accounting for 15.4%, 14.3% and 10% of the total Italian goldsmith export in 2020. However, Switzerland and France have experienced a percentage reduction near 40% while the USA of 14% in comparison to 2019. On the other hand, Emirates were the leading market in 2010 with 28.20% of total export while it experienced a sharp drop to only 8.4% ten years later. In addition, despite the economic crisis of the sector, the jewellery exportations towards Ireland and South Africa have grown of about 218% and 70% respectively so that these two markets have fostered the goldsmith companies' sales in 2020.

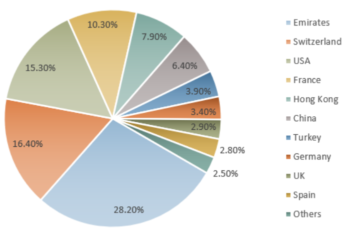


Figure 26: Export of Italian goldsmith industry per country in 2010
source: Contrino, et al. (2012)

COUNTRY	2020	% 2020	% VAR 2020
USA	821	15.4%	-14.2%
SWITZERLAND	766	14.3%	-37.7%
FRANCE	536	10.0%	-37.0%
EMIRATES	450	8.4%	-47.2%
HONG KONG	438	8.2%	-45.3%
IRELAND	304	5.7%	217.6%
UK	200	3.7%	-20.2%
TURKEY	179	3.4%	-33.1%
SOUTH AFRICA	173	3.2%	69.3%
GERMANY	169	3.2%	-17.4%
CANADA	85	1.6%	-24.8%
SPAIN	80	1.5%	-45.0%
JAPAN	78	1.5%	-1.5%
DOMINICAN REPUBLIC	69	1.3%	-46.2%

Figure 27: Italian goldsmith industry export in foreign markets in M€, 2020
source: elab. of data from "Sintesi quantitativa del settore orafo italiano" by Club Degli Orafi Italia and Intesa Sanpaolo Direzione Studi e Ricerche

Regarding import figures, only slight fluctuations interested the value of goods imported in Italy in the period 2017-2019. In fact, import was always almost 3,000 M€. Of course, the same phenomena which have affected both revenue and export have led import too to fall to 1,862 M€. France, Belgium, and Switzerland are the first three Countries from which Italian goldsmith companies import pieces of jewellery, bijoux, and stones. They have covered the 40% (in M€) of total import in 2020, but France and Belgium experienced -41% (in M€) and -33% (in M€) with respect to the previous year (see Figure 28). Switzerland, instead, has registered a more dramatic fall of -67% (in M€).

COUNTRY	2020	% 2020	% VAR 2020
FRANCE	271.7	14.6%	-40.6%
BELGIUM	242.3	13.0%	-32.3%
SWITZERLAND	218.7	11.7%	-66.5%
INDIA	130.3	7.0%	-23.5%
CHINA	125.9	6.8%	-23.9%
GERMANY	107.2	5.8%	-51.5%
THAILAND	96.9	5.2%	-28.6%
BOLIVIA	86.6	4.6%	88.0%
UK	63.8	3.4%	-20.6%
USA	60.6	3.3%	-39.9%
ROMANIA	47	2.5%	-23.0%
VIETNAM	39.4	2.1%	5.9%
HONG KONG	36.2	1.9%	-65.4%
ISRAEL	32.1	1.7%	-44.4%

Figure 28: Italian Goldsmith industry import in foreign markets in M€, 2020
source: elab. of data from "Sintesi quantitativa del settore orafo italiano" by Club Degli Orafi Italia and Intesa Sanpaolo Direzione Studi e Ricerche

6. MARKET OF MATERIALS

Goldsmith companies and artisans use mainly precious metals and stones as raw materials. Their procurement cost is affected by the fluctuations of precious metals quotations that cannot be controlled. In fact, the prices of these materials depend on the extraction activities in mines so that companies are price-takers (Contrino, et al., 2012).

Considering gold, for example, jewellery was the leading demand sector worldwide. However, in 2020 the jewellery share dropped to 37% equal to 1,400 metric tons while 2,119 metric tons more had been demanded in the previous year. Because of the pandemic and the rising price of gold, Investment with 47% share and 1,774 metric tons became the leading sector asking for gold thanks to an increase in the demand for ingots. Central banks accounted for 8.6% share while Technology sector 8% because the conductive properties of gold are good for electronical devices. In 2020, the biggest producers of gold were China, Australia, and Russia with respectively almost 380,320 and 300 metric tons produced (Garside, 2021).

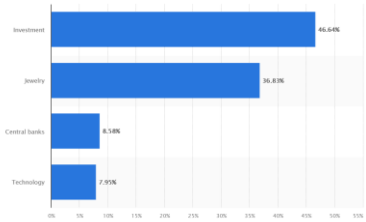


Figure 29: Distribution of global gold demand in % per sector in 2020
source: [2]

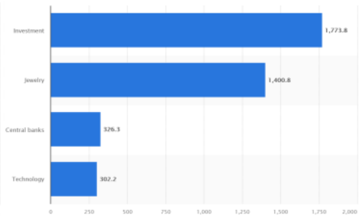


Figure 30: Distribution of global gold demand in metric tons per sector in 2020
source: [2]

Furthermore, the goldsmith market is influenced by the quotations of the precious metals. Gold, platinum, and silver all experienced a price drop in 2018 compensated by an uprise in the following years. While the price of platinum rose more steadily, gold price increased steeply in 2020 reaching 1,550.5 €/ ounce (305.2 €/ounce more than in 2019). Silver quotations were interested just by small variations and the price was 17.9 €/ounce in 2020, only 3.4 €/ounce above the price in 2019.

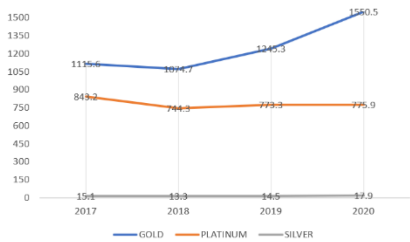


Figure 31: Trend of precious metals quotations in €/ounce
source: elab. of data from "Sintesi quantitativa del settore orafo italiano" by Club Degli Orafi Italia and Intesa Sanpaolo Direzione Studi e Ricerche

7. THE ITALIAN GOLDSMITH DISTRICTS

The production of jewels is strictly linked to the presence of the Industrial Districts (IDs) that sprang in the Italian territory in the past. In fact, the reality of IDs is peculiar of Italy thanks to the combination of specific socio-cultural factors as the main responsible for their birth and growth. In the Treccani dictionary, IDs are stated as "production systems made of a multitude of firms, mainly small-medium enterprises, with a tendency to vertical and horizontal integration and job specialization; situated in a specific territory; united by a common historical, social, economic and cultural experience" (Enciclopedia Treccani, 2012). In his book "Principles of economics" (1890) Alfred Marshall was the first to investigate the districts describing them as places where people learn to do a particular job so naturally that it is like they are "breathing it into the air". Because people do similar jobs there, the mysteries of such professions are not secret, and children learn them unconsciously. The Marshall's study was continued by Giacomo Becattini (1987) who focused on the importance of history and culture with respect to the informal relationships among the actors involved. In fact, what is essential in a district is the "mixture between the professional and the personal relations among people because knowledge spreads faster". This local learning process allows a high degree of job specialization that can be marked as the driver of the IDs success. Each small firm is specialized in a certain production stage of the supply chain achieving great cost advantages. Referring to Marshall again, the benefits of the single firm can be expanded externally to all the other agents belonging to the whole system and to all the "economies which depend on the general development of the industry" (Marshall, 1890). The IDs, indeed, represent a good source of specialized labour at low cost and they give cheap access to production services and collective resources (Treccani Dictionary of Economics and Finance, 2012). In Italy there are several places which are known for a high concentration of small firms specialized in specific phases of the same production process. Some of them are Prato, Oleggio and Carpi, districts of the textile production; Belluno, district of optics and glasses; Fabriano, district of household appliances production and assembly; Sassuolo and Faenza for ceramics. The goldsmith industry relies on the production from different areas, but Arezzo, Valenza Po (AL) and Vicenza are the biggest leaders of the market. Considering the data from the first semester of 2019, the three provinces of Arezzo, Alessandria and Vicenza include the largest number of jewellery units in Italy respectively making up 15.5%, 9.8% and 7.8% of the National total amount.

Furthermore, considering the first 12 provinces accounting for at least 1% of the National exportations, Arezzo and Vicenza gained respectively the third and the fourth place in terms of propensity to export with 29.2% and 28.3% between October 2019 and September 2020 while Alessandria reached only 16.2%.

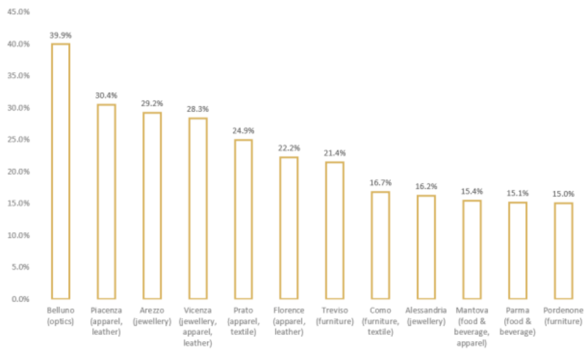


Figure 32: % export from the first 12 provinces in sectors with high concentration of SMEs (Oct 2019-Sep 2020) source: elab. by the Research Office of Confartigianato

8. AREZZO

8.1 HISTORY

The origin of precious metals manufacturing in Arezzo can be traced back to the Etruscans, a people of gold masters. The birth of the goldsmith art between the IX and I century B.C. is alleged to come from a particular gold working technique called "granulation" that in Etruria was used to reduce the metal in small crumbs then soldered on a thin foil to shape jewellery [12]. The Etruscan tradition of gold working was continued by the local gold craftsmen in their workshops in the XVI century. Then, the jewellery from Arezzo artisans reached the courts of Florence and Rome during the Renaissance Age. It was when the papacy started to commission some pieces of jewellery that the goldsmith production became devoted mainly to the religious art until the modern jewellery spread in the XX century. The development of this small artisan firms into an industrial centre was favoured by the company "Gori & Zucchi" now "UnoAErre". It was founded in 1926 by a travelling salesman, Leopoldo Gori and an artisan, Carlo Zucchi. The success of this company contributed a lot to the industry growth thanks to the proliferation of spin-offs and the decentralization of some production processes (Lazzeretti, 2003). In fact, some groups of employees founded their own companies while local small labs were entrusted with specialized activities from the supply chain following a vertical disintegration strategy. In the '60s the goldsmith economy boomed because the production expanded from local to foreign markets. However, the rise of gold price and the inflation represented a setback few years later and the companies began to consider alternative materials to gold like silver. The fragmented reality of the district kept up with the economy growth. Nonetheless, the alternation of periodical crisis challenged the small firms, but it was a stimulus for innovation as well. New metals and alloys were introduced because lighter and cheaper; products range was enlarged to serve new segments; innovative technologies like the Electroforming were adopted to realize more complex shapes allowing the companies to preserve their profitability (Lazzeretti, 2003). Moreover, two important exhibitions are held annually in Arezzo: OroArezzo and Gold Italy. The Made in Italy jewellery is the protagonist of the OroArezzo event where international experts and buyers can examine the quality of the Italian goldsmith districts production. The international workshop Gold Italy is a high-tech exhibition where the best jewellery producers encounter the best representatives from the global market.

8.2 ECONOMIC OVERVIEW

Arezzo is known for producing chain-like jewellery intended for large-scale distribution at very competitive prices (Moccia, 2018). In 2018 the number of goldsmith firms in the district was 1,119 and the number of employees 7,673 respectively accounting for the 24.4% and the 14.2% of the national total amounts (Galleri, 2021). Nowadays, among all the raw materials manufactured, gold ore is the predominant and it is used for the industrial production of generic pieces of jewellery for the medium-low market segment. However, the pandemic situation has led to an increase in the demand for ingots since gold is a safe investment against the negative interest rates as Luca Benvenuti, CEO of Chimet, the biggest Italian company producing gold, said (Pieraccini, 2020). The production of gold bars and lingots for both professional and private usage has helped the Arezzo market of gold to deal with the 29.1% decrease of jewellery exportations. Actually, the uprise of precious metals export in the first half of 2020 has been the natural continuation of the boom happened in the previous year because Arezzo already experienced +77% in 2019 (Pieraccini, 2020). The main buyers are the US, the UK, Switzerland and, of course, banks. In addition, unlike other competitors, some firms such as Chimet and Tca have built a centre where precious metals are recovered from the waste by the chemical-pharmaceutical companies rather than extracting them from virgin sources like a “district in the district” (Pieraccini, 2020).

9. VALENZA PO

9.1 HISTORY

The beginning of the goldsmith production in Valenza Po, the Italian district with the major number of goldsmith firms, took place when Francesco Caramora settled down in Piedmont. He was from Pavia where he managed with his uncle a shop of gold artifacts. In 1817 he inaugurated his workshop in Valenza and then, he taught the secrets of the goldsmith art to his two apprentices. One of these, Pietro Canti, went on sharing his master's lessons enriching them with his personal experience [13]. In 1845 one of Canti trainees, Vincenzo Morosetti, opened a laboratory. Thanks to his experience abroad, Morosetti adopted innovative techniques and hired two local artisans, Francesco Zacchetti e Carlo Bigatti, who left afterwards to start their own business. In fact, Bigatti hired a group of employees specialized in goldsmithing, etching, enamelling, and finishing promoting a strong division of labour. Then, in 1872 the number of goldsmith labs was 5 and it further increased when Vincenzo Melchiorre set up his business, Melchiorre & C. in 1873. Melchiorre had travelled across Europe and he decided to bring into his company the techniques learnt in Turin, the experience made in the luxurious Paris, in Florence and in Rome as well. So, the jewellery manufactured and commercialized by Melchiorre was far better than the others from the same district because of the achievement of great quality and the employment of precious stones as raw materials. In addition, new firms such as Raselli Nicola (1875), Cunioli e Repossi (1880), Marchese e Gaudino (1882) sprang up contributing to the growth of the district. In 1902 there were 44 companies in Valenza and the cooperative "Produttori Di Generi di Oreficeria" was founded. The machinery to produce jewels was supplied by the company Mino G.B. from Alessandria while the precious metals and stones came, for example, from Milan, Paris, and Amsterdam. In 1910, the chains manufacturing joined the manual goldsmith production in the expansion of the market from the local areas to the whole Country allowing a greater degree of automation. After the Second World War, the Italian economy boomed and the jewels from Valenza were exported even in the South America thanks to the entrepreneurs directly going promoting the products to potential clients. Due to the increase of the gold prices, the oil crisis, the companies suffered from the several setbacks the Italian economy experienced over the last years. In 2007 Valenza covered the 13.8% of the Italian goldsmith industry export. However, the entrance in the market of new Counties like India, China and Turkey and the rising competitiveness of international brands have put the business of such small firms at peril (Allio, 2010). Nonetheless, the so-called “Consorzio del Marchio Orafo” has obtained an enormous international success as the owner of DiValenza company. It is the symbol of the mixture between the century-old tradition of the small firms of the district and the capability of embracing the innovation. The mission of the brand DiValenza is, indeed, to protect the local producers and declare that the products comply with the EU regulation and the quality standards typical of Valenza. Furthermore, in 2019 a digital platform named Joyluxury.it has been created to support the Consortium of the goldsmith brand DiValenza through the promotion and the sale of the hand-made pieces of jewellery coming from the district [14]. Finally, it is worth to mention two hubs of talents recently raised: the Mani Intelligenti Foundation and the Bulgari Academy. Their mission is to train search and train future goldsmiths so that the craft of goldsmithing is passed on from one generation to another. The tradition is also mixed with innovation to stimulate students’ creativity and keep up with the new trends in the global market.

9.2 ECONOMIC OVERVIEW

In comparison to the districts of Arezzo and Vicenza, Valenza is specialized in the high-end segment of the goldsmith jewellery (Galleri, 2021). The hand-made production, the sophisticated design and the premium quality have intensified the brand awareness of the large companies while those small without any self-owned brand have mainly put their know-how at service of third-party (Moccia, 2018). According to the data by Intesa Sanpaolo, in 2018, the number of firms in the province of Alessandria working in the goldsmith industry was 802 representing the 10.1% of all Italian goldsmith firms whereas the number of employees was 5,494, the 17.5% of the total at the Country level. Valenza is the main centre of the whole district and, in fact, it accounts for the 86% (693) of the firms and the 90% (4,963) of all employees in the province of Alessandria while the remaining 14% and 10% are in situated in nearby towns like Bassignana, Pecetto di Valenza and San Salvatore Monferrato. Regarding export, between 2008 and 2019 the goldsmith district of Valenza contributed most (60%) to the increase of 2,6 billion of euros (+68.5%) in the products sold abroad from

Alessandria. In fact, one third of Alessandria total export is due to the jewellery sector (see Figure 33).

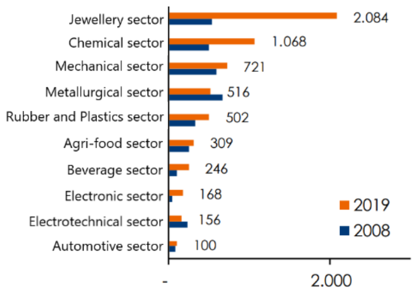


Figure 33: Export per sector from Alessandria in millions of euros
source: ISTAT data processed by Intesa Sanpaolo

As figure 34 shows, in the first quarter of 2020, the main Countries where export was addressed were Ireland (29%), France (20%) and Switzerland (12%). Referring to 2019 values, export to Switzerland dropped of 80%, the USA 50%, Hong Kong 10% accounting for 123 M€ lost globally. Only Ireland, Japan and the UK were interested by a positive trend because of export increase.

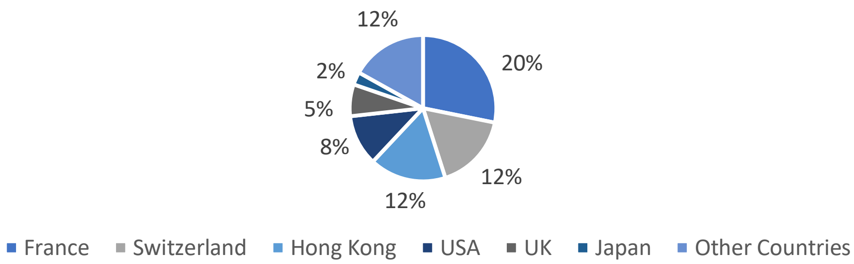


Figure 34: Main Countries of goldsmith export from Alessandria, 2020 (March 31)
source: elab.of data from Intesa Sanpaolo (2021)

10. VICENZA

10.1 HISTORY

In the north-east of Italy, the city of Vicenza and the two centres of Bassano del Grappa and Trissino make up the goldsmith district in Veneto. The discovery of some archeologic artifacts from VII century B.C. such as rudimental jewels, fibulae, plates proved that the goldsmith manufacturing finds its roots in the Paleo-Veneta Age. Then, the goldsmith art flourished in the Lombard Era. Vicenza became the location of a mint so that it gained the right to issue gold coins, but jewels and small crosses also were manufactured [15]. In 1399 the first public act confirming the existence of a thriving goldsmith activity in Vicenza was drawn up: the establishment of a corporation of 150 goldsmith artisans named "Fraglia degli Orafi di Vicenza" [16]. The corporation could vote for a representative in the Council, one of the town government bodies so that it could influence the decisions taken by the most powerful men of that time. It was in the Renaissance and Baroque periods that the district further developed thanks to some local experts like Valerio Belli, Battista Della Fede and Giorgio Capobianco and the production of artworks for religious purpose. The XIX century represented the turning point in the production process since Luigi Merlo built the first machines intended for goldsmith manufacturing only to keep the pace with the new opportunities coming from the market in expansion. In addition, in 1858 the Olympic Academy founded the "Scuola di disegno e plastica", a design school to train the future employees of the goldsmith industry. So, the adoption of new techniques and cutting-edge machinery together with the education of the technical teams helped the shift of Vicenza from being an agglomeration of small workshops to become a real industrial district [15]. Since then, all the firms have kept on improving their productive operations and their product portfolio. In fact, they are known for realizing pieces of jewellery and mini jewellery in gold and silver, settings, straps, medals, crockery, cutlery, sculptures. Moreover, several fairs are hosted in Vicenza annually. The most important event is VicenzaOro, an international exhibition where the new jewellery collections are presented, and the new trends launched. It is a Business Hub for the industry allowing the most authoritative actors from the gold and jewellery sector to get in contact [17]. It is held in September, but also in January when the T.Gold takes place as well. T.Gold is an international show for the most innovative technologies and machines for jewellery and precious metals processing. A new event recently set up is VO Vintage arranged specifically for vintage watches collectors and lovers.

10.2 ECONOMIC OVERVIEW

Vicenza is positioned in those market segments which are a bit below the high-end ones served, instead, by Valenza (Moccia, 2018). The specialization of the small firms matches the large productive capacity of those bigger and, together with their innovative attitude, they have been able to expand their distribution globally (Pieraccini, 2020). The data from Intesa Sanpaolo show that in 2018 the number of goldsmith firms in the district of Vicenza reached 565 while the number of employees 4,127 corresponding respectively to the 7.1% and the 13.1% of their relative total amounts in Italy. In the first quarter of 2019, the local goldsmith units were 4.4% and the employees 2.8% over their relative total amounts of the whole manufacturing sector of Vicenza province [18]. Then, the main export areas are Asia, Europe, and America. In 2018, the US with 19.7% share, Hong Kong 13.6% and the Emirates 11.5% were the top three export destinations, but they did not contribute enough to improve the sales revenue. In fact, the last two quarters of the same year were affected by a dramatic drop of sales revenue (-10.6%). Although at the beginning of 2019 the sales revenue went up, their trend continued to still be negative, especially for the effects of the recent events which have marked 2020 year.

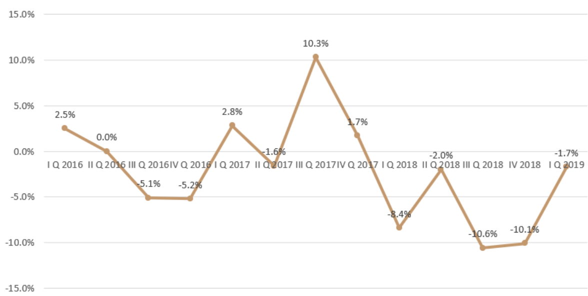


Figure 35: % var. of Vicenza district sales revenue from 2016 to I quarter of 2019
source: elab. of data from [18]

11. DISTRICTS COMPARISON

Looking at the ISTAT data from 2018, the three districts of Arezzo, Valenza Po and Vicenza are characterized mainly by micro (0-9 employees) and small (10-49 employees) companies. About 80% of total units present in each district is represented by micro firms while small ones range from 15% in Valenza Po to 20% in Arezzo and Vicenza (Galleri, 2021). Medium (50-250 employees) and large (> 250 employees) companies account only for 2% at most. Regarding the number of people hired, about 30% of local employees work in micro firms; 40% in small. 14% and 11% work respectively in medium and large firms in Valenza Po; 12% and 4% in Arezzo while 24% work exclusively in medium companies in Vicenza (Galleri, 2021). These figures show how strong is the presence of micro and small units representing the principal source of employment in these areas.

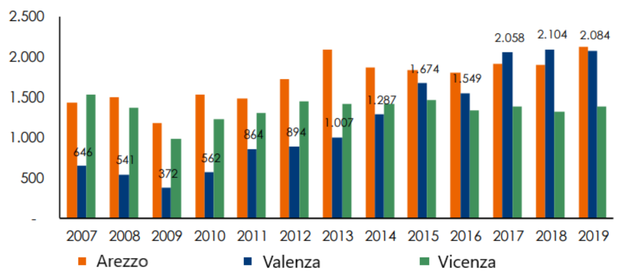


Figure 36: Export from Italian goldsmith districts in millions of euros source: ISTAT data processed by Intesa Sanpaolo

The budget documents of companies belonging to the three districts have shown that in 2019 Vicenza reached the largest total revenues as expression of the bigger dimensions of the firms in this area. However, the revenues achieved by Arezzo and Valenza, respectively 1.9 M€ and 1.7 M€, were not so far from the 2.2 M€ of Vicenza. Regarding the EBITDA (Earnings before Interest, Depreciation and Amortization), the result from Valenza was 9.2% of revenues, so 156.4 k€; Arezzo and Vicenza only 5.1% and 4.9% equal to 96.9 k€ and 107.8 k€ (Galleri, 2021*)*. The cost of labour per employee was 28.7 K€ for both Arezzo and Vicenza. Labour was more expensive in Valenza since equal to 31.5 K€, but the Value Added was 50.5 K€, so above the 40.4 K€ of Arezzo and the 41.6 K€ of Vicenza as depicted in Figure 37.

Figure 37: Comparison among VA and labour cost per employee in thousands of euros – median values, 2019 source: Galleri (2021)

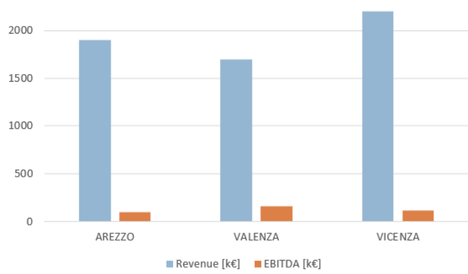


Figure 38: Comparison among revenue and EBITDA in thousands of euros – median values, 2019 source: Galleri (2021)

Moreover, the ROI index values calculated for the firms from these three districts (see Figure 39) have been compared to assess whether the capital investment made has led to a great level of profit. Arezzo and Vicenza achieved two similar values, 5.6% and 5.7%, while the companies from Valenza proved to have used their resources the most efficiently among all with 7.1% of ROI.

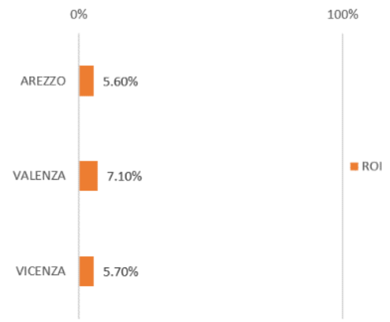


Figure 39: Comparison among ROI values – 2019
source: ISID data processed by Intesa Sanpaolo

In 2020, due to the pandemic, the Italian goldsmith industry has gone through a dramatic crisis resulting in -27.6% of production and -23.6% of profit (Galleri, 2021). The global demand for pieces of jewellery made of gold have decreased of 33.5% (in tons) on average so that the Italian exportations have shrunk of 29% (in units) leading to bad effects on the sales of all districts (Galleri, 2021). Between 2019 and 2020 the exportations from Vicenza have dropped down to -21.4% corresponding to -297 M€. Arezzo has experienced -29.1% decrease equal to -620 M€ even though in 2019 it had surpassed Valenza being the top district exporting abroad. However, Valenza has struggled the most with this demand reduction. The exportations have almost halved (-44%) causing a loss of 918 M€ with respect to the previous year.

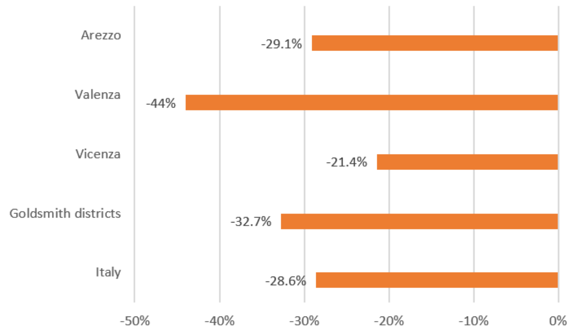


Figure 40: Export from jewellery industry in 2020
(% variation w.r.t. 2019)
source: ISTAT data processed by Intesa Sanpaolo

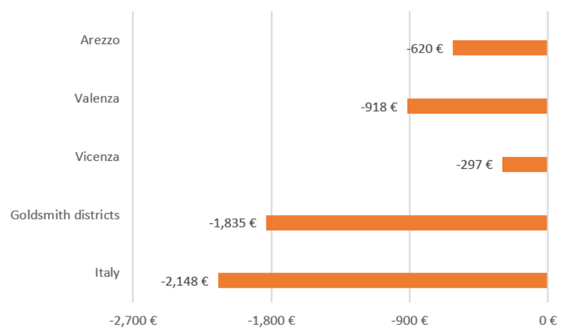


Figure 41: Export from jewellery industry in 2020
(M€ variation w.r.t. 2019)
source: ISTAT data processed by Intesa Sanpaolo

Considering import values, Arezzo's trend only was positive both in 2019 and 2020 with +71.4% and +57.8%. Pieces of jewellery imported in Vicenza shrank of 1.5% in 2019 and 25.3% in 2020 due to the pandemic. In the province of Alessandria, there were two opposite trends in 2019 since +28.4% of jewels were imported while in other areas -

11.9%. In 2020, the value of jewels, bijoux and precious stones imported was above 500 M€, but the percentage variation with respect to the previous year ranged from -38% to -45%.

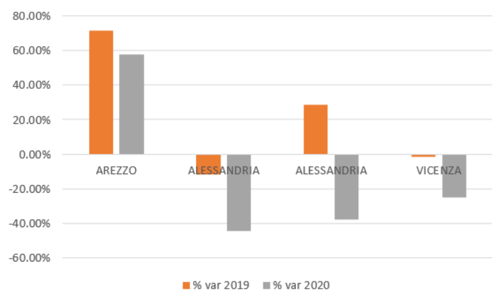


Figure 42: Import % variations for jewellery industry (M€ variations in 2019 and 2020) source: elab. of data from Intesa Sanpaolo

CHAPTER 3: THE GOLDSMITH PRODUCTION PROCESSES

1. INTRODUCTION

The discovery of some small objects and ornaments dated back to 6,000 years ago is the proof that metal casting is one of the first techniques used by humans for modelling materials into shapes. In the jewellery world as well, starting from a sketch and then, a wax model both made by hand, the artisans have been used to create their pieces of art by pouring the precious metals (gold, silver, platinum) into a mould. The usage of this technique is the expression of a long-lasting tradition founded on the principles of top quality, uniqueness, and brand identity. However, thanks to the spread of new technologies, many companies have recently started trying more innovative techniques, materials, and equipment to exploit their benefits in terms of design flexibility and costs reduction. So, nowadays there are different production processes available whose adoption depends on the costs-benefits trade off and, of course, on the culture of each goldsmith firm.

2. TRADITIONAL INVESTMENT CASTING (LOST WAX CASTING)

The Investment Casting, also known as "Lost Wax Casting", is an ancient technique whose origins can be traced back to the Egyptian, Chinese, and Aztec populations for the realization of bronze objects and tools. In the VI B.C., the artisans of the Ancient Greece used it mainly to manufacture sculptures. The wax model of the object was first covered with some refractory material, melted away ("lost") and then, the liquid bronze was poured into the mould assuming the desired shape. Across the centuries, this method has been innovated and adopted for different purposes, for example, in 1897 the American doctor D. Philbrook thought of it as a good technique for creating dental prosthesis [19]. In 1907 doctor W.H. Taggart wrote an essay where the potential of Lost Wax Casting for industrial applications were investigated for the first time [19] and since then, several fields such as aerospace, automotive and healthcare have made a huge use of it. Furthermore, the Investment Casting is the traditional technique for producing pieces of jewellery. It allows to reproduce even very complex shapes and achieve good surface finishing and dimensional tolerances (Actis Grande & Forno, 2014). The Investment Casting process is composed of a sequence of common steps as shown in Figure 43.

Figure 43: Investment Casting (Lost Wax Casting) common steps source: Actis Grande & Forno (2014)

- MODELLING/PROTOTYPING

The first step is the realization of a model or prototype by manually carving out of the wax the desired geometrical shape previously sketched. Other techniques available for creating the model are building it up from a stack of wax layers or using sheet wax (Sias, 2005). The complexity, dimensions and the accuracy of details depends on the expertise of the artisan and the casting equipment he/she is provided with [20]. When working on the design of the final product, it is worth not to neglect the potential failures that might occur during the casting stage. Because alloys are more frequently used rather than pure metals, the metal solidification after casting "does not take place at a specific temperature, but at a range of temperatures between solid and liquid" [21]. Consequently, porosities and macro-segregation phenomena due to the presence of material grains into the liquid can cause the presence of defects; the volume and the dimensions of the piece can vary [21]. Furthermore, natural wax like beeswax is not the only material used because the artisans can work with resins, metals, and by-products of oil (Sias, 2005) with wax-like properties as well. For example, in the goldsmith companies it is customary to use mainly mixtures of paraffin and synthetic polymers or natural resins (Angeloni, 2020).

- RUBBER MOULDING

Since there are two types of Investment Casting, at this point the final part can be realized directly from the wax model ("Direct method") jumping straight to the tree assembly stage [20] or from a mould replicating the original wax model ("Indirect method"). Considering the second process, the next step is the creation of a mould made of rubber from the master model. The rubber, that can be natural or silicone, is heated and then, subject to a thermal process known as "vulcanization" (RTV) around the master casting [20] and the vulcanized moulds can be "tear-up" or "whole" matrixes. Here are the main phases of this moulding process:

- The rubber enclosing the model is scattered with talcum powder or a spray to avoid that the surfaces adhere into a single piece in case of building a tear-up mould; on the other hand, to build a whole mould, the model of the steering column that will be the main sprue is just put in the middle of two rubber layers.
- The "sandwich" made of the rubber holding the model inside is compressed between the plates of the bracket for being vulcanized.
- The bracket is vulcanized in a specific vulcanizer where the temperature ranges from 140°C to 180°C. The vulcanization temperature is affected by some factors such as the rubber type, the thickness of the mould and the time required for completing the process (usually between 30 min and 75 min).
- When cooled, the mould halves are just open to take the model out if it is a tear-up matrix; in the event of a whole matrix, it is necessary to cut the die with a scalpel following a zig zag pattern because it will be easier to reclose the two parts after the wax injection.

Finally, the mould is employed for creating faithful copies of the original through repeated wax injections.

- WAX INJECTION

The third step is the injection or pouring of wax into the rubber mould to obtain as many copies of the same master model as desired. It is essential that the surface quality of the model is high to avoid the replication of any defects in both the mould and the parts. A mould with poor surface quality has a high coefficient of friction so that the fluid does not run well; does not prevent turbulences which are responsible for the erosion of the mould itself; potentially determines the lack of adequate surface finishing in the final pieces [21].

- TREE ASSEMBLING

This stage implies that all the wax copies must be assembled on a main sprue from which several other sprues can branch out in a tree-like structure. The sprues are the channels through which the molten wax flows out and the liquid metal flows in. The position and the dimensions of the runners matter a lot because they affect the metal casting success. The size of the main sprue and of the others must be proportioned; placed correctly so that the tree is balanced; allow the fluid to be distributed homogeneously without any excessive turbulences.

- FLASKS PREPARATION

Once the tree is finished, it is enclosed with a material that will harden and withstand the elevated temperatures of the following stages (Sias, 2005). It can be dipped into a bath (or in more than one) of refractory material many times until thick enough for resisting the high temperature and the pressure of the molten metal that will be cast [22]. In the past, the artisans used a refractory mix made mainly of clay, but then they shifted towards the plaster of Paris, an investment material obtained from gypsum. Now the sprues system is often covered with a ceramic shell. In case of gold and silver jewellery, the typical investment used is made of gypsum, quartz, and other additives to increase heat resistance and reduce the volume shrinkage (Sias, 2005). Because platinum melting point is higher than the other precious metals, a pure silicone-dioxide is preferred to the gypsum for this material (Sias, 2005). In addition, the liquid plaster investment needs to be contained before it hardens. So, a cylindrical container called flask is used. It consists in a segment of a stainless-steel pipe that is sealed at the bottom with a rubber sprue base to avoid any liquid leak. In order to reduce the resistance to the air going out of the mould during the casting, some firms have adopted perforated flasks. Then, the flask is put into an oven where the refractory investment is baked, and the molten wax is burnt out [22]. The oven temperature is further raised to vaporize any wax that may have soaked into the investment (Sias, 2005).

Figure 44: Steps: model creation - wax trees – flasks

- METAL CASTING

After being melted, the metal is poured into the cavity left by the molten or vaporized wax. During the injection, it is necessary that air and gases are driven out. There are some techniques to avoid the formation of dangerous air bubbles into the sprues. One is the *centrifugal casting*: the mould spins fast while the metal is poured in by centrifugal force. Others are the *vacuum-assisted casting* that implies the usage of a vacuum pump so that the liquid metal is forced into cavity by the atmospheric pressure and the *steam casting* in which the force to drive the metal in comes from the steam formed above the molten metal itself (Sias, 2005). In other methods, it is exploited the force of compressed air. The mould is further heated because, when in contact with the liquid metal, the refractory coating might undergo a thermal shock. When the metal is solid, the refractory investment is removed with a scalpel and dispersed into water if possible whereas the sprues are cut off to extract the completely cooled part [20]. Moreover, because of the temperature gradient, the solidification of the metal usually leads to volumetric shrinkage of the piece [21]. This phenomenon must be considered since the beginning of the process when modelling the final product.

- FINISHING

The last step includes all those post-processing operations aimed at improving the surface finishing of the part and prepare it for specific applications. In case of a piece of jewellery, the traditional sandblasting could be performed to remove any refractory residues together with polishing to further minimize any possible defect. When several components are designed for being manufactured separately, then, it is necessary to assembly them together into the desired final product or join them using specific techniques like laser melting. If the piece has been designed for stones setting, then it is necessary to proceed with mounting the stones on their specific cavity. Many other operations such as heat-treatments and enamelling are possible to achieve a high surface quality and satisfy the client.

3. DIRECT INVESTMENT CASTING

This technique is pretty like the Lost Wax Casting except for the initial phases of the process. Direct Investment Casting, indeed, takes advantage of digital design and 3D printing technologies. The CAD software tools allow to easily reproduce the most creative and complex geometries and iterate this step many times. Using 3D-printed patterns helps reduce the manual labour necessary for casting. In fact, these new technologies and tools simplify and shorten the sequence of stages for manufacturing pieces of jewellery.

Figure 45: Direct Investment Casting common steps

- DIGITAL MODELLING

Once the idea of the designer has been sketched, the model or prototype is digitally designed using a CAD software rather than being carved manually. Such tool allows the so-called "freedom of design" because it is very had for artisans to create intricate geometrical shapes by hand. Moreover, if unsatisfactory, the design step can be continuously repeated in a time-effective manner. The usage of digital equipment is also useful to improve the quality of the piece and increase the probability of having very few surface defects and dimensional inaccuracy to be corrected though further finishing operations.

- PROTOTYPING

When the digital modelling is completed, the next step is the building of the prototype. It is possible to realize the traditional wax patterns or exploit 3D printing technologies for creating 3D-printed patterns made of resins. The combination of 3D printing techniques and special resins helps reduce the formation of sharp corners and edges which may favour the occurrence of turbulences and excessive stress in the mould during the metal casting.

- TREE ASSEMBLING

This stage of the manufacturing process is equal to the correspondent for Lost Wax Casting. However, 3D printing methods could be employed as well. The sprues of the tree can be 3D-printed when it is difficult to assemble the wax sprues channels because of inaccessible areas connected. In case the sprues are to be printed, it is advisable to include them in the digital modelling of the piece to improve the printing process. On the other hand, the additional digital design and printing of the sprues mean that the duration of the entire process is larger.

- FLASKS PREPARATION, METAL CASTING, FINISHING

The last phases of the process are the same of Lost Wax Casting. So, please see paragraph 2.

4. SELECTIVE LASER MELTING

The spread of AM technologies pushed companies to explore new techniques and tools for jewellery manufacturing not just in few stages of the production process. In the Direct Investment Casting, digital design and 3D printed moulds are the results of AM technologies application to the traditional sequence of jewels production. It is possible to extend the benefits of AM to more steps in order to further reduce the process duration and the need for manual job. Therefore, Stereolithography (SLA) has been recently adopted to realize pieces of jewellery made of plastics thanks to the photopolymerization of a resin. Regarding the goldsmith companies, Selective Laser Melting (SLM) has been preferred as a more suitable technology for precious alloys. So, goldsmith production has been turned into a fully 3D-based process, from the digital design until the selective melting of the metal powder directly into the final product.

Figure 46: Selective Laser Melting common steps

- DIGITAL MODELLING

The initial stage is the same of Direct Investment Casting since the model or prototype of the piece is designed digitally using a CAD/CAM software system. So, please see paragraph 3.

- METAL POWDER MELTING

This second phase of the sequence substitutes the realization of the mould, the tree assembly, and the metal casting because the piece is directly manufactured layer by layer. The metal in form of powder is spread on the pre-heated machine bed where it is scanned by a UV laser according to the contouring of the desired shape. The temperature of the laser beam is set so that the metal reaches its melting point. The material melting is very localized since the laser scans narrow areas which cool down and solidifies fast. Once a layer of powder has been sintered, a new one is deposited to be scanned by the laser. The un-melted powder in excess works as support structures to ensure strength to the part especially in case of overhanging components.

- FINISHING

The last step of the process includes the same post-processing operations of Lost wax Casting and Direct Investment Casting. So, please see paragraph 2.

The only difference with the two previous techniques is the necessity of removing the support structures if any. Then, they are disposed although new methods to recycle them are being explored.

5. TECHNIQUES COMPARISON

Traditional Investment Casting, Direct Investment Casting and SLM present several differences in terms of performance, technical and economic aspects. Considering the analysis of the most popular goldsmith techniques carried out by Progold S.p.A. (Zito et al., 2017), a company producing alloys, it is possible to compare the main features of these production processes to better assess their strengths and weaknesses. (Zito et al., 2017)

The initial difference can be traced down to the core technology of each technique. Traditional and Direct Investment Casting imply first the production of a model to create many faithful copies of the same object, then the assembly of the tree, the baking of the mould and the final casting of the liquid metal. An essential parameter of this process is the temperature. In both Micro Fusion methods, the whole mass of material is utterly heated into an oven where it reaches the optimal melting temperature. SLM, on the other hand, implies the interaction between the metal powder and a laser beam that melts the material grains together. In this case, heating is localized in narrow areas around the points scanned by the laser beam. Solidification is very fast, and the material engaged with the melting phase is minimum (Zito et al., 2017). The implications are that materials with a high melting point can be heated more rapidly and easily by a laser because not all machines can withstand very high temperatures; the usage of moulds and ovens can cause surface defects due to the migration of material particles during the heating step. However, the reflectivity of materials represents a potential drawback of SLM. With more than 97% of reflectivity, gold, silver, and copper can be difficult to be scanned in a cost-effective way since they easily reflect the laser beam and, for this reason, it is necessary to supply more energy to the machine.

Regarding the need for supports, Micro Fusion techniques require structures to feed the metal into cavities whereas SLM to sustain the layers and any overhanging components. Despite their presence in all the three processes, support structures are differently related to volume parameter. In case of Traditional and Direct Investment Casting, voluminous feeders are necessary for manufacturing big objects, also constraining the thickness of jewels walls to the moulds size. Feeders might be a large portion of the total mass of the piece leading to a major quantity of scrap and, consequently, higher production costs and lower productivity. On the other hand, there is no relationship between support structures and volume. The number and the dimensions of supports depend only on surfaces width. That is why if the mass of the part gets bigger, the scrap production does not increase. However, residuals of material can be left by these support structures on the final product; cracks and defects can be generated from their removal; collapse, overheating or position change of the piece may occur. If the feeding operation is not performed correctly, phenomena such as volume shrinkage and fractures can also be observed after the Micro Fusion processes.

Moreover, important differences can be noticed from the perspective of the pieces' geometry. Monolithic pieces of jewellery with an internal cavity totally insulated from the outside cannot be manufactured by Traditional or Direct Micro Fusion. Hollow parts can be produced traditionally by placing a water-soluble wax core inside the rubber mould or welding the two halves of the objects after being separately injected in the dies. In the former case, the walls of the jewel must be pierced to let the wax flow away so that the presence of holes prevent the manufacturing of objects completely hollow; in the latter, welding could deform the piece and generate defects due to thermal stress. Direct Investment Casting is similarly critical because the numerous holes made to favour the homogeneous distribution of the refractory material around the wax model impede the production of hollow parts (Zito et al., 2017). SLM performance, instead, is far better. Albeit a limited number of microscopic holes must be still drilled to let the powder come out of the part, hollow objects can be easily built. The consequent mass reduction achieved represents the main advantage of manufacturing these types of pieces.

In addition, the usage of rubber moulds prevents the possibility of manufacturing thin parts and filigrees. The rubber usually shrinks or swells up resulting in distortions of the model walls and the removal of the piece from the mould might be responsible for defects generation. Then, the lower bound of material thickness achievable with Lost Wax Casting is 0.3 – 0.4 mm for filigree and 0.4 – 0.6 mm for the internal sides of an object while it is 0.2 – 0.3 mm for filigree and 0.2 – 0.4 for the inner walls in case of Direct Investment Casting. SLM allows to reach even lower levels of thickness like 0.2 and 0.1 mm because there is no constrain set by the mould. The laser tracking, however, still limits the minimum thickness achievable because it depends on the parameters and the type of printer and the metal powder used (Zito et al., 2017).

	Thickness [mm]	
	filigree	*internal sides*
Lost Wax Casting	0.3 - 0.4	0.4 - 0.6
Direct Investment Casting	0.2 - 0.3	0.2 - 0.4
Selective Laser Melting	0.1 - 0.2 *	0.1 - 0.2 *

** The minimum thickness achievable is function of the laser tracking, so the type of printer and metallic powder used*

Figure 47: Lower bound of thickness achievable with the most used goldsmith production processes source: elab. from Zito et al., 2017

As far as surface quality is concerned, the porosity and the roughness of objects manufactured using these three techniques can be evaluated to investigate the presence of any differences. As shown in the study by Progold S.p.A., a piece made of an alloy of gold, silver, and copper, if produced through SLM, present a porosity that is twenty-five times lower than if realized through Traditional or Direct Investment Casting. About total roughness (Rt), the material to be removed during polishing operation to obtain a smooth surface has been taken into account. Figure 48 shows that total average roughness is greater for SLM-produced objects because of the typical additive technology while it decreases when going from Direct to Traditional Investment Casting. However, in case of Direct Micro Fusion, roughness is influenced by the type of machine used that was a multi-jet wax printer for this analysis carried out by Progold S.p.A.

	Porosity [%] **Au-Ag-Cu alloy**	**Rt avg [μm]** **gold 18 K alloy**
Lost Wax Casting	0.25	22.0
Direct Investment Casting	0.25	27.3
Selective Laser Melting	0.01	31.3

Figure 48: Comparison between porosity and total average roughness measured for the most used goldsmith production processes
source: elab. from Zito et al., 2017

Furthermore, the hours necessary to produce 1, 10 or 100 gold rings using the three techniques have been compared. Being the alloy the same for all, the pieces weight was 10 g, the volume identical, but the shape different since dependent on the technique considered. A band and a hollow ring were chosen for both Micro Fusion methods and SLM respectively. The overall Lead Production time was calculated as the sum of the time intervals necessary to perform the single steps of each production sequence. In the classic Micro Fusion, prototyping, preparation and wax injection into the mould, tree assembly, flasks preparation and baking, melting, casting, and finishing were the phases considered; wax model printing, support structures removal, tree assembly, flasks preparation and baking, melting, casting, and finishing were taken into consideration for Direct Micro Fusion; SLM sequence included digital modelling, printing, machine cleaning, removal of the piece and the support structures. The stages which are common to all the three sequences were excluded from the analysis. On one side, Figure 49 clearly highlights how it is possible to manufacture a piece by SLM in just a couple of hours while Classic and Direct Casting require between 20 and 35 hours. On the other side, as the volume of the batch to produce increases, SLM is no longer convenient because building the prototype, moulding and flasks baking from Micro Fusion become quicker. Almost 80 hours are necessary to manufacture 100 pieces by SLM while only 30 using Direct Investment Casting. If the lot size is further wide, Lost Wax Casting is even better than Direct Micro Fusion due to the large time required for prototyping. These results suggest that SLM can be successfully adopted to easily customize products by directly realizing unique pieces fast to address the specific needs of customers. Micro fusion techniques, indeed, are preferred for manufacturing larger lots, so products in series, since moulds and models already available can be employed to produce high volumes of parts in a short time.

	Production time [hours]		
	1 piece	*10 pieces*	*100 pieces*
Lost Wax Casting	34.0	34.5	37.5
Direct Investment Casting	18.5	18.5	28.5
Selective Laser Melting	2.0	8.0	78.5

Figure 49: Time estimated in hours to produce 1, 10 or 100 pieces with the most used goldsmith production processes source: elab. from Zito et al., 2017

Finally, from an economic perspective, market prices for jewels manufactured by the three techniques have been evaluated. They are affected by different parameters such as labour cost, electric energy consumption and geography. Progold S.p.A. considered in their research Italy as the reference market for labour cost assessment and estimated a price range for each process depending on their productive performance i.e. flasks filling, occupation of the 3D printer platform, scrap (support structures and defective products) and types of objects. Traditional Investment Casting is the least expensive methodology because the equipment used is cheaper and the production of pieces in large volumes and/or in series allows to amortize the cost of the most onerous phases of the process. Direct Micro Fusion is more expensive that Lost Wax Casting and, indeed, market prices are like those of SLM. 3D printers are far more costly, but the product customization, the geometry complexity and, consequently, the possibility of manufacturing original and unique jewels justifies a higher price for these products up to 12 €/g.

	Market price [€/g]
Lost Wax Casting	0.2 - 1
Direct Investment Casting	2 - 6
Selective Laser Melting	4 - 12

Figure 50: Comparison among market prices of jewels manufactured by the most used goldsmith production processes source: elab. from Zito et al., 2017

6. CAD SOFTWARE SYSTEMS

The first AM breakthrough adopted by goldsmith companies is the digital modelling of parts through CAD software systems. Even the most geometrically complex objects can be designed, and the possibility of surface defects and dimensional inaccuracy is low. Among the most sophisticated systems used for jewellery production there are:

- *3Design*: the solution by 3Design is a CAD software that takes inspiration from the graphics of the videogames to ensure the best real-time designing experience. The platform includes all the equipment that a goldsmith may need to shape different pieces of jewellery, and it is not required to be an IT expert to be able to use all the tools available. In addition, the files can be exported in STL format in case of 3D printing [23].

- *Autodesk Fusion 360*: it is a software that allows 3D, CAD, CAM, CAE, and PCB designing. The platform is cloud based and the tools included are useful for modelling and optimize the aesthetics and the shape of jewels. The freedom of design and the low impact of changes to the digital model leads to real-time product customization and cost- and time-effective manufacturing process [24].

- *Rhinoceros*: this CAD software is the most popular among the largest manufacturers in the jewellery industry. Any design can be developed allowing fast product customization. Moreover, Rhino platform can link 3D models to real-time inventory such as gemstones and mountings because it supports many brand-specific plugins [25].

7. 3D PRINTERS

The increasing spread of 3D printing technology in many sectors has boosted the demand for machinery. Thanks to the progress of technology, now there are several 3D printers available in the market which are very innovative, reliable, and affordable as

well. *3D Systems* is a company that has been providing AM solutions for more than 30 years. Their industrial-level printer FabPro 1000 has been thought to optimize the quality of polymeric prototypes and cast patterns for jewellery faster than competitors. Reliable materials and design iteration are just some of the benefits that leads to product customization satisfactorily [6].
The application of the Selective Laser Melting technology to the goldsmith production has proved to be promising in terms of low coefficients of roughness and quality of the piece. Using only one machine, objects can be directly printed without any intermediate steps and achieving good levels of surface accuracy. *SLM Solutions* is the leading supplier of AM machines for SLM of metal alloys. It is provided with an open architecture platform so that it is possible to control the process parameters as desired. Its product portfolio includes a wide range of 3D printers which are differentiated by the volumes of production (low or high), the number of lasers (single or multiple), powder handling method (manual or automated) and the materials [26]. All these features allow to improve the productivity and the creativity of goldsmiths.

8. MATERIALS

The production of pieces of jewellery involves the usage of different categories of materials. In fact, not only precious metals are employed by goldsmiths, but also wax, resins and polymers to build the master models and the moulds depending on the type of manufacturing process. The most common materials used are:

- *Wax*: this material is mainly used for Lost Wax Casting and there are various types available for jewels makers. *Natural wax* is produced by bees and its melting point and hardness depend on the pollen and flowers it is created from. During casting phase, it reduces the shrinkage phenomenon. *Synthetic wax* is derived from petroleum and it is divided into microcrystalline wax and paraffin wax. *Microcrystalline wax* has a small crystal structure and a very high melting point. It is one of the most popular waxes used in the jewellery sector. On the other hand, *paraffin wax* has a large crystal structure. Since hard, it is not good for modelling pieces of jewellery by hand. So, it is manly employed as an additive to harden softer waxes. Furthermore, there are many specialty waxes depending on the specific application. For example, *sticky wax* is hard at the beginning, then, it becomes tacky until totally melted when the temperature raises. It is used by goldsmiths for attaching the sprues and assemble the tree. *Modelling wax* is used by jewels manufacturers as clay because it becomes very soft and easy to shape if exposed to heat. It is usually a mix of different ingredients such as natural wax, paraffin or microcrystalline wax and fillers.

- *Resin*: castable, castable wax, grey and high temp resins belong to this category. The *castable resin* is used to realize models of complex and detailed pieces of jewellery through Lost Wax Casting. When melting, this resin is gradually transformed into gas to avoid the formation of cracks into the investment during the expansion. Then, the combustion is a clean process because no residues are left. Once the piece is printed, a post-printing photopolymerization is necessary before casting. The *castable wax resin* is a photopolymer made of solid and liquid waxes developed for ensuring clean and reliable casting experiences. The amount of cast wax in the mixture ranges from 20% to 40%. It can be used for rapid prototyping and 3D printing of moulds. Thanks to its little expansion property, it is perfect for intricated jewellery and highly detailed and complex designs like filigree and pave geometries. The 3D printed components do not require any post-printing photopolymerization, but casting can be performed immediately so that combustion is accelerated, and the casting process is optimized. The *grey resin* is a standard resin employed for 3D prototyping. It is very resistant to stretching and friction and, in fact, it is useful to realize durable models. Good dimensional accuracy and details precision are quite common. The *hi temp resin* has been developed for parts that must undergo high temperatures like the master models during vulcanized rubber moulding. The thermal distortion temperature (HDT) is 238° C at 0.45 MPa and the suitable printing resolution for small pieces of jewellery is 25 microns. The printing of detailed components is usually performed with support structures because the surface of the piece may adhere to the machine platform. Even in this case, the post-printing photopolymerization is required once the support structures have been removed.

- *Metals*: the metal alloys used for 3D printing are usually available in two forms which are powders bound into filaments or raw powders. Metal-based 3D printing is useful for manufacturing parts which are hard to machine or mill and whenever is cheaper, especially for low volume batches. The goldsmith companies mainly use *precious metals*, but there are other alloys which are very popular like steels, titanium, and specialty alloys (Inconel, cobalt chrome). *Steel* is employed for many applications thank to its low cost and versatility. There are two types of steel: *stainless steel*, known for its corrosion resistance, and *tool steel*, mainly used for tooling because hard, resistant to abrasion and high temperatures. The most common tool steels are *A series* (used for building dies and punches because tough and wear resistant), *D series* (used for cutting tools like blades and knives since optimized for resisting to wear and stress) and *H series* (they maintain their strength and stiffness at very high temperatures). Then, *titanium* is lightweight, resistant to corrosion and heat and it is used when a high strength-to-weight ratio is necessary. *Inconel* (nickel alloys) and *cobalt chrome* are two groups of *superalloys* and they are suitable for hostile environments because anti-corrosion, heat resistant, stable, and strong. However, they are quite expensive.

CHAPTER 4: TRADE OFF OF BENEFITS AND CHALLENGES FOR THE APPLICATION OF AM TECHNOLOGY

1. INTRODUCTION

What has supported most the public spread of AM technologies in the manufacturing industry is the plethora of benefits which companies can enjoy. Innovation and technology have been successfully working together to come up with cutting-edge solutions. The majority of goldsmith companies have understood the potential of 3D printing techniques and equipment since powerful tools to improve their business value and competitiveness. On one hand, the possibility of optimizing the design and the production stages seems an incredible breakthrough for manufacturing pieces of jewellery which traditionally require a lot of manual effort by artisans. On the other hand, there are still several challenges to address because the adoption of such technologies is costly and presents companies with constraints to the full performance of their activities. Here there is the description of the main benefits and challenges of AM technology.

2. BENEFITS

AM techniques have opened up many opportunities to revolutionize positively the supply chain of goldsmith companies. The digital rather than manual design of pieces speeds up the initial phase of the production process in a time-effective manner and lower the labour cost. Then, the unnecessity for tooling and realization of moulds determines a further decrease of costs since the final product is fully 3D printed through a one-step process. The most complex and detailed geometries can be designed and printed; products can be fast adapted to the desires of the customer; prototypes can be built in little time so that the commercial launch of the product can be accelerated. Moreover, innovative design and shapes have been searched for obtaining lightweight pieces which might be less expensive to produce and transport.

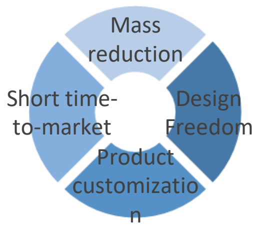


Figure 51: The main advantages of AM technology

- *Design freedom*

The usage of a CAD software gives the opportunity to digitally model a wider range of shapes. In fact, it allows to reproduce even the most elaborate geometries that would be impossible or at least hard to shape by hand in terms of both difficulty and time needed. So, potentially there are no restrictions to the design complexity that a jeweller can achieve and, considering the so-called "complexity for free" concept, the marginal cost of production rises only marginally whenever the complexity of a piece increases. Now the CAD software systems available in the market have been getting more sophisticated incorporating all the tools that goldsmiths may need. They also suggest how to model specific sections of a part and complement existing design; they encourage the creativity of users and allow to shape quickly all the details of an object with high definition.

- *Iterative design and fast product customization*

Another advantage of a CAD software system is that several design iterations can be tried by users until the result is satisfactory with low additional costs. Over 60% of designs submitted for tooling are usually changed once in the production stage (Attaran, 2017). So, the possibility of repeating the design reduces the increase in costs and time delays that will occur when modifying the model in the final steps rather than in the initial phase of the production process. Moreover, 3D modelling systems enable fast product customization. The desires of customers can be fulfilled real-time, whenever they change, at more affordable costs than conventional subtractive technologies. Therefore, customer satisfaction and loyalty can be preserved along time since the lead time is shrunk and the company is able to serve immediately the market demand. Then, customized products show the firm commitment into always offering their customers the best value proposition tailored to their needs. Furthermore, the chance to personalize a piece of jewellery justifies the companies to charge customers a premium price for the original and unique jewels produced and delivered. Such business strategy helps keep revenue steady, if not boost, whereas small firms may survive the competition by bigger companies focusing on market niches.

- *Topological optimization*

The upstream phases of design process account for the 75% of the total development costs of an object (Gardan & Alexander, 2015). This means that optimizing the design through the best topological shape of pieces possible may result in costs savings. The term topology refers to the geometrical properties and the spatial relations among objects and how they are not affected by any deformations of their shape or dimensions. Considering the goldsmith production, topology optimization means finding the best distribution of material into the design space (Gardan & Alexander, 2015) to reduce the mass and the volume of the part while retaining its mechanical properties and improving its strength. Thanks to some algorithms run on CAD software systems, the set of parameters such as thickness, density, and angles orientation can be manipulated until their best combination is found. So, mass and volume can be improved while the functionality of the piece is utterly preserved or enhanced as well like, for example, when cooling channels are better designed. Consequently, mass reduction and volume optimization allow to save material so that the procurement costs decrease. Not only the cost per part is smaller, but also the energy to be consumed for the product applications is lower if light in weight. In addition, shaping parts clearly and accurately helps reduce the amount of scrap that could be produced during the manufacturing process. Finally, design optimization enables the integration of all the functions into only one piece so that there is no need for sub-components to be built and assembled. So, time and cost for assembling multiple parts is reduced ramping up the efficiency of the entire manufacturing process.

- *Short time-to-market*

The application of 3D techniques also entails the shrinkage of the product development process. Because some intermediate phases of the traditional manufacturing sequence are not needed any longer, an object can be designed, built, and launched very fast. CAD systems and 3D printers let goldsmiths model shapes and realize prototypes quickly so that the design stage is accelerated. The physical production of the piece can start immediately as to anticipate its distribution among customers. So, companies can benefit from a shorter time-to-market in terms of time savings and improved competitiveness. In fact, they could launch their collections of jewels before their competitors gaining a larger market share and raising barriers for new entrants, especially in the event of volatile markets. At the same time, they may influence the market trends with their innovative creations aiming at boosting their sales and revenue.

- *Economic production of small batches*

Due to the large investment in equipment and the time required for printing, the production of few unique pieces only was the first main application of AM technology. As soon as the CAD systems, 3D printers and materials got more affordable, the shift from the traditional subtractive techniques towards 3D printing became more intense and the application fields numerous. Now it is economically feasible to produce small batches of customized parts through 3D techniques. Companies, indeed, have realized that it is less expensive to use 3D printing than, for example, conventional machining or milling for manufacturing little amounts of specific end-use items. As innovation and technology have been going on, AM technique might be devoted to line production as well so that, not only low-volume batches, but even medium/large series of production at volumes of 100,000 units can be achieved monthly [27] promoting mass customization at low cost. Then, the small-volume manufacturing in AM industry is expected to increase up to 1.1 B$ in 2025 and it will probably drive down the price of materials too (Attaran, 2017).

- *Lower cost for inventories and logistic services*

The topological optimization enabled by 3D technology directly affects the cost for warehousing and logistics. Lightweight components can be shipped at lower cost and because there is no need for assembling multiple components and sub-systems, space savings for storage in the warehouses can be reached. Moreover, on-demand manufacturing of customized parts means that bulk inventories are no longer necessary and, since products can be printed even in remote locations by local distributors, there are no delivery restrictions (Attaran, 2017). Then, thanks to digital design, manufacturing may not be centralized. In fact, objects might be manufactured nearby the distribution centres or final customers to benefit from lower shipping costs (Attaran, 2017).

- *No tooling expenses*

When going for AM to print pieces in one step, the conventional tools used by designers and engineers are no longer required. Tools, cutting edges, dies or moulds are not necessary for manufacturing processes. In traditional production systems, the investment in tooling is amortized over high volumes of units produced thanks to economies of scale whilst 3D printing allows to completely avoid such costs in the first place. So, companies income statements do not include any tooling expenses. Then, the manufacturing process lasts less thanks to no idle time affecting its duration. In fact, the time for setting up and changing tools is reduced to zero.

3. CHALLENGES

Although the implementation of AM methods brings several advantages to manufacturing companies, however, some aspects are still in need of being further improved. In order to print objects, capital investments in special equipment like printers and CAD systems must be made; additional procurement of material is necessary to build the structures which support the piece; metal powders are quite expensive. Then, the dimensions of 3D printers limit the size of the parts that could be produced. Dimensional tolerances and surface accuracy might not be satisfactory enough so that post-processing operations must be performed to fulfil these requirements. Furthermore, the printing rate of machines is not very fast yet and manufacturing high-volume batches takes a lot of time compromising the competitiveness of a company.

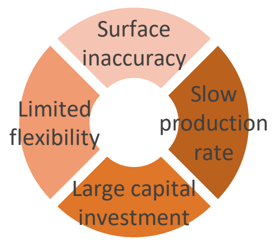


Figure 52: The main challenges of AM technology

- *Slow production rate*

In comparison to the standard manufacturing processes, 3D printing technology is considered more time efficient. Nevertheless, the build rate of printers is still slow, especially when large volumes of pieces are to be produced layer by layer. Some solutions to improve the speed of AM processes have been suggested like equipping printers with multiple printheads for manufacturing parts in parallel and printing different materials at the same time (Attaran, 2017). In case of big objects, their dimensions slow down the production process and optimizing the design might be helpful to overcome this barrier (Attaran, 2017). Then, large nozzles, faster moving printheads and high-speed lasers able to cut wider areas are useful to further improve the speed of printers. According to 2017 report by Siemens, the production speed is forecasted to reach 80 cm3/h doubling the relative amount of 2018.

- *Large capital investment in equipment*

Picking a new technology always involves capital investments and switching costs. AM processes require special equipment to invest in and expertise for using it. First, companies need to procure all the necessary tools such as 3D printers, CAD software systems and materials. Previously, it was possible to find top-performing printers only at a high price since their cheaper versions had just primitive functionalities. Now enthusiasts can purchase 3D printers with high capabilities for less than 4,000€ while professional and industrial printers range from 4,000€ - 20,000€ and 20,000€ - 100,000€ respectively [28]. The annual fee for CAD software systems is less than 3,000€ and the price of materials depends on their composition and how they have been processed. For example, goldsmith companies use metal powders which are expensive, not only because of the high quotations of precious metals, but also because the process of metals atomization into powder form is costly. Then, employees training is another aspect to take into account. Some time and money, indeed, must be devoted to teaching workers how to use digital systems and machines and companies might not benefit from learning economies. In addition, 3D printing methods are not suitable yet for building high volumes of units. Therefore, equipment cost cannot be amortized over a large number of products. Economies of scale are not achievable as well.

- *Need of support structures*

When printing an object, additional structures are required to support the piece. Printing such ancillary parts and removing them after increase the global manufacturing time because it is necessary to wait longer before the final piece is ready for eventual finishing operations. Then, extra material must be purchased raising up the total procurement cost. Another issue linked to the presence of support structures is their removal. Once they are taken away from the machine bed, they may damage the piece surface and make mandatory post-processing activities. Moreover, support structures, once removed, are usually disposed as scrap because it is difficult to reuse them. However, metal powder can be recycled because, unlike polymers, metals preserve their mechanical properties after the recycling process. New sustainable solutions also are currently under analysis.

- *Limited flexibility of 3D printers*

Another drawback of AM is the lack of flexibility of 3D printers both in terms of materials allowed and size of parts. Printers can be fed only with some specific materials and that is why firms can use only a limited set of polymers and metals. Then, the dimensions of the pieces to be printed are constrained by the build volume of the printer so that they must be adapted to it. Even though there are many big printers available to manufacture larger parts, not all firms may have enough room to accommodate them properly (Attaran, 2017).

- *Possible dimensional inaccuracy and poor surface finishing*

If using 3D printing, companies can risk dimensional and surface inaccuracy. The dimensional tolerances of the final part could be different from those required; surface quality could be poor due to excessive roughness, porosity, cracks, and other defects caused by the removal of support structures or the wrong movement of the nozzle. So, additional finishing operations are to be performed for fixing such defects, but the global production time and costs go up.

CHAPTER 5: AM TECHNOLOGY ADOPTION IN THE GOLDSMITH DISTRICT OF VALENZA PO (AL)

1. INTRODUCTION

To further investigate the current adoption of AM technology in the Italian goldsmith industry, a survey was carried out. Valenza Po was chosen among the three major goldsmith districts in Italy for sharing the questionnaire. About 100 goldsmith companies from the province of Alessandria were reached by phone and asked for doing the questionnaire. The firms that were available for filling the survey in were provided via email with the link of a Google Form file. Then, the responses collected were analysed to mainly assess

- the degree of 3D printing diffusion among firms;
- the reasons which brought them to opt for 3D printing;
- the benefits and the costs they experienced;
- their position about future investments in AM techniques.

It was interesting to analyse the results especially because this research was conducted in a place of mainly SMEs traditionally founded on the hand-made principle to supply rare, luxurious, and high-quality products.

2. THE METHODOLOGY

The methodology through which the survey was conducted is characterized by a sequence of steps.

1) The very first step was the identification of the population. Since the Italian goldsmith industry is mainly concentrated in three districts (Arezzo, Valenza Po, Vicenza), it was decided to select one of these for discriminating the data about AM diffusion in the goldsmith sector. In fact, it would have been too complex to consider all the local units spread over the National territory. The Valenza Po district in Piedmont was chosen. However, the research was not limited to this town, but was expanded to the whole province of Alessandria.
2) The second step was defining the questions to ask according to the topics to be investigated.

3) Then, a list of companies was written down and, for each of them, the phone number was searched on the Internet. The companies of the list were called before sharing the questionnaire. A direct contact is usually more effective to obtain firms' real commitment for answering the questions of a questionnaire. Those that answered to the phone were asked to do a survey and, in case of a positive reply, they were invited to provide an email address for sharing via email the link of the questionnaire. In addition, a deadline (Oct 20th) for doing the questionnaire was set and communicated to the companies for further encouraging them to do it as soon as possible.
4) The link to the survey in Google Form format was shared to collect the responses.
5) Finally, the answers received were analysed drawing some graphs and trying to deduce conclusions about the real attitude of goldsmith firms today towards AM technology.

3. THE SAMPLE

Once the district was selected, it was necessary to find a list of companies to get in contact with. On the website of the "Camera di Commercio" of Alessandria [29], the register of all companies assigned with a trademark for selling, manufacturing, or importing precious metals was publicly available. The so-called "identification trademark for precious metals" is mandatory for trading precious pieces of jewellery in Italy because it allows to identify the manufacturer and the province where his/her legal head office is situated. Since the register includes 75 pages of companies, only 140 were selected randomly for being reached by phone. Those that accepted to fill in the questionnaire were sent by email the relative link. A subgroup of 24 companies were not reached because the phone number found resulted to be not in service. Among the 116 companies that answered to the phone, 2 companies replied to be shutting down their business while other 2 declared not to be involved in any manufacturing activities because just jewels retailers. 67 accepted to do the questionnaire providing their email address while the remaining 45 were not willing to do it because they were too busy or not allowed to due to their policy. In the end, only 29 firms really filled the survey as promised.

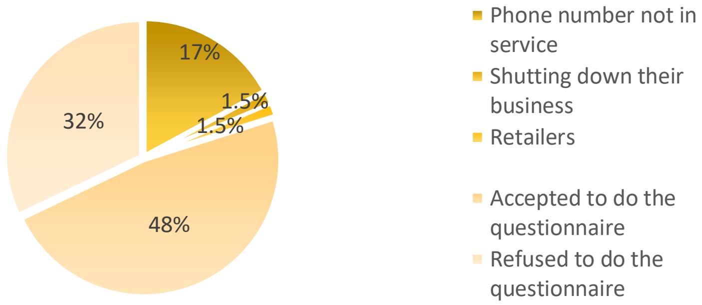


Figure 53: Categorization of the initial sample

Retailers of jewels, companies for which a valid phone number was not available or about to shut down their business were excluded from the initial sample that, therefore, was reduced to 112 elements. So, 59.83% of this reduced sample accepted to do the survey whereas only 29 really did so accounting for 25.90% of response rate.

	N°	%
Phone number was not in service	24	17.14%
About to shut down their business	2	1.43%
Retailers	2	1.43%
Accepted to do the questionnaire	67	47.86%
Refused to do the questionnaire	45	32.14%
Sample size	140	100.00%
Really filled in the questionnaire	**29**	**25.90%***

***** *percentage calculated on a sample reduced to 112 companies*

Figure 54: Sample composition

4. THE QUESTIONNAIRE

The questionnaire was made of an introduction, a conclusion and 6 sections of questions.

In the introduction, the aim of the survey was explained while the purpose of the conclusion was to thank the companies that devoted a couple of minutes to fill it.

In the middle, the questions of the first section asked for general information about the company such as the name, the size and whether their production process involved any 3D printing techniques. The second and the third sections included similar questions about the equipment. Specifically, these questions were aimed at investigating the use frequency of 3D printers and CAD software systems, if any; the main reasons why they were bought or leased; their procurement cost. The following section was focused on the type of production process used by the company while the sixth on the environmental sustainability of AM technology since a recent hot topic. The last section was intended especially for those that do not use 3D printing yet because they still prefer to manufacture pieces of jewellery traditionally by hand or they cannot afford the investment in new tools. So, they just were asked whether they would ever consider the adoption of AM techniques in the future and in how many years.

For further details about the questionnaire, please see Appendix A.

5. ANALYSIS OF RESPONSES

5.1 SECTION 1: GENERAL INFORMATION

The first aspect investigated in the initial section of the questionnaire was the companies' size. According to Istat data, micro and small firms in the district of Valenza Po are 98% and the survey, indeed, confirmed this result. As Figure 55 shows, the companies that answered to have at most 10 employees were 18 accounting for 62.1% of the sample. 8 declared to have between 11 and 30 employees while 1 between 31 and 50 respectively representing 27.6% and 3.4% of those who took the questionnaire. Only 6.9%, corresponding to 2 companies, had more than 50 employees. The responses collected live up to expectations since 90% of the sample are micro/small companies such as artisanal laboratories and family-run businesses whereas larger firms with more than 30 employees are only 10%. These figures are clearly in line with the structure of the Italian goldsmith industry that rests on the activities carried out by agglomerations of SMEs in the local districts.

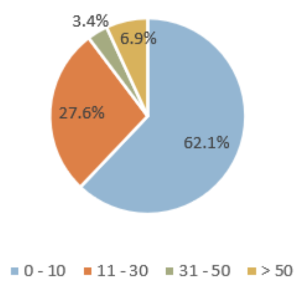


Figure 55: Answers to the question "How many employees does the enterprise have?"

The attention was then drawn to 3D printing adoption. 21 companies answered to be currently using AM technology in their production process. Although more than half of the sample (72.4%) already went for 3D printing, 27.6% still manufacture pieces of jewellery traditionally by hand.

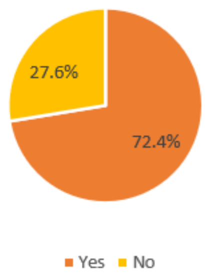


Figure 56: Answer to the question "Does the enterprise currently use any AM technologies in its production process?"

These figures, however, must be taken with a pinch of salt. The real percentage of enterprises which adopted 3D technology may be lower than 72.4% since this result is strictly bound to the sample reached. It is quite likely that companies already using 3D tools were more prone to answer the questionnaire. This may have jeopardized the authentic proportions of firms using AM and those not using it so that the sample turns out to be biased. In Figure 57, the responses to the questions about enterprises size and the AM implementation/no-implementation have been crossed to find out the data correlations, if any. The adoption rate of micro firms (0 – 10 employees) is only 61%. Such no-adoption trend can be due to the perception of AM techniques not as opportunities, but rather threats to the goldsmith craftsmanship. As expected, small business and artisanal laboratories seem reluctant to adopt more innovative methods. Since their competitive strategy is usually based on differentiation, they go on pursuing a unique and original product portfolio through handcraft. Then, not only brand image and reputation, but also the high cost of equipment may further restrain them from switching. On the other hand, AM technology is spread more widely among larger companies. 91% of the enterprises which answered to have more than 10 employees is already using some 3D tools. Their decision-making process may have embraced innovation more thanks to bigger financial resources at disposal that may have encouraged the experimentation of new methods for jewels design and manufacturing. Nonetheless, it is important to point out that very few firms with large dimensions filled the questionnaire (only one firm with 31 – 50 employees and two with more than 50). This means that the observations derived from the results obtained may apply only in relation to the sample.

	Enterprises size			
	0 - 10	**11 - 30**	**31 - 50**	**> 50**
n° enterprises	18	8	1	2
n° AM implementations	11	7	1	2
% adoption rate	**61%**	**88%**	**100%**	**100%**

Figure 57: Crossing of answers to the questions "How many employees does the enterprise have?" and "Does the enterprise currently use any AM technologies in its production process?"

In addition, the companies that answered "yes" to the adoption question were asked to write the year when they introduced 3D printing. The majority (19.05%) replied in 2010, 2016 or 2018; 2 companies (9.52%) in 2005; other 2 in 2007. Others wrote in 2012, 2015 and 2017 proving that AM diffusion has become intense from 2010 on. However, 2 companies declared to have purchased the first 3D printers in 1998 and 1999. So, they can be considered as innovators since they understood the potential of such technology before others did.

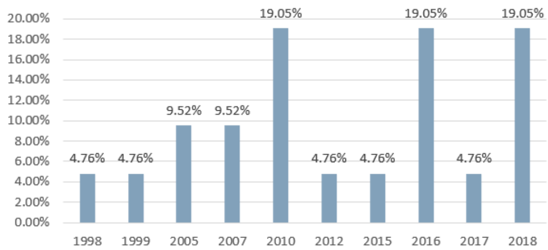


Figure 58: Answer to the question "In what year did the enterprise introduce for the first time the current AM technologies in use, if any?"

5.2 SECTIONS 2, 3: 3D PRINTERS AND CAD SOFTWARE

The second and the third sections were focused on the equipment. First, companies were asked to provide the number of 3D printers and CAD software systems at their disposal. 52.4% replied to have only one printer, 38.1% two while only 2 firm three. About digital modelling, 52.4% answered to have only one CAD software; 38.2% two; 1 firm three; another 1 more than 3. Although the price of 3D printers has been lowered in the last years, many companies are still restrained from purchasing more than one machine because of their cost. Specifically, mainly companies with 0 – 10 employees declared to have one printer and one CAD software whereas some of those with more than 10 employees had more. This means that there might be a correlation between the size of the firm and the equipment purchased since micro companies cannot afford huge investments in printers and software for 3D modelling and their production volumes are so that it is not necessary to have many units of the same tools. The next questions were about the frequency of use and the reasons why they were adopted. 52.4% used printers daily; 14.3% one a week; 9.5% twice a week; 23.8% more than twice a week. 76.2% answered to use CAD software daily; 4.8% once a week; 4.8% twice a week; 14.3% more than twice a week. These results demonstrate that 3D printing and digital modelling are mainly involved every day in the activities of most firms, not only occasionally. Then, it seems that goldsmith enterprises invested more in CAD software systems than printers. This proves that the benefits deriving from digital design are weighted more than those coming from jewels additive manufacturing in comparison to costs.

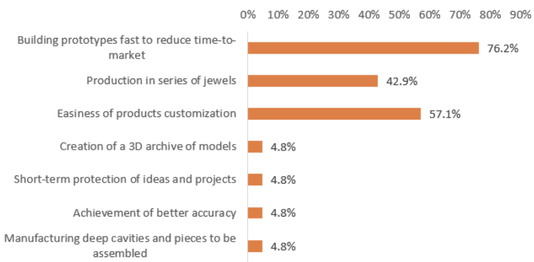


Figure 59: Answers to the question "the main reason/s why 3D printers were adopted by the company in the production process"

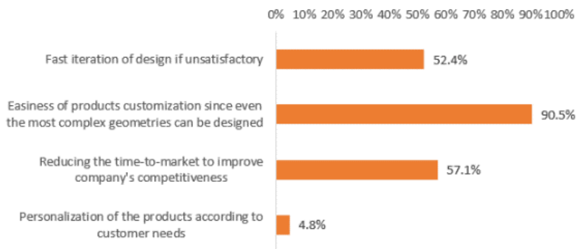


Figure 60: Answers to the question "the main reason/s why CAD software systems were adopted by the company in the production process"

Figure 59 and Figure 60 show the principal reasons that brought companies to go for printers and 3D software systems. Building prototypes rapidly and products customization were the two options that most companies picked up. They reflect their needs of launching products fast to beat their competitors and being able to satisfy their customers' desires in real time. Speeding up the product development process and allowing the customer to personalize his/her jewels helps companies to be more competitive while saving time and costs. 43% of the sample declared to use AM technology for producing parts in series as well. Since, for now, 3D printers limit the production to small batches, it is easier to micro and small firms to manufacture their low volumes of pieces in series. Other firms chose printers for creating a 3D archive of their models; protecting their ideas and projects from imitation at least in the short-

term due to quick in-house production; manufacturing deep cavities and components to be assembled; achieving better accuracy of products surfaces and geometries. The possibility of customizing products is responsible for the diffusion of CAD software systems as well. In fact, digital modelling allows to reproduce detailed and complex shapes while meeting customers need to personalize their jewels. Iterative design and improved competitiveness are other two benefits considered by firms since design can be modified repeatedly in a time-effective way and without any high additional costs.
After its benefits, the procurement cost of equipment was investigated. Companies were asked to select one of the proposed ranges which were shaped to the online prices of the most popular printers and software systems available on the market.

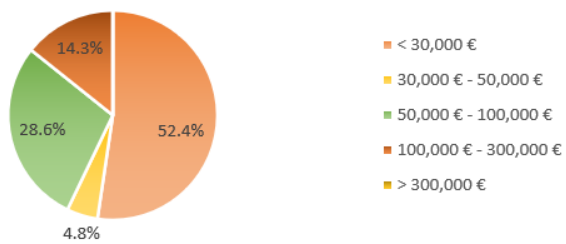


Figure 61: Answers to the question "which price range describes the company investment amount in printers purchase?"

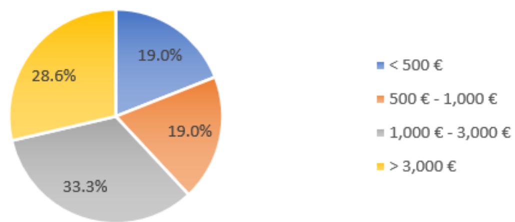


Figure 62: Answers to the question "which price range best best describes the company annual investment amount 3D in CAD software?"

The responses collected show that most companies (52.4%) spent less than 30,000 € for purchasing 3D printers. Six firms (28.6%) invested between 50,000 € and 100,000 €; only three firms (14.3%) invested between 100,000 € and 300,000 €; one (4.8%) between 30,000 € and 50,000 €; no-one invested more than 300,000 €. These figures are coherent with the machines' prices and with the fact that only few firms declared to have more than one printer. Nowadays it is possible to find sophisticated and multifunctional machines at a very competitive price and printers for industrial purpose can be bought for only 20,000 €. Regarding CAD systems, seven firms (33.3%) spent annually between 1,000 € and 3000 €; six (28.6%) more than 3,000 €; four (19%) less than 500 €; other four between 500 € and 1,000 €. These results are more heterogenous than those about printers because the diffusion trend of software is more variable as confirmed in the answers provided in section 1. Since near 50% wrote to have at least two CAD platforms, it can be confirmed the precedent deduction about the wider adoption of 3D technology more in the design phase than in the manufacturing one. Then, CAD systems are more affordable than printers and they serve well enough the aim of firms to iterate design and customize products fast for being more competitive. Moreover, the presence of any correlations between companies' dimensions and their investment in equipment has been explored.

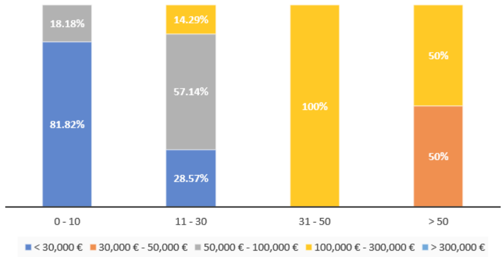


Figure 63: Crossing of answers to the questions "how many employees does the enterprise have?" and "which price range best describes the company investment amount in 3D printers purchase?"

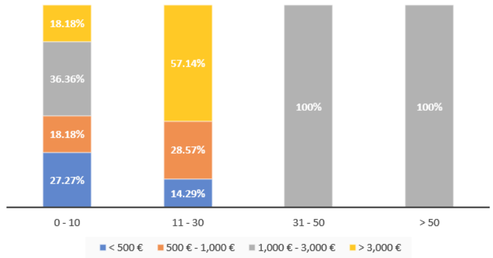


Figure 64: Crossing of answers to the questions "how many employees does the enterprise have? and "which price range best describes the company annual investment amount in CAD software?"

Figure 63 shows that, except for two, the investment in 3D printers by all the micro companies of the sample accounts for less than 30,000 € in their balance sheet. Their sales and production volumes do not allow them to spend much in innovation and that is why they purchased at most only one printer. As shown in figure 64, however, the attitude taken by micro firms towards CAD software adoption is more diversified. Each range proposed was picked up by at least one firm. The availability of several versions for the same software on the market gave firms a wide range of alternatives where they could look for the best solution depending on their needs and budget. Considering companies with 11 – 30 employees, near 15% spent between 100,000 € and 300,000 € and less than 500 € respectively in printers and CAD software; 57% between 50,000 € and 100,000 € in the first case and more than 3,000 € in the second; 29% less than 3,000 € and 500 € - 1,000 €. It is evident that these small firms were more prone to invest resources in innovative technologies probably because financially stronger. Then, the only one firm with 31 – 50 employees that filled the questionnaire selected the range 100,000 € - 300,000 € for printers while 1,000 € - 3,000 € for 3D software. Although the bigger dimensions of this firm clearly allowed to devote more financial resources to innovative equipment, however, these results cannot be generalized to all the firms with this same size. Furthermore, the firms with more than 50 employees declared to have spent 1,000 € - 3,000 € in CAD software. One invested between 30,000 € and 50,000 € in printers while the other between 100,000 € and 300,000 €. Despite the fact that these figures may not be true for other firms of the same category, various trends can be already recognized. In fact, the size of these two companies that filled the questionnaire is identical, but they took utterly different investment choices. Such heterogeneity might be due to a different budget at their disposal or position towards the adoption of 3D technology.

Finally, a question about materials also was added to the survey. 15 companies (71.4%) declared to use resins which are consequently the most popular materials. They allow to build intricated and detailed geometries so that their versatility facilitates products customization. Nonetheless, 66.7% still use wax. Specifically, 9 firms wrote to use wax and other materials too such as resins and metals while 5 to use exclusively wax. This means that more than half of the sample is reluctant to give up waxes for building models not only because less expensive, but also because they are hesitant on replacing traditionally known materials with others more innovative but risky. 3 firms (14.3%) used polymers as well. 2 of them answered to have 1 printer and use resins and polymers since the same machine can process both whereas the third wrote to have 2 printers and use resins and waxes because these materials presume different manufacturing techniques and printers. Then, only 2 firms used metals together with waxes and resins. The high and volatile price of metals, particularly precious alloys, prevents most companies from including them in their production processes, though having good properties.

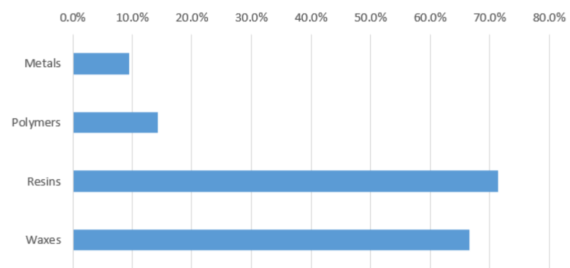


Figure 65: Answers to the question "what are the main materials the company uses most for printing parts?"

5.3 SECTION 4: PRODUCTION PROCESSES

The fourth section was based on the type of production process carried out in the 21 goldsmith companies currently using 3D techniques and tools.

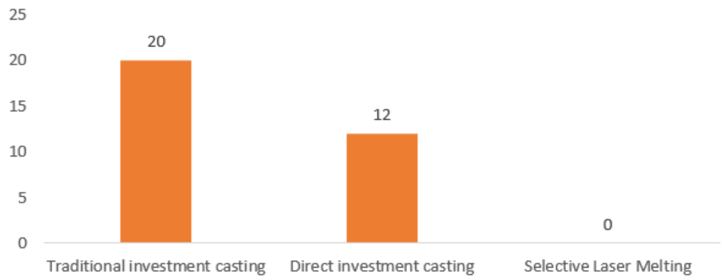


Figure 66: Answers to the question "what is the main technology that the company's production processes are currently based on?"

Traditional investment casting is still the most popular since used by 20 firms. 1 firm declared to use the direct investment casting only while 11 both the traditional and the direct Micro Fusion. No matter the size, most companies still manufacture their pieces of jewellery through Lost Wax casting. It seems difficult to companies to abandon the methods traditionally used for developing their products despite the advantages of 3D printing. In fact, Lost Wax casting is a complex technique that include many more steps such as building the wax model, rubber moulding and baking of the die than directly printing models and objects. Regarding direct investment casting, 6 firms using this method declared to spend less than 20 hours for prototyping and manufacturing one piece (for example a band ring); 3 between 20 and 30 hours; 3 more than 30 hours. On the other hand, 15 of the companies performing Lost Wax casting wrote to need less than 30 hours from prototyping until part finishing (for example a band ring); 2 between 30 and 40 hours; 3 more than 40 hours. It is clear that the adoption of 3D techniques, even just partially and in few steps of the product development process, helps save time improving the efficiency. In fact, one firm wrote that the sequence for building a hollow ring would require less than 1 hour from the preparation of the printer until the removal of the support structures. Furthermore, no firm interviewed had adopted Selective Laser Melting yet. Such technology is not considered mature enough and the capital investment required is thought not to be balanced by the resulting benefits.

Figure 67: Answers to the question "how many hours does it take from prototyping to finishing one piece (ex. a band ring), if the enterprise adopted traditional Investment casting?"

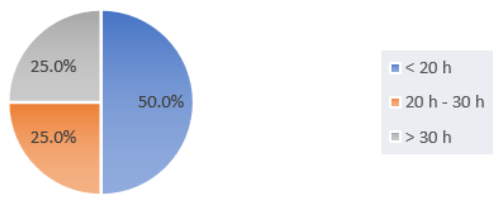


Figure 68: Answers to the question "how many hours does it take from prototyping to finishing one piece (ex. a band ring), if the enterprise adopted direct investment casting?"

5.4 SECTION 5: SUSTAINABILITY

Thanks to a major sensitivity towards the environmental impact of human activities, a new trend about the sustainability of companies' production processes has emerged. Therefore, the aim of section 5 was to investigate how much sustainability is important to the goldsmith companies from Alessandria and whether they have already experienced any benefits from 3D technology in terms of a smaller carbon footprint. In figure 69, the firms from the sample using 3D technology (represented by 21 letters of the alphabet) were asked to rank from 1 ("not important") to 5 ("extremely important") the importance of environmental sustainability when thinking about their production processes. 43% (9 firms) picked up 4 ("very important") confirming the rising trend of not neglecting any more the effect of production activities on the surrounding environment. The extraction of precious metals from mines contributes to the depletion of these natural sources; the value still embedded in scrap is totally wasted; a longer sequence of multiple steps like for Micro Fusion techniques means more energy and materials to be consumed. 33% (7 firms) ranked environmental sustainability as extremely important to them because they are aware that it adds value to their business and their competitive position. Only 1 firm selected 2 ("a little important") while 19% (4 firms) 3 ("indifferent") showing that just a small percentage (less than 30%) is still not giving enough attention to this issue. One of the reasons might be the disequilibrium between the benefits and the costs to achieve them. 23.8% think that the benefits in terms of sustainability improvements are overweighted by the cost for investing in 3D techniques. 52.4% believe that benefits and cost are balanced whilst 23.8% say that benefits are greater than costs.

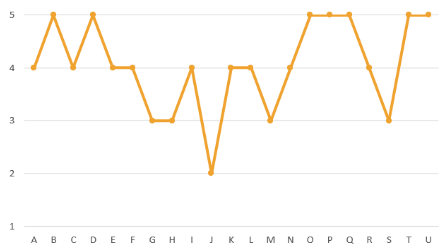


Figure 69: Answers to the question "How important is the environmental sustainability of production processes to the company?"

Furthermore, as a consequence of the adoption of 3D tools, some of the benefits and drawbacks in terms of environmental sustainability were listed to the firms interviewed for being ranked within six ranges. Regarding energy consumption, 1 firm spent between 40% and 70% more of energy; another 1 between 70% and 90% more; the rest of the sample experienced an increase up to 40%. Then, most firms benefited from a greater degree of efficiency of the materials used. Specifically, 33.3% had 5% - 20% of efficiency increase; 28.6% between 20% and 40%; 19% between 40% and 70%; 2 between 70% - 90% and more than 90% respectively. The figures positively show how 3D methods and tools allow to optimize the materials usage reducing waste. As two firms commented, "*AM technology allows to decrease the usage of rubbers for Lost Wax casting*" and "*it is responsible for the reduction of material waste and consumption. It allows to boost the efficiency of production activities in terms of both used materials and time savings which help the company employ fewer resources*". By designing and manufacturing pieces through 3D technologies, only material volumes really necessary are used so that the room in the warehouses for their storage can be reduced in a cost-effective manner, as one firm explained. About procurement cost, 38% had a small increase up to 5% while few firms more than 40% because only small amounts of additional material for printing the support structures are necessary and, sometimes, they are recyclable. Then, a valuable advantage of digital design and 3D manufacturing is the possibility of realizing lightweight parts. Near 45% of companies noticed 20% - 40% less of mass; 5% between -70% and -90%. These results confirm that multiple geometries can really be designed while reaching topological optimization and mass reduction. However, the recyclability of 3D printed parts seems still low. The majority (52.4%) answered to have noticed only a slight improvement (0% - 5%). On the other hand, one firm wrote to have achieved 40% -70% more of recyclability and another one 70% - 90%. These data point out that goldsmith companies not only are committed to make their manufacturing activities more environmentally friendly, but also are projected to the final stage of their products life when materials could re-enter into the manufacturing cycle. Another positive aspect of 3D technology is the reduction of scrap. Thanks to a more efficient use of materials, 28.6% highlighted between -20% and -40% of scrap produced; 19% between -70% and -90%. However, 48% of the sample declared to have lowered waste down to 20% only since they are just approaching for now a partial optimization of their materials usage and their production methods. In fact, such group is composed of companies that mainly use waxes and resins to realize pieces of jewellery by traditional investment casting. This technique makes hard to reduce the quantities of resources employed while the materials cannot be easily recycled without any degradation of their properties and high costs.

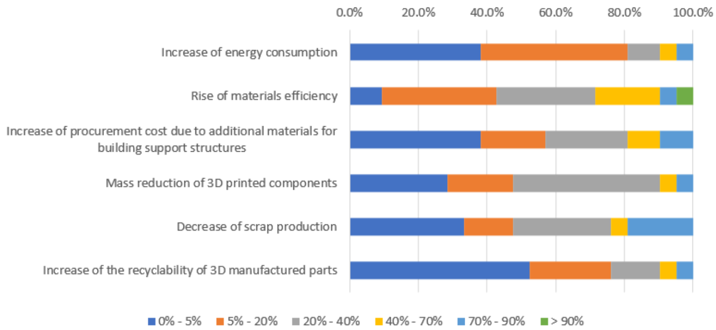


Figure 70: Answers to the question "Which percentage range best describes the following advantages and drawbacks in terms of environmental sustainability experienced by the enterprise after the adoption of 3D techniques?"

5.5 SECTION 6: FUTURE PERSPECTIVES

The companies which answered in section 1 not to be currently adopting AM technologies were sent straight to this final section. Here, the questions were intended to explore their plans about future investments in 3D technology. Among the 8 firms that did not introduce any 3D techniques or tools, only one (12.5%) was interested in investing resources into 3D technology within 1 or 2 years. These figures might be justified by the fact that the 87.5% not planning to switch their current production processes were made of micro firms whose brand image rests on handicraft and luxury principles. As far as enterprises using 3D technology are concerned, 43% had no intention to further invest in such technology; more than a half were planning to go on investing resources soon within 1 – 2 years except for 2 firm within 3 – 4 years. It is encouraging that lots of companies are planning to invest in innovation, sooner or later. In addition, they pointed out that one of the determinants for this choice is the opportunity to enjoy the advantages of shrinking the environmental impact of their production activities. Nonetheless, there is still an important percentage that is not willing to adopt 3D technology. Perhaps more incentives like lower equipment prices, quality improvement would persuade them to embrace these innovations which can really bring them several benefits.

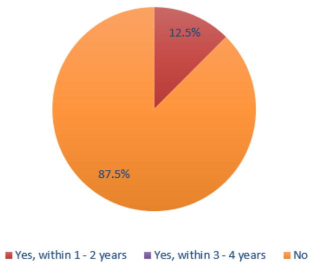


Figure 71: Answers to the question "is the company willing to invest in AM technology in the future?" - if not currently using AM

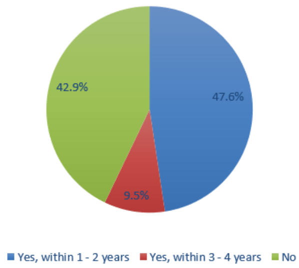


Figure 72: Answers to the question "is the company willing to invest in AM technology in the future?" - if currently using AM

CHAPTER 6: SUSTAINABILITY ISSUES OF AM IN THE GOLDSMITH INDUSTRY

1. INTRODUCTION: TOWARDS CIRCULAR ECONOMY AND SUSTAINABLE MANUFACTURING

The urgency of a more sustainable lifestyle that come out in the last years has been affecting manufacturing sectors as well. Due to their significant impact on society in terms of employment, product and services provided to meet consumers' needs, an environmentally friendly version of manufacturing processes turned out to be necessary. The spread of Circular Economy concept is an example of how it is no longer possible to neglect the environmental impact of enterprises' activities. Until now, a linear model based on *"take-make-consume-dispose"* (Mendoza, Gallego-Schmid, & Azapagic, vol. 220) paradigm has prevailed, but the necessity of disposing high volumes of scrap produced, the massive depletion of non-renewable natural resources and their prices volatility have undermined the ancient success of the Linear Economy [30]. Due to its potential for implementing business opportunities with a low social and environmental impact, the Circular Economy represents a valid alternative whose essence can be summarized in *"take-make-consume-return"* proposed by Schilling (2013). In addition, Stahel & Reday-Mulvey (1981) suggested to close the flows of resources switching from a "cradle-to-grave" toward a "cradle-to-cradle" philosophy since the value still embedded in resources at the end of their first life can be recovered. This recurrent idea of circularity well expresses the integration of the sustainability issue into a manufacturing process. Such a process, indeed, is considered sustainable if the so-called "Triple Bottom Equilibrium" applies as Sutherland, et al. (2016) explained. The "Triple Bottom Line" or "People, Planet and Prosperity" embraces three dimensions: ecological (or environmental), economic and social (Sutherland, et al., 2016). The point where the three dimensions intersect and balance one other represents a perfectly sustainable manufacturing system. This leads to point out that the performance of an enterprise should be environmentally, economically and socially sustainable at the same time. CSR (Corporate Social Responsibility), brand image and reputation, carbon footprint reduction and outsourcing are just few of the issues about sustainability which companies usually struggle with. For all these reasons, this chapter is intended for investigating the sustainability dimension in different manufacturing processes. Both traditional and more innovative technologies have been analysed to assess their environmental impact from a qualitative and a quantitative perspective. AM processes have been included in these studies. Selective manufacturing layer by layer and geometry optimization allows to save materials, energy and water while reducing the carbon dioxide emissions. Despite the novelty of this topic and the limited data available, it is worth to extend this analysis to many application fields. In the wake of the last section of the questionnaire shared with the enterprises from Valenza district, it has been decided to go on investigating these AM sustainability issues, even though goldsmithing is a usually less explored application field. One of the companies interviewed suggested *"casting light on the consumption of electric energy, scrap produced, coils requirements, spare parts necessary and so on"* to encourage a deeper analysis of this topic. The goldsmith industry, indeed, is a good candidate for further exploring sustainability because of its moltitude of socio-economic and enviromental issues. Considering the upstream processes of the supply chain, the negative social impact of gold mining and refining activities in terms of bad working conditions, health and safety protection is well known. The S-LCA (Social Lifecycle Assessment) carried out by D'Eusanio et al. (2019) confirmed the social impact of a pendant called "Stregonia", made by hand in Abruzzo, on the local community. Such "Gate-to-Gate" study showed that goldsmithing affects the environment as far as clean technologies use, waste management, energy and natural resources consumption are concerned. It also contributes to support safe and healthy working conditions and to protect cultural heritage and social identity.

2. ENVIRONMENTAL IMPACT OF AM IN GOLDSMITH PROCESSES

Many authors have dedicated their attention to the environmental performance of AM techniques, though only in general terms. Regarding raw materials feedstocks, estimates of the energy requirements for powder atomization have been provided on the basis of theoretical calculations and data collected during laboratory simulations due to the absence of databases shared by real powder manufacturers (Kellens, et al., 2017). The Specific Energy Consumption (SEC) i.e. the energy in MJ necessary to produce 1 kg of input material has been compared for different AM processes. As Figure

73 shows, several authors have estimated on a logarithmic scale the SEC values referred to the demand for electrical energy of multiple AM systems. These energy values are globally one or two orders of magnitude higher than those reported for conventional manufacturing processes such as machining and casting. Specifically, the SEC values of FDM and SLM present wider energy ranges while DMD value is dramatically high (7,709 MJ/kg min) because of the slow deposition rate considered during the analysis (Kellens, et al., 2017).

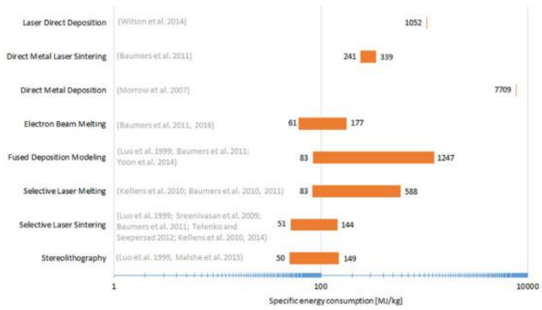


Figure 73: SEC values on a logarithmic scale representing the electric energy demand of AM systems in [MJ/kg] source: Kellens et al. (2017)

Then, Gebler et al. (2014) estimated that, in the most promising manufacturing industries for AM technology application, the primary energy supply for products total life cycle will be between 2.54 and 9.30 exajoules by 2025; savings of carbon dioxide emissions between 130.5 and 525.5 megatonnes; costs reductions between 170 and 593 B$. On the other hand, AM technology encompasses a lot of benefits that turn out to be advantageous from the sustainability perspective too. The optimization of design and geometry result in the production of lightweight components so that, not only functional benefits in the use phase can be achieved, but also cost savings for transportation and greater efficiency for coolant flows (Kellens et al., 2017). Furthermore, AM techniques can be used for repairing and remanufacturing worn-out parts without building new-brand pieces (Kellens et al., 2017).

Considering the goldsmith production systems, the numerous and great advantages brought by AM methods are undeniable, but whether these manufacturing processes are sustainable still need to be fully addressed. Gold extraction activities are known to be socially and environmentally controversial; the energy requirements of machines are high especially because of the low production rate. Innovative biomaterials would be more environmentally friendly and cheaper than gold. However, not so many studies have been conducted to investigate these issues. Despite the absence of a rich literature, the articles and the papers found on academic sources can be classified in two groups based on their subject matter for being analysed each in a more systematic way. These research streams both suggest some process eco-innovations to reduce the environmental impact of goldsmith companies by following different approaches. The solutions proposed are, in one case, more pragmatic; in the other, their nature is more strategic. The streams identified are

- *Eco-materials*: gold can be replaced, or at least paired, with more sustainable materials whose production and disposal activities do not harm the environment.

- *Sustainability-driven design*: luxury enterprises can opt for new business strategies that rest on a more innovative form of design. In fact, design can be shaped to embrace the "zero-waste" approach boosting companies' commitment to a more sustainable supply chain.

3. ECO-MATERIALS

Manufacturing industries are totally dependent on materials which feed their activities. However, each phase of materials, and products too, lifecycle has its own environmental impact that can be expressed in terms of resources consumed and carbon dioxide emissions. Such impact is usually monitored and evaluated through a methodology named LCA ("Life Cycle Assessment"). The so-called "embodied energy", "processing energy" and "carbon footprint" are three of the eco-properties considered to assess the impact of materials on the environment as far as energy and CO2 are concerned. The embodied energy is the energy to commit in order to produce 1 unit mass of usable material from its raw form like mineral deposits and ores and it is usually calculated as the sum of the lower heating value of fuels used and any other primary energy contributions (Gutowski et al., 2013). The processing energy represents the energy committed to transform 1 unit mass of material. It is influenced by the manufacturing practises and equipment used. The carbon footprint is described as the kg of CO2 released into the atmosphere when producing, transforming, shipping, using, or disposing 1 unit mass of material. Because gold is the king of materials used for goldsmithing, it is worth to mention its material profile provided by Ashby (2013) in relation to energy and water requirements and CO_2 emissions. As shown in Figure 74, breaking down the total energy requirements upon its life steps, the embodied energy for the primary production of gold reaches very high values up to 265,000 MJ/kg in comparison to other materials. For example, the embodied energy for primary production of silver is between 1,400 and 1,450 MJ/kg while, if stainless steels are considered, it ranges from 81 up to 88 MJ/kg only. In fact, gold harvesting from natural resources and refining are the dominant phases of energy consumption. In case of metals extracted from mineral deposits like gold, these two steps include mining, crushing, washing before the ore is split from the adjacent material (known as "gangue") and the chemical process of refining the material from its ore (Gutowski et al., 2013). The material production stage dominates the carbon footprint as well. The main contributions come from the fossil fuel used for the primary production energy as carbon dioxide, oxides of sulfur and nitrogen, heat losses and other liquid and solid waste. They vary by energy sources, equipment and material (Gutowski et al., 2013), but CO_2 footprint for primary production of gold is generally between 25,000 and 28,000 kg CO_2/kg. For materials with a high dilution (reciprocal of the ore grade or metal mass concentration in the mine) such as gold and platinum, not only most energy consumed is attributed to mining and separation activities, but also it increases as long as the ore gets more diluted (Gutowski et al., 2013). As far as water is concerned, gold production implies the usage of 126,000 – 378,000 litres per unit mass of material produced. Stainless steels and silver need only 112 – 336 and 1,150 – 3,460 litres of water per kg respectively. The other steps of materials lifecycle need energy and release CO_2 as a by-product as well, though they are not dominant. Materials flows are transformed into products through different manufacturing stages and, after products have been used, they are disposed to landfill as waste or they can be recycled to enter a second life in new goods. Considering different manufacturing techniques, the energy required for processing gold is 6.0 – 6.6 MJ/kg in case of casting whilst 1.0 – 1.7 MJ/kg in case of deformation so that the former is a more energy-intensive process. The relative CO_2 footprint values are also not so similar. Gold casting is responsible for 0.45 – 0.5 kg of CO_2 emitted per unit mass, deformation only 0.11 – 0.14 kg CO_2/kg. On the other hand, it is possible to reduce the energy consumed and the carbon dioxide emissions by recycling gold rather than extracting new feedstocks of material from virgin sources. The embodied energy for secondary production, indeed, can be lowered down to 650 MJ/kg and the carbon footprint to 41 kg/kg allowing to achieve large savings.

MATERIAL PRODUCTION		
Embodied energy, primary production	240,000 - 265,000	[MJ/kg]
CO2 footprint, primary production	25,000 - 28,000	[kg/kg]
Water usage	126,000 - 378,000	[l/kg]
MANUFACTURING		
Casting energy	6.0 - 6.6	[MJ/kg]
Casting CO2 footprint	0.45 - 0.5	[kg/kg]
Deformation processing energy	1.0 - 1.7	[MJ/kg]
Deformation processing CO2 footprint	0.11 - 0.14	[kg/kg]
END OF LIFE		
Embodied energy, recycling	650 - 719	[MJ/kg]
CO2 footprint, recycling	41 - 45	[kg/kg]

Figure 74: Eco-properties of gold for production, manufacturing, and end-of-life phases of material lifecycle source: Ashby (2013)

Albeit recycling gold powder can improve goldsmith processes from the sustainability point of view, however, there are still a lot of other issues to deal with such as the volatility of gold price, the social implications of extraction activities and the natural resources getting scarce. Eco-design strategies such as gold replacement and conversion of traditional manufacturing processes into green techniques are raised by Lerma et al. (2018) as potential solutions for goldsmith SMEs to purse sustainable development and improve their brand identity. Specifically, the authors described the strategic materials selection made by Mattioli, a goldsmith company established in Turin producing pieces of jewellery under its own and other International brands. Always trying to be innovative, Mattioli opted for the usage of new finishes and alloys to mix gold with or totally substitute it in order to be more sustainable. Although gold can be recycled and the market offers some lightned versions of gold containing a lower percentage of pure gold, Mattioli preferred to experiment innovative materials into new jewels collections meeting the needs of those consumers asking for green products. Mattioli selected stainless steel, aluminium and copper-beryllium alloys as the top candidates for replacing or pairing gold due to their lower values of embodied energy, carbon footprint and water usage. Diamond-like-Carbon (DLC) was chosen for coating finishing because black was identified as the best colour for representing elegance, fineness and, simultaneously, the brand image. After running some tests on samples of a ring from "Yin Yang " collection, stainless steel with DLC coating resulted to be, from both a mechanical and an aesthetic point of view, the best materials combination allowing to incorporate environmental responsibility in the enterprise products and processes. Some can argue that sustainability and luxury run on separate tracks because consumers may perceive green jewels as a contradiction being less valuable. However, sustainability can represent an added value to products giving them a new elegant aspect as confirmed by Lochard & Murat (2011). To boost customers acceptance of green items, De Angelis et al. (2017) recommended luxury fashion companies to design green products which are similar to their previous non-green models, especially if consumers are knowledgeable about the brand and the goods are durable like watches because perceived as a better investment.

Figure 75: Mattioli's Yin Yang ring items, one made of gold while the other of stainless steel coated with DLC

The case study of Mattioli proved that gold can be substituted or, at least, coexist with non-precious alloys while preserving jewels preciousness and elegance. Such approach is shared by other luxury enterprises and jewellery designers as described by Manlow (2021). She interviewed, for example, Mark Bloomfield, an innovative designer whose peculiarity is the ability to mix traditional hand manufacturing techniques with 3D technology and recycled materials. In fact, his jewels collections are designed and manufactured using advanced digital technologies like 3D printing and reycled plastics too since waste is valuable. This design strategy, therefore, demonstrates that, in the goldsmith industry, the marriage of luxury with sustainability is possible. In addition, the experiment by Puglia & Terenzi (2020) of integrating 3D printing with recycled materials and biopolymers thanks to nanotechnology for manufacturing a Made-in-Umbria jewels collection represented another valid attempt at paving the way to more innovative alternatives. In their article, they described a strategic approch towards design that can open up new opportunities to stimulate innovation. Specifically, their research, part of the Interregional European CLAY programme whose leading region is

Umbria, aimed to highlight the technological, aesthetical and cultural innovations that arise from the overall strategy of a project about Territorial Design. The interaction of Umbrian goldsmith enterprises with product and process innovations resulted in the adoption of digital technologies and innovative materials aiming at promoting the regional excellences through an originally designed collection of pieces of jewellery. Recycled basalt and oak powder were the two materials selected. The basalt powder was provided by Basalti Orvieto srl whereas the oak flour by a local carpenter. These biopolymeric filaments are cheaper and simplier to extrude for jewellery moulding. Ivanova et al. (2013) explained that the synthesis of gold nanoparticles by chemical reduction can enhance the sintering features and the production of innovative materials for AM. The melting temperature of gold nanoparticles can be lowered down to 900 °C leading to a better quality of the printed parts. Nonetheless, metal nanoparticles are not economically suitable for 3D printing and, for this reason, eco-filaments produced in a laboratory following a non-industrial manufacturing process were preferred. The objective was to reach a controlled viscosity of the filaments as to overcome the limit of excessive fragility typical of the ceramic- and wood-filled polymers already available in the market. Granulometry was monitored too so that the final piece surface would look like real stone or wood. A spool of polymeric filaments including 20% of filler by weight was loaded into a 3D printer. The machine was equipped with a micro extruder to mix the molten nanoparticles of material into a filament of 1.75 mm average diameter. After the definition of their size, the granules were put into the extrusion chamber for being melted. The filament was, then, extruded at a temperature of 180 °C to build layer by layer the pieces of jewellery. The methodology presented by Puglia & Terenzi (2020) encourages the minimization of gold environmental impact through the contamination of local goldsmith specialization with innovation. The resources flows are closed thanks to recycling practises whilst more sustainble materials substitute precious metals. On the other hand, the performance of such production cycle can be still further improved. For example, nanofillers pigmented with natural colours might be experimented for extruding coloured filaments directly into original pieces of jewellery.

4. SUSTAINABILITY-DRIVEN DESIGN

Several studies have been conducted about a more conscious management of resources and waste. Most of them have debated the so-called “zero-waste” principle about preventing waste production through sustainable design and responsible consumption of resources (Zaman, 2017). The implementation of strategies such as new business models and eco-design can be acknowledged as one of the approaches aiming at avoiding waste. Redesigning products in a more sustainable way allows to embrace the zero-waste principle along the enterprises supply chain by saving resources for manufacturing, reducing scrap and easing recycling and disassembly at end of products first life (Indranil & Deepak, 2021). An essential role is, indeed, played by technology. In fashion industries like apparel and jewellery, AM has widely spread in the last years because it gives manufacturers design freedom and facilitates mass customization (Indranil & Deepak, 2021). On the other hand, AM technology shows many eco-friendly aspects which can be linked to the environmental, social, and economic dimensions of sustainable manufacturing (Indranil & Deepak, 2021). In fact, smaller amounts of waste are generated since only the materials necessary for building a piece are used; lightweight and geometrically optimized objects are printed layer by layer minimizing the environmental impact of the whole process and in a cost-effective way. Pasricha & Greeninger (2018) provided an example of zero-waste philosophy application for developing sustainable fashion products. 5 necklace pendants and 2 pairs of earrings were, first, digitally designed through a CAD software and then, 3D printed without generating scrap. Since support structures become waste, the items were designed avoiding irregular surfaces, sharp angles and overhanging parts which would have required the presence of supporters and rafts. The CAD software allowed to model creative and unique geometries maximizing materials efficiency and ensuring zero waste. The printer was loaded with a biodegradable plant-based plastic, PLA, that is more environmentally friendly than gold. Such experiment confirmed the benefits provided by AM technology in terms of unlimited design freedom and minimization of scrap. Berman (2012) wrote that the material waste produced by 3D printing application to metal production is 40% lower if compared to subtractive techniques. However, the reasearch by Pasricha & Greeninger (2018) proved that waste production can be further reduced up to 0% thanks to the optimization of design in the light of sustainability improvement.

Figure 76: Design of jewellery pendants 4 (on the left) and 5 (on the right) made of white PLA filament and respectively brush and spray painted with gold paint
source: Pasricha & Greeninger (2018)

5. GOLDSMITH PRODUCTION PROCESSES AND MATERIALS: COMPARISON BETWEEN ENERGY AND CARBON FOOTPRINT

Except for few papers, the literature about AM sustainability in goldsmithing sector lacks a large quantity of studies conducted in this realm. However, from the questionnaire shared with the goldsmith companies established in Valenza district, a great sensitivity toward the reduction of the environmental impact of manufacturing activities has emerged. In fact, near 50% of the sample considered sustainability a very important matter. Then, the enterprises interviewed proved to be aware of the environmental benefits ensured by the adoption of AM technologies. The increase of materials efficiency was one of the major advantages noticed among all. Achieving even more than 90% of materials efficiency can enhance the optimization of the materials use and decrease the production of scrap. Mining and refining are energy-intensive activities which cannot be classified as eco-friendly. This means that a more conscious usage of materials can help firms be more sustainable. Considering gold, silver, stainless steels, copper alloys and zinc alloys as the materials mainly used for goldsmithing, in Figure 75 their average values of embodied energy and carbon footprint have been plotted on a graph both in case of primary and secondary production. Energy and carbon footprint look proportional since consuming more energy leads to larger carbon emissions. Gold is the metal with the highest embodied energy and carbon footprint while the second place is taken by silver. Using these materials more efficiently would mean huge savings of energy and, consequently, smaller quantities of carbon dioxide emitted into the atmosphere. Moreover, the production of non-precious alloys affects less the environment, especially if materials are recycled. Since stainless steel, copper and zinc have a lower embodied energy and carbon footprint, pairing precious metals with them would reduce the environmental impact of goldsmith processes.

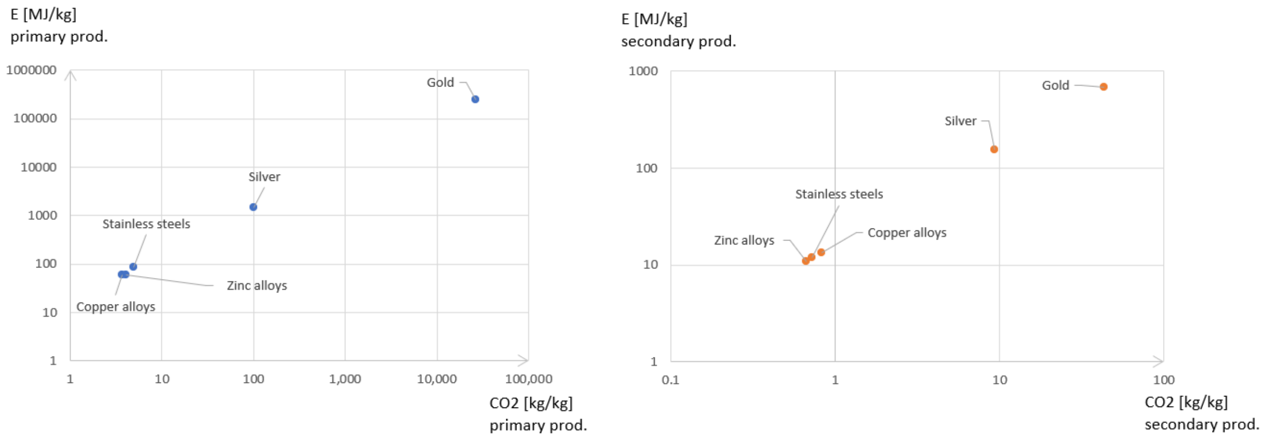


Figure 77: Comparison between average values of Embodied Energy [MJ/kg] and Carbon Footprint [kg CO2/kg] for both primary production (on the left) and secondary production (on the right) for the materials used most in goldsmithing processes
source: Ashby (2013)

Furthermore, another aspect positively highlighted by the enterprise from Valenza was the mass reduction of components reached through 3D printing. The design optimization allows to build lightweight parts by using only the necessary materials and reducing transportation and storage costs. These results are also confirmed by the analysis carried out by Progold S.p.A. (2017). The most popular goldsmith manufacturing processes i.e. Lost Wax Casting, Direct Investment Casting and SLM were compared from a technical and economic point of view as described in chapter 3. Progold S.p.A. measured the environmental impact of the three techniques too through the approximation of the carbon footprint as the GHG quantity in CO2 eq emitted during each process. The carbon footprint was estimated by considering the phases and the materials required for producing 1 kg of pieces of jewellery. The sequence steps were always prototyping, preparation and wax injection into the mould, tree assembly, flasks preparation and baking, melting, casting, and finishing for traditional Micro Fusion; wax model printing, support structures removal, tree assembly, flasks preparation and baking, melting, casting, and finishing in case of direct Micro Fusion;

digital modelling, printing, machine cleaning, removal of the piece and the support structures for SLM. The contributes from each of them were summed up to obtain the GHG total value. EcoInvent 2.2 was the database used for calculating the CO2 emissions deriving from material production and scrap disposal while electric energy figures refer to the Italian electric grid features. Following a "Gate-to-Gate" approach, the carbon dioxide emitted during raw materials extraction and production, building and maintenance of machinery and additional equipment were not included within the study boundaries. As shown in Figure 78, the CO2 emissions by SLM are, indeed, the lowest with 14.7 kg CO2/kg. They are influenced by the printing parameters like speed, deposition rate and piece geometry. CO2 kg emitted during Micro Fusion processes are larger due to bad materials efficiency. Manufacturing speed can be low, and the oven used for baking the flasks can be underused since not full at its maximum capacity. In the latter case, the emissions are spread over an inferior number of flasks amplifying their effect.

	Carbon footprint [kg $CO_{2\ eq}$/kg]
Lost Wax Casting	28.8
Direct Investment Casting	23.8
Selective Laser Melting	14.7

Figure 78: Comparison among the carbon emissions by the most used goldsmith production processes source: Zito et al. (2017)

In addition, the data available about the materials and the manufacturing processes have been graphically compared to give an organic representation of the environmental impact of goldsmith production. As shown in Figure 79, the carbon footprint values for materials and goldsmith production processes have been plotted on a graph. Gold, silver, stainless steels, copper alloys and zinc alloys are the materials considered since the most used for goldsmithing; Lost Wax Casting, Direct Investment Casting and SLM are the goldsmith manufacturing processes taken into account because the most popular. The graph is made of three areas: the first two are dedicated to the materials in case of primary and secondary production; the third to the manufacturing techniques. Considering the figures available in Ashby's "Materials and the Environment: Eco-informed Material Choice" (2013), the precious metals have the biggest environmental impact. For primary production, the carbon footprint values of gold and silver range between 25,000 and 28,000 kg CO2/kg and 95 and 105 kg CO2/kg respectively. The carbon emissions of stainless steels, copper and zinc alloys are only 4.7 – 5.2 kg CO2/kg, 3.5 – 3.9 kg CO2/kg and 3.9 – 4.3 kg CO2/kg. However, gold and silver have a higher percentage of recyclability in comparison to non-precious materials. The recycle fraction in the current supply of gold is at least 40% whereas 65% for silver. Except for copper (40%), the other alloys have lower percentages of recyclability. As far as manufacturing processes are concerned, both Micro Fusion methods emit more carbon dioxide than SLM considering the figures provided by Progold S.p.A. (2017). Specifically, the carbon footprint of Lost Wax Casting (28.8 kg CO2/kg) almost doubles SLM value (14.7 kg CO2/kg) while Direct Investment Casting is in an intermediate position (23.8 kg CO2/kg).

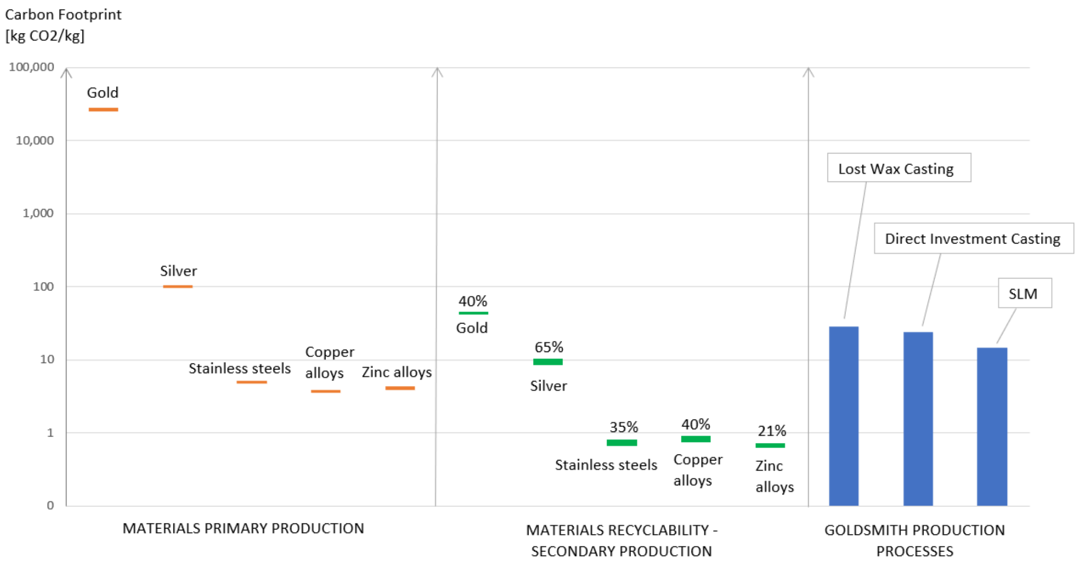


Figure 79: Comparison among carbon footprint values [kg CO2/kg] of goldsmith production processes and materials

Finally, it is evident that the precious metals such as gold and silver, typically used by goldsmiths, are less environmentally friendly than non-precious alloys. On the other hand, their high recyclability degree opens up many possibilities of re-introducing these materials in the production cycle without resorting to natural virgin sources. Then, SLM appears to be a suitable production process from the environmental sustainability perspective thanks to a more efficient use of resources. This means that AM technology combined with eco-friendly materials could represent a good investment by goldsmith companies to reduce the environmental impact of their business. Overall, it would be a worthwhile solution for sorting out the environmental issues currently worrying the Italian enterprises by improving their supply chain sustainability and their brand image.

CONCLUSIONS

Since Additive Manufacturing is increasingly finding new application areas where to expand, the aim of this thesis was to investigate the diffusion of such technology in the Italian goldsmith industry, specifically in the district of Valenza. Nowadays there are several AM techniques and tools available to enterprises, as described in chapter 1. Despite the setback due to the pandemic of last year, the goldsmith sector represents an interesting field for implementing AM processes. In fact, Selective Laser Melting (SLM) is a valid alternative to the conventional Micro Fusion techniques for goldsmithing. As proved by Progold S.p.A. study (2017) in chapter 3, SLM appears technically convenient because complex pieces like hollow rings can be easily manufactured; minimum values of thickness can be achieved; producing small batches is economically feasible. Then, to have a comprehensive understanding of their perspective, the answers of the goldsmith companies from Valenza district to the questionnaire were analysed both analytically and graphically in chapter 5, drawing important results about the current adoption of AM technology. Although not so many responses were collected, however, the final sample of 29 enterprises was useful to try depicting at least a nuanced picture of the adoption trend of 3D techniques. The figures obtained showed that CAD software for digital modelling and 3D printers for prototyping are widely spread since 1998, even though 28% of the sample still manufacture jewels by hand using conventional rather than digital tools. This means that many companies are open to embrace technological innovations actively investing resources, but with caution. In fact, most spent only up to 30,000 € in printers and 3,000€ in CAD software. Another relevant aspect emerged is that no firm has totally abandoned Micro Fusion. The majority still use Lost Wax Casting while a limited percentage Direct Investment Casting. There is no company of the sample that declared to have adopted SLM. Firms, indeed, are still sceptical about the maturity of such technology. Especially micro and small ones are afraid of switching to a new technology that would change their production process radically requiring big capital investments as well. On the other hand, the potential of AM is well recognised. Goldsmith enterprises seem aware that AM allows to optimize jewels design and manufacturing. Design can be repeatedly iterated without any additional cost and tailored to the optimal topology of the piece. Products customization is easy and fast giving the possibility of meeting customers' needs real-time. What lots of companies noticed is the improvement of materials efficiency after the adoption of 3D tools. It is possible to manufacture lightweight parts optimizing the quantity of material used while reducing waste. This more efficient use of materials can be connected to the environmental sustainability matter that was explored too through the questionnaire. Goldsmith enterprises have demonstrated a great sensitivity towards sustainability issues being seriously committed to reduce their carbon footprint. As explained in chapter 6, few studies have addressed AM sustainability topic referred to the goldsmith industry. However, the analysis carried out by Progold S.p.A. (2017) is the proof that SLM is also sustainable. In comparison to traditional and direct Micro Fusion, such manufacturing process has a lower carbon footprint so that its negative impact on the environment is limited. Other than this, some ancillary solutions such as sustainability-driven design and eco-materials have been proposed. Because gold mining and refining consume much energy, designing jewels in a more responsible way and replacing or pairing gold with eco-friendly materials would reduce the virgin sources depletion and the carbon dioxide emissions.

On one side, AM technology has undeniably several technical and environmental benefits. On the other, there are still some limits to the full adoption of such technology which have been spotted. SLM is not a speedy process. Therefore, the specific energy demanded is high. Then, the time-to-market might be slowed down and SLM turns out to be advantageous for producing small batches rather than big volumes of pieces in series. Parts surfaces lack accuracy and smoothness so that additional operations are necessary. About sustainability, it is difficult to reach zero waste. Support structures and worn-out tools need to be disposed and goldsmith enterprises seemed worried about the cost for disposal. Finally, AM results to be a very promising technology that goldsmith companies can benefit from. Customers' needs and tastes change very fast, and it would help them keep the pace while improving, at the same time, their competitiveness in the market. The data collected show a positive trend of diffusion in the district of Valenza, but it is just in a starting phase. Perhaps, more incentives would encourage companies to invest more in innovative and sustainable solutions. In the next years, the prices of printers will probably go down making these devices more affordable. The commitment of Governments about sustainability issues will become higher so that funds might be provided for the enterprises to invest in more environmentally friendly technologies like AM. In addition, the questionnaire confirmed the abundance of micro and small firms in the province of Alessandria since they are mainly family-run business and artisanal laboratories. Because firms of such size are more reluctant towards innovation, the availability of incentives could make them more prone to fully embrace new technologies. So, giving support is a key for fostering the spread of technological progress in every possible area of application.

APPENDIX A

ADOPTION OF 3D TECHNOLOGY IN THE ITALIAN GOLDSMITH DISTRICT OF VALENZA

I am Francesca Guido and I am investigating the adoption of the Additive Manufacturing technologies in the Italian goldsmith industry, specifically in the district of Valenza (AL), in collaboration with the Department of Management and Product Engineering (DIGEP) of the Polytechnic of Turin.
I would kindly ask you to answer the questions of the following questionnaire to support my research. It will take only few minutes.
The data collected will not be shared with any third-party because they will serve scientific purposes only.
The identity of the enterprises will be protected by privacy.

* Required



General information about the enterprise

1. What is the name of the enterprise? *

2. How many employees does the enterprise have? *

- 0 - 10
- 11 - 30
- 31 - 50
- > 50

3. Does the enterprise currently use any Additive Manufacturing technologies in its production process? *

- Yes
- No

4. In what year did the enterprise introduce for the first time the current Additive Manufacturing technologies in use, if any? *

____

5. Is the CAD software used for 3D modelling owned by the enterprise?

- Yes
- No
- We do not use this type of software

6. Are the 3D printers used during the manufacturing process owned by the enterprise?

- Yes
- No
- We do not use this type of tools

3D printers

7. How many 3D printers does the enterprise use? *

- 1
- 2
- 3
- > 3

8. How often is/are the 3D printer/s used? *

- Daily
- Once a week
- Twice a week
- More than twice a week

9. The main reason/s why the 3D printers were adopted by the company in the production process is/are *

Check all that apply.

- [ ] Building prototypes fast to reduce the time-to-market
- [ ] Production in series of jewels
- [ ] Easiness of products customization

Other: [ ] ______________________

10. What are the main materials the company uses most for printing parts? *

Check all that apply.

- [ ] Metals
- [ ] Polymers
- [ ] Resins
- [ ] Waxes

Other: [ ] ______________________

11. Which price range best describes the company investment amount in 3D printers purchase? *

- ( ) < 30,000 €
- ( ) 30,000 € - 50,000 €
- ( ) 50,000 € - 100,000 €
- ( ) 100,000 € - 300,000 €
- ( ) > 300,000 €

12. Are there any further investments planned for the future?

- ( ) Yes
- ( ) No

CAD software

13. How many CAD software systems does the enterprise use?

- 1
- 2
- 3
- > 3

14. How often is/are the CAD software used? *

- Daily
- Once a week
- Twice a week
- More than twice a week

15. The main reason/s why the CAD software systems were adopted by the company in the production process is/are *

Check all that apply.

- [ ] Fast iteration of design if unsatisfactory
- [ ] Easiness of products customization since even the most complex geometries can be designed
- [ ] Reducing the time-to-market to improve company's competitiveness

Other: [ ] ____________________

16. Which price range best describes the company annual investment amount in CAD software? *

- < 500 €
- 500 € - 1,000 €
- 1,000 € - 3,000 €
- > 3,000 €

17. Are there any further investments planned for the future?

- Yes
- No

Production process

18. What is the main technology that the company's production processes are currently based on? *

- Traditional investment casting
- Direct investment casting
- Selective Laser Melting
- Other: ______________________

19. How many hours does it take from prototyping to finishing one piece (ex. a band ring) if the enterprise adopted traditional investment casting? *

- < 30 hours
- 30 - 40 hours
- > 40 hours
- We do not use this technique

20. How many hours does it take from prototyping to finishing one piece (ex. a band ring) if the enterprise adopted direct investment casting? *

- < 20 hours
- 20 - 30 hours
- > 30 hours
- We do not use this technique

21. How many hours does it take the process of printing one piece (ex. a hollow ring) from the printer preparation to the removal of the support structures if the enterprise adopted Selective Laser Melting? *

- < 1 hour
- 1 - 3 hours
- > 3 hours
- We do not use this technique

22. If the technology used by the enterprise is NOT Selective Laser Melting, what is the main reason?

- We have never heard about it
- It is not mature enough for being adopted
- It requires capital investments which are bigger than its benefits
- Personnel should be highly skilled and specialized
- Other: ____________________

Sustainability of 3D technology

23. How important is the environmental sustainability of the production processes to the enterprise? *

	1	2	3	4	5	
Not important	○	○	○	○	○	Extremely important

24. How does the enterprise consider the cost-benefit trade off linked to a minor environmental impact achieved through Additive Manufacturing technologies? *

- Costs are greater than benefits
- Benefits are greater than costs
- Costs and benefits are balanced

25. Which percentage range best describes the following advantages and drawbacks in terms of environmental sustainability experienced by the enterprise after the adoption of 3D techniques? *

	0% - 5%	5% . 20%	20% - 40%	40% - 70%	70% - 90%	> 90%
Increase of energy consumption	⬭	⬭	⬭	⬭	⬭	⬭
Rise of materials efficiency	⬭	⬭	⬭	⬭	⬭	⬭
Increase of procurement cost due to additional materials for building support structures	⬭	⬭	⬭	⬭	⬭	⬭
Mass reduction of 3D printed components	⬭	⬭	⬭	⬭	⬭	⬭
Decrease of scrap production	⬭	⬭	⬭	⬭	⬭	⬭
Increase of the recyclability of 3D manufactured parts	⬭	⬭	⬭	⬭	⬭	⬭

26. If any, what are other advantages and drawbacks linked to environmental sustainability issues experienced by the enterprise after adopting Additive Manufacturing technologies?

NO Additive Manufacturing

27. Is the company planning to invest any resources in Additive Manufacturing technologies in the next years? *

- Yes, within 1 - 2 years
- Yes, within 3 - 4 years
- No

28. Will the advantages in terms of environmental sustainability be determinant factors in the decision-making process about the adoption of 3D techniques? *

- Yes
- No
- We are not planning to invest in any 3D techniques

Questionnaire completed!

The questionnaire is done.
Thank you for your time.

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