# *Module 1: Introduction to 3D Printing Technologies in Libraries*

## Content

### 1.1 The role of libraries and 3D Printing

Recently (despite the pandemic crisis and the sanitary restriction in the universities) there have been recognized the positive trend and the attractiveness for engineering education for Additive Manufacturing (AM) and 3D printing technologies. These offers to educators a quick demonstration of engineering activities from ideas (good and bad, innovative one) to artefacts (real models of products) by offering new and challenge opportunities for new teaching – learning – assessment approaches that could be adopt and adapt to a large variety of subjects [1]. Thus, the new required engineering knowledge and skills are quick achieved by the students. In addition, studies presented in the literature or in companies reports related to these educational practices are also, emerging.

The involvement of 3D printing in education and training is growing rapidly. All around the world, higher education institutions are developing new curricula and purchasing equipment, software, and materials to support research and instruction. In response to the growing opportunities in the additive manufacturing job market, interests among students in AM-related manufacturing and design courses have increased dramatically [2].

Education and instruction can be benefited through additive manufacturing by creating excitement in learning and educational practices, supporting and complimenting STEM (Science, Technology, Engineering and Mathematics) curriculum, opening new possibilities for learning, critical and analytical thinking, innovation, and entrepreneurship, giving access to new materials and applications not available before and promoting problem-solved skills and methodologies. One great feature is that 3D printing supports students to take their design to the next level by allowing them to get involved in the fabrication stage [2].

Aside of universities and companies, there are some relevant examples of public libraries offering 3D printing trainings (together with related services). In 2017, the 3D printing media network has recognized that there were more than 800 3D printers in libraries worldwide and the public needs and interests for this domain of services is increasing (3D printing Media Network, 2017); the dynamics of this field of services is positive, related to 2015 when there have been reported 250 3D printers in libraries in the United States supporting the related services to users, according to data published by the American Library Association (ALA). There have been found that most printers and services are provided by libraries located in United States and other English-speaking countries (e.g., United Kingdom, Australia), but the “Chinese libraries alone could have three to five times as many”. Other geographic areas such as South America are also very likely to be offering 3D printing through libraries and European countries, which only recorded a few dozen in this map, are likely to have several hundred (or even thousands) already [3;4].

Definitively, the Covid-19 pandemic has positively impacted the 3D printing technology use because of the increase interest and the huge number of medical shields, 3D respirator, valves and other devices that were used by hospitals and were donated by public (as libraries, universities) or private providers all over the world (as is demonstrated by INNO3D project implementation during the pandemic period, https://www.inno3d.eu/covid-19).

Summarizing, **libraries’ major role in promoting 3D printing technologies** consists in supporting training and research activities through the following actions [4]:

- Provide access to literature in the filed (books, articles, journals, reports in the field etc. even by assuring online access);
- Facilitating access to 3D CAD models databases;

- Provide 3D printing technologies, equipment, and scanning technologies (capacities organized in FabLabs or Maker Space areas) to be easy access by different users;
- Provide 3D printing short term trainings as a library service;
- Facilitating consulting activities for different companies (acting as brokers of ideas and solutions);
- Organizing 3D printing workshops and demonstrations, best practices dissemination and even exhibitions with prices and assemblies.

## 1.2 Towards Digital Literacy: 3D Printing and Makerspaces in Libraries

### 1.2.1. Digital Literacy: 3D Printing

The notion of digital literacy is not new. Indeed, arguments for “computer literacy” date back at least to the 1980s. In recent use of the concept ***digital (or computer) literacy appears to amount to a minimal set of skills that enable user to operate effectively with software tools, or in performing basic information retrieval tasks*** (referring to the ability to use search engines for basic information retrieval). This is essentially a *functional definition* which in the case of 3D printing training has the meaning of self-discover and finding the right resources (open educational resources or open research communications) to achieve related knowledge and/or to solve specific problems. Basically, digital literacy for 3D printing refers to users’ skills in undertaking different actions for information retrieval [3].

Another context in which the notion of digital literacy has arisen in recent years is in relation to ***online safety*** which in the case of 3D printing is much related to the evaluating online sources and assessing one’s own information needs. Safety problems are less relevant in this case, but the discussion about the critical evaluation of online content is still actual.

Most discussions of digital literacy remain primarily preoccupied with ***information*** and tend to neglect some of the broader cultural uses of the internet. To a large extent, the concern here is with promoting more efficient uses of the medium as for example, via the development of advanced search skills (or so-called “power searching”) that will make it easier to locate relevant resources amid the proliferation of online material. This is the case of the researchers in the 3D printing field.

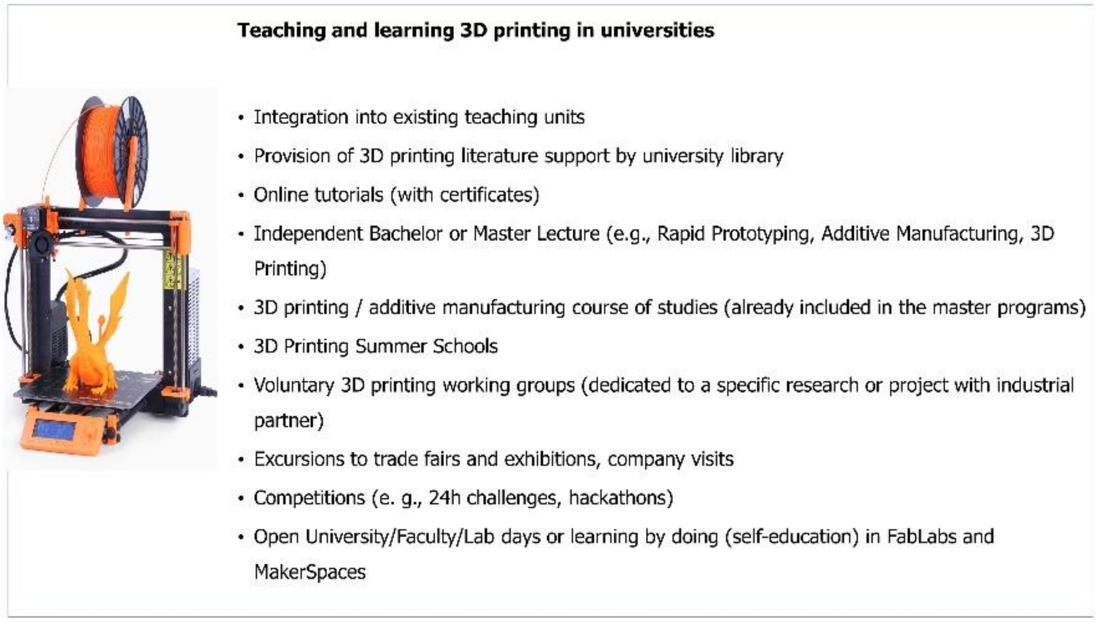
Finally, observing the communities of users, learners in the 3D printing field, there have been identified a specific ***culture consists of makers-people dedicated to learning and sharing any type of craftsmanship skills*** in this field. They value individual or small group creation, rather than mass production, and support creation over consumption. To assist with the sharing of knowledge, supplies, and projects, makers often construct and congregate in *makerspaces, Fab Labs, or hackerspaces*.

### 1.2.2. 3D Printing and Makerspaces in Libraries

In many cases, universities, research centres or laboratories expand beyond 3D printing into makerspace territory by offering services like scanning and printing, motion capture, virtual reality, and even a digital production classes or trainings where students learn computer graphics. Although in many cases these spaces do involve this type of high-tech machinery, a makerspace can really be any place where people gather to create and participate in ***Do-It-Yourself projects***, ranging from creating electronics to writing software to designing their own clothing. ***Makerism is not about the specific tools, but about the creation process and spirit***.

At many universities and higher education institutions, 3D printing has been integrated into conventional undergraduate and graduate programs, offering advanced additive manufacturing courses and additive manufacturing areas of concentration as part of their engineering, technology, and design curricula [2;5]. Thus, 3D printing is currently being integrated into higher education teaching in very different ways and to different degrees. At universities, important use is to integrate 3D printing in sciences. Models are fabricated to support students learning in the classroom or lab [6;7;8], and for example, test models can be used for experiments and test specimens for learning about mechanical properties of materials [1;9].

Furthermore, the created infrastructure using ***FabLabs or MakerSpaces*** are based on techno-creative activities and spaces of universities [10], where students could develop their technical skills and competences by practical exploration of the 3D printing technologies and thus, better connect theoretical knowledge with applications. Furthermore, in a recent published study [10]), there have been recognized that FabLabs and MakerSpaces “go beyond digital 21st century skills as they are mixed digital and physical environments”. The learning solution has expanded internationally being recognized that FabLabs are those makerspaces that have signed the Fab Charter of the Fab Foundation; actually, more than 1,750 active FabLabs centers exists all over the world (as supported by the Fab Lab Network) [11]. The approaches differ sharply in duration, the learning objectives, and the competencies that are to be taught. The following list (Figure 1) is intended to give an overview of different tools, formats, and instruments which today are used at universities to teach additive manufacturing technology.



**Teaching and learning 3D printing in universities**

- Integration into existing teaching units
- Provision of 3D printing literature support by university library
- Online tutorials (with certificates)
- Independent Bachelor or Master Lecture (e.g., Rapid Prototyping, Additive Manufacturing, 3D Printing)
- 3D printing / additive manufacturing course of studies (already included in the master programs)
- 3D Printing Summer Schools
- Voluntary 3D printing working groups (dedicated to a specific research or project with industrial partner)
- Excursions to trade fairs and exhibitions, company visits
- Competitions (e. g., 24h challenges, hackathons)
- Open University/Faculty/Lab days or learning by doing (self-education) in FabLabs and MakerSpaces

Fig. 1. The typology of teaching and learning 3D printing in universities [3;4].

Recently, Motyl and Filippi (2020) have provided a comprehensive overview of “the current state of education and dissemination of educational practices related to the training of young engineers at university on the issues of AM and related to Industry 4.0. The results show that the introduction of AM education represents an important leverage in the preparation of young engineers who benefit from it both in terms of personal preparation and in terms of learning and refining different skills. However, certain aspects, linked to the need to have adequate equipment and a properly trained teaching staff, should not be overlooked" [12].

Practical experiences achieved in the context of Do-It-Yourself projects have generated the development of the ***hackerspaces***, that could be characterized as following [13]:

- "It is a flexible workspace designed for people who are interested in the same thing – namely technology;
- It is one of a growing list of flexible space variations, which is indicative of the sector's growing reach and appeal;
- Unlike most coworking spaces, hackerspaces are not-for-profit organisations that are used for "extra-professional" projects".

The word "hack" has negative connotations, and it is associated with illegal online activities. But the "hack" in hackerspace is synonymous with verbs like invent, innovate, and experiment. Thus, a hackerspace (similar with hackspace, hacklab) is a physical space in the community where programmers, coders, developers, or anyone with a keen interest in tech can meet, work, share skills and engage in creative problem solving. It is a community-orientated and not-for-profit concept [12;13].

Makerspaces and hackerspaces are different; makerspace is a coworking space related to people who make tangible things. Typical makerspace members include carpenters, metal workers, textile technicians, ceramicists, and so on.

### 1.3 Library Policy for 3D Printing

Based on the industrial interest on 3D printing competencies and the literature investigation related to this topic, there have been answered the question on: *How 3D printing is being used in the education system?* The holistic answer refers to (Figure 2) [3;4]:

(1) Teach students about 3D printing;
(2) Teach educators about 3D printing;
(3) Teach design, creativity skills and methodologies;
(4) Produce artefacts (pieces, assemblies) to empower the learning process.

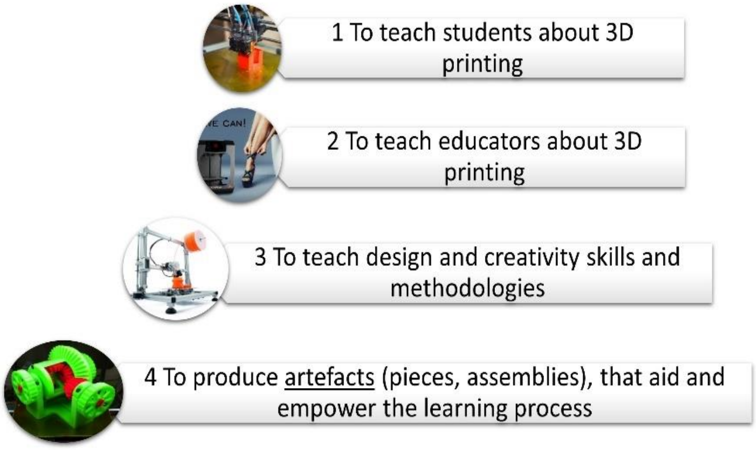


Fig. 2. Categories selected for describing the teaching - learning process of 3D Printing

Regarding the library policy for 3D printing there have been studied various cases from different libraries worldwide as the perspective offers by the American Library Association which includes samples from different libraries in United States, too (https://www.ala.org/advocacy/intfreedom/3d_printer_policy)

Library policies in this case should reflect the library's commitment to learning and the exploration of ideas through new technologies as the 3D printing. A ***mission statement*** (similar with a statement of purpose) should encourage users to learn about new technologies, exercise their imaginations, and assure their freedom to create, and design new projects within the parameters imposed by the technology [14].

It is recommended that libraries that are offering 3D printing services should adopt written policies governing the use of these technologies, equipment, and know-how. It is recommended to include and explain the following topics:

- Establish and recommend the users eligible to use the library's 3D printer;
- Provide specific rules and regulations concerning user access, fees, and training requirements, including details about the capacity of printing (printers specifications!);
- Clearly explain which are the activities that are NOT accepted to be developed using the library's 3D printing facilities (*forbidden and illegal*);
- Define a STATEMENT (to be signed by the user) informing that all other library policies apply when using the library's 3D printer or printing services, including policies addressing user behaviour, acceptable use, cybersecurity, copyright, intellectual freedom, and user privacy;
- Mention the area (real or virtual) where the 3D printing educational resources and literacy are available for users.

In conclusion, library policy should provide guidance for users and librarians on implementing policies and for managing makerspaces and 3D printing services in libraries [14].

## 1.4. General Description of the Manufacturing Principles

### 1.4.1. Classification of manufacturing techniques

Most manufacturing techniques can be categorized into three groups (Figure 3). At the simplest level, these groups can be defined as:

- **Formative manufacturing**: best suited for high volume production of the same part, requiring a large initial investment in tooling (moulds) but then being able to produce parts quickly and at a very low unit price.
- **Subtractive manufacturing:** lies in between formative and additive, being best suited for parts with relatively simple geometries, produced at low-mid volumes, that are typically made from functional materials (particularly metal).
- **Additive manufacturing:** best suited for low volume, complex designs that formative or subtractive methods are unable to produce, or when a unique one-off rapid prototype is required.

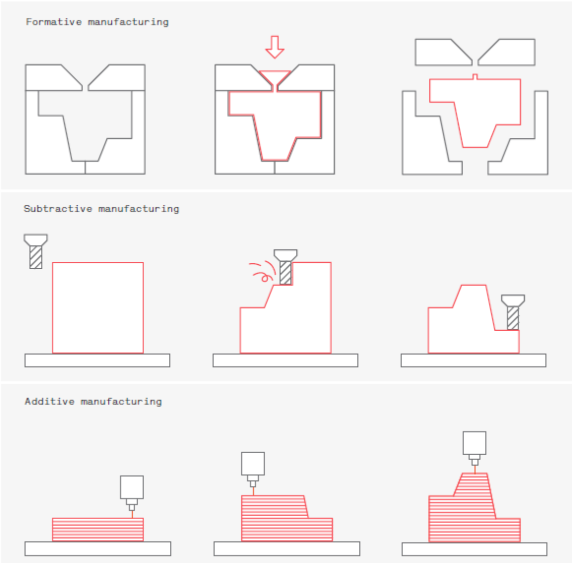


Fig. 3. A schematic comparison between Formative manufacturing, Subtractive manufacturing, Additive manufacturing [15]

Additive Manufacturing (AM) is the “process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies”, as defined in the ISO/ASTM 52900-15 standard [16].

Additive manufacturing machines complete a build in one step, with no interaction from the machine operator during the build phase. As soon as the CAD design is finalized, it can be uploaded to the machine and printed in one step in a couple of hours.

The ability to produce a part in one step greatly reduces the dependence on different manufacturing processes (machining, welding, painting) and gives the designer greater control over the final product [17].

The importance of the AM methods and their impressive further development is nowadays a fact that cannot be ignored. The AM machines enable rapid, tool-free production of sophisticated, highly complex, filigree components, and systems that go beyond the limits of conventional production technologies. Additive production processes offer important advantages over traditional methods. Compared to subtractive processes such as cutting, drilling, or milling the additive processes add material, instead of removing it. This is much more resource efficient. Moreover, very complex shapes or even assemblies with functional properties can be produced in one piece. This reduces tremendous the expensive assembly work [17].

**Main principle**: a digital model is turned into a physical three-dimensional object by adding material a layer at a time. This where the alternative term Additive Manufacturing comes from - 3D printing is a fundamentally different way of producing parts compared to traditional subtractive (CNC machining) or formative (Injection moulding) manufacturing technologies. In 3D printing, no special tools are required (for example, a cutting tool with certain geometry or a mould). Instead, the part is manufactured directly onto the built platform layer-by-layer, which leads to a unique set of benefits and limitations - more on this below. The process always begins with a digital 3D model - which is the blueprint of the physical object. This model is sliced by the printer’s software into thin 2-dimensional layers and then turned into a set of instructions in machine language (G-code) for the printer. Every 3D printer builds parts based on the same main principle: a digital model is turned into a physical three-dimensional object by adding material a layer at a time to execute. In Figure 4 an overview of the AM techniques is presented.

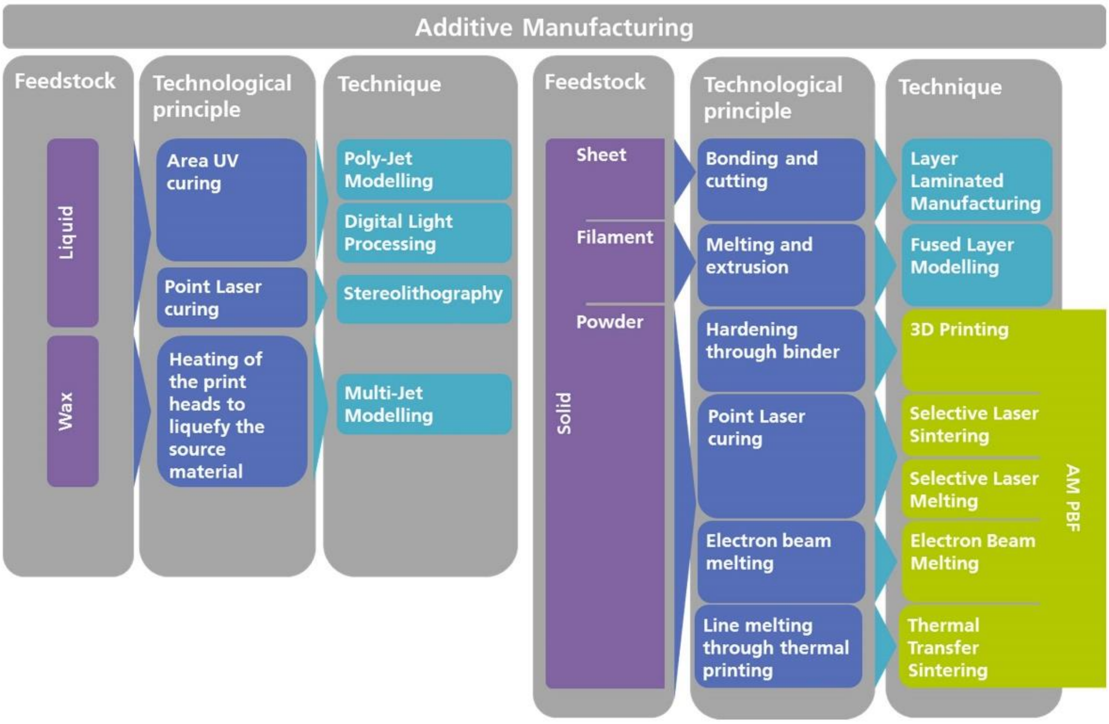


Fig. 4. Additive Manufacturing techniques

The way a 3D printer works varies by process. For example, desktop FDM printers melt plastic filaments and lay it down onto the print platform through a nozzle (like a high-precision, computer-controlled glue gun). Large industrial SLS machines use a laser to melt (or sinter) thin layers of metal or plastic powders. The available materials also vary by process. Plastics are by far the most common, but metals can also be 3D printed. The produced parts can also have a wide range of specific physical properties, ranging from optically clear to rubber-like objects. Depending on the size of the part and the type of printer, a print usually takes about 4 to 18 hours to complete. 3D printed parts are rarely ready-to-use out of the machine though. They sometimes require some post-processing to achieve the desired level of surface finish. These steps take additional time and (usually manual) effort.

Rapid prototyping means technologies that make it possible to create a physical representation of a three-dimensional (3D) model directly from a digital representation of a CAD model, and a fully functional and relatively complex working prototype.

Alongside robotics and intelligent systems, additive manufacturing, or 3D printing, is a key technology driving Industry 4.0. Within the context of Industry 4.0, 3D printing is emerging as a valuable digital manufacturing technology. Once solely a rapid prototyping technology, today AM offers a huge scope of possibilities for manufacturing from tooling to mass customization across virtually all industries (as seen in Figure 5).

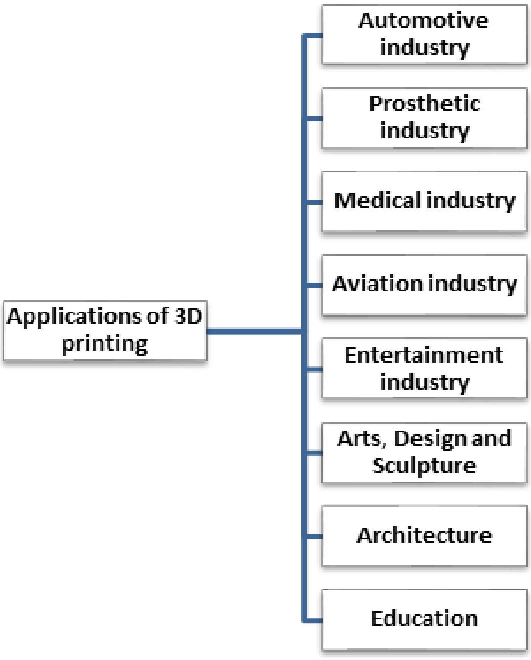


Fig. 5. Applications of 3D printing

Rapid Prototyping devices build a model, unlike CAM technologies that realize geometry by removing materials. The construction of the model is based on digitally cut layers of the model, which are glued layer by layer in the final shape in the physical space. The advantage of building in layers is the creation of complex shapes that are almost impossible to create with classical methods. It is possible to build complicated structures inside the model and thin walls. All RP technologies (additive methods) build the model by applying layer by layer of material in the form of cross sections of the model in the x-y plane along the z axis.

### 1.4.2. A short history of 3D printing

In 1860 François Willème (Figure 6) laid the foundation for AM technologies. He reproduced a sculpture of himself, as the sum of its profiles: the subject had to sit completely still within a circle of 24 cameras. The resulting images have been used then to create sculptures. The photographs were projected onto a screen and then a pantograph used to match up the images to a 3D likeness created in clay. The process was called “photosculpture”.

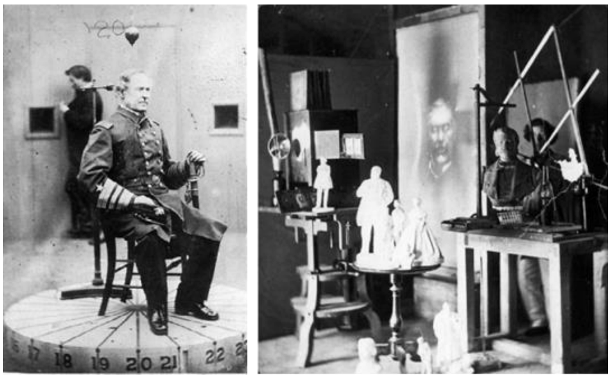


Fig. 6. François Willème experiments

Three decades later, J. E. Blanther patented a layered method for producing 3-dimensional maps, so-called "topographical relief maps" The method consisted of impressing topographical contour lines on a series of wax plates and cutting these wax plates along the lines.

By 1956, Otto John Munz had described in his US patent 2.775.758.1956. a system with impressive similarities to Stereolithography. The “Photo-Glyph Recording” method was born. Much like Stereolithography, this method uses a photographic emulsion contained in a vat with an elevator platform.

The development of lasers by Theodore Maimann (1960), laid the foundation for the currently used Stereolithography process, and in a way also for the SLS. Therefore, Stereolithography is regarded as the first of the new additive techniques. The company 3D Systems, founded by Chuck Hull, introduced the first machine in 1987 [18].

First concept of 3D printing made in 1974 David E. H. Jones in the journal New Scientist. Early additive manufacturing equipment and materials were developed in the 1980s. In 1981, Hideo Kodama of Nagoya Municipal Industrial Research Institute invented two additive methods for fabricating three-dimensional plastic models with photo-hardening thermoset polymer, where the UV exposure area is controlled by a mask pattern or a scanning fibre transmitter.

On July 2, 1984, American entrepreneur Bill Masters filed a patent for his Computer Automated Manufacturing Process and System (US 4665492). This filing is on record at the USPTO as the first 3D printing patent in history; it was the first of three patents belonging to masters that laid the foundation for the 3D printing systems used today.

The technology used by most 3D printers to date, especially hobbyist and consumer-oriented models, is fused deposition modeling, a special application of plastic extrusion, developed in 1988 by S. Scott Crump and commercialized by his company Stratasys, which marketed its first FDM machine in 1992.

Reports about 3D printing and manufacturing trends are forecasting significant growth of investment and market share. For example: The Wohlers Report 2019 forecasts for 2020 is $15.8 billion for all AM products and services worldwide. The company expects that revenue forecast to climb to $23.9 billion in 2022, and $35.6 billion in 2024 [2].

In the 90’s and 00’s other 3D printing technologies were released, including FDM by Stratasys and SLS by 3D Systems. These printers were expensive and mainly used for industrial prototyping.

In 2009, the ASTM Committee F42 published a document containing the standard terminology on Additive Manufacturing. This established 3D printing as an industrial manufacturing technology.

In the same year, the patents on FDM expired and the first low-cost, desktop 3D printers were born by the RepRap project. What once costed $200,000, suddenly became available for below $2,000.

According to Wohlers the adoption of 3D printing keeps growing more than 1 million desktop 3D printers were sold globally between 2015 and 2017 and the sales of industrial metal printers almost doubled in 2017 compared to the previous year [17].

3D printing is an evolving technology. Every year new 3D printers are released that can have a significant impact on the industry. For example, HP launched their first 3D printing system relatively late (in 2016), but it proved to be one of the most popular industrial 3D printers already by 2017 [17].

### 1.4.3. The need for additive production

Certain products requirements are increasing presently the need for additive technologies: already an item, from the three ones in the figure bellow (i.e., functional integration, complex geometries, and individualisation), may be enough to justify an additive production. Already in the design step should be considered if a fulfilment of the other items is at the same time possible, and if this could generate benefit for the product. If all three criteria are fulfilled, other production processes and methods are virtually eliminated.

Figure 7 shows that individualised products with complex geometries and integrated functionalities require an additive production.

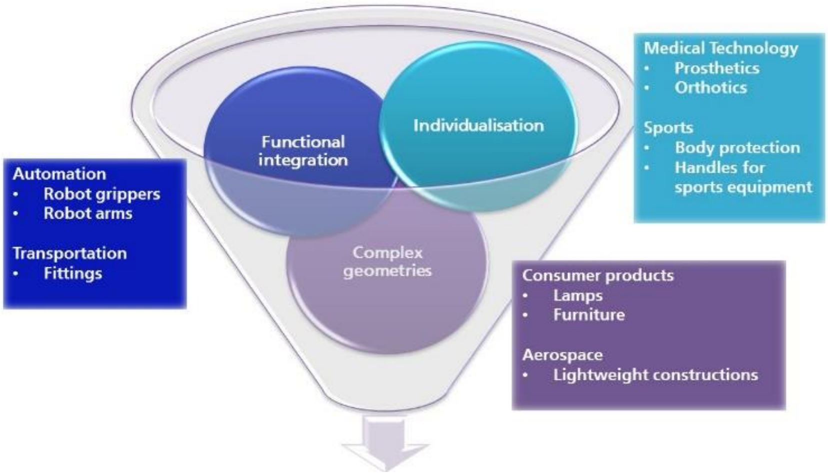


Fig. 7. Need for additive manufacturing [17]

*Functional integration* means implementing as many technical functions as possible into a few parts as possible. AM offers a clear advantage for this requirement, often allowing the production of all required product parts in a single-step process, including functional components like e.g., hinged joints or even pneumatic actuators. In this way many, otherwise necessary, assembly steps can be dispensed with this technology. This saves money and minimises the likelihood of errors in production. With the newfound possibilities, simple components (e.g., springs or hinge pivots), as well as complex parts (e.g., pneumatic actuators) can be realised very quickly. The geometrical freedom and the high elasticity of the feedstock, for example PA 12, give the possibility to manufacture complicated geometries as leaf springs or coil springs [18].

One of the challenges in this filed is to succeed providing the actual functionality by replacing multiple components with one single AM part. In Figure 8 the 2-finger angular gripper from Schunk GmbH & Co. KG is compared with the one-piece AM gripper from Fraunhofer IPA; here a bellows expands, and the gripping movement is assured by the deflection realised via an integral hinge. The additively produced parts are extremely resistant, e.g., several thousand operations can be done without damages of the product and its functionality. Therefore, such PA 12 parts can be used nowadays in e.g., automation technology [19].

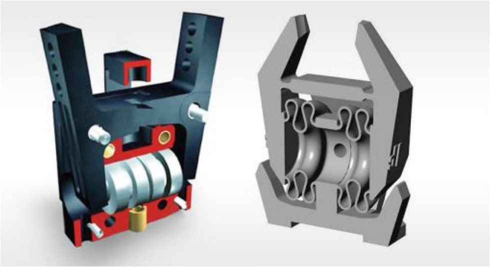


Fig. 8. 2-Finger angular grippers from Schunk (left) and IPA (right) [18]

*Complex geometries,* understood in this context as three-dimensional structures, which by conventional manufacturing processes are very difficult to be produce; the undercuts and cavities of such structures are causing very often problems or at least very high production costs. Organic structures, such as the tree one shown in Figure 9, are problem-free produced with AM. The main advantage of the layered process is that any shape generated in a 3D CAD program, is producible [17].

Fig. 9. Additively manufactured branch [18]

Free-form surfaces and weight-based topologies are completing the widely spectrum of complex geometries. These became reality with the help of these manufacturing technologies. [17].

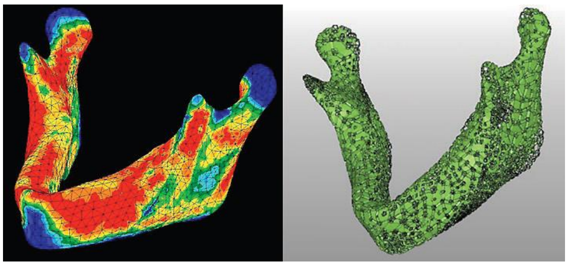


Fig. 10. Simulation and CAD model of a jawbone [18]

*Individualisation:* with the additive technologies a strong personalization and adaptation to the customer needs is possible, through [17]:

- An active personalisation: the customers are becoming indirectly producers, being the ones responsible for the customized product design (e.g., jewellery). They are directly using than the services in the layered manufacturing field.
- A passive personalisation: understood as a direct implementation of the AM technology for special customer requirements (e.g., prostheses and implants based on scan data).

Fig. 11. Additively manufactured prosthesis [18]

The product development and production stages are summarised in Figure 12 [18].

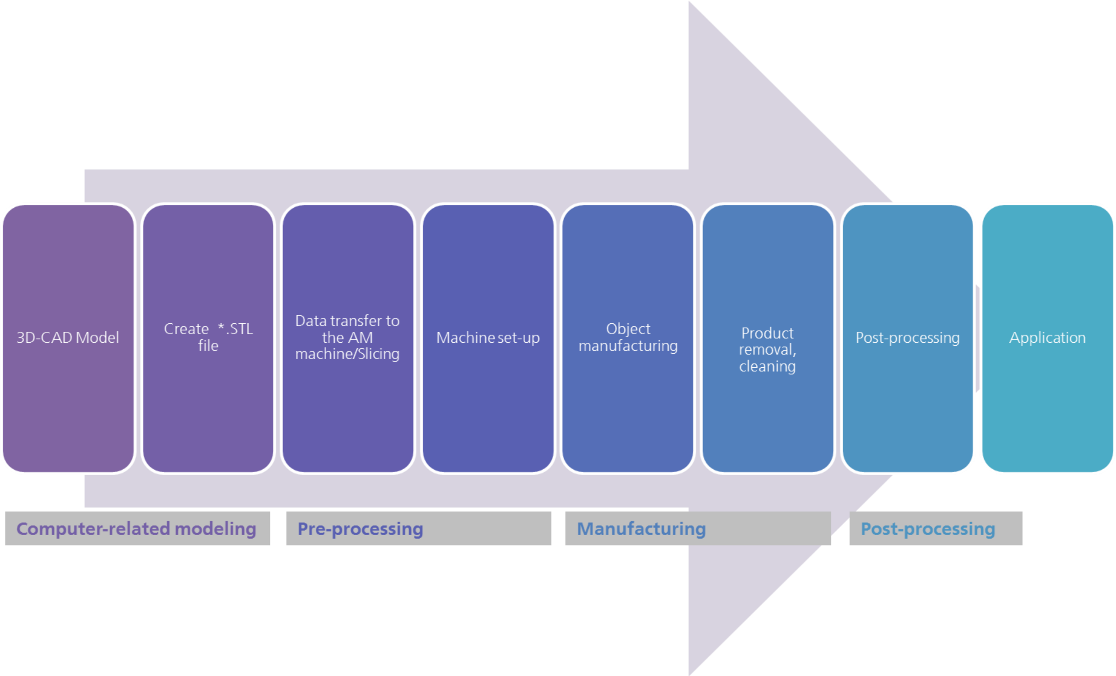


Fig. 12. AM - process steps [18]

The starting point of the AM processes is the creation of the *3D-CAD model*, considering the characteristics of each technology. Once the design data is completed in accordance with the design requirements, the data is saved in the specific data format of the AM machine.

The Surface Tessellation Language (*STL) format* is the de facto industry standard, despite recent data formats such as „Additive Manufacturing File Format” (AMF) or the „3D Manufacturing Format” (3MF). STL is the interface between the CAD program and the AM machines. In this case, the surface geometry of an object is represented as a tessellation of triangles (see Figure 13). The resolution of an STL can be adjusted by specifying the number of its triangular facets. A low resolution forms the model no longer correctly and therefore the accuracy of the object produced is reduced. On the other hand, high resolutions mean a higher memory storage and usage, which makes the handling of the data sometimes difficult [6].

Figure 13. STL example [18]

Once the STL data is loaded on a machine, the *pre-processing* stage can start fix and repair the STL data, enhance it, and *slice the data*. Each manufactures have its own software already on the machine installed, which allows the user to make the mentioned operations. However, there are also companies that are directly providing these tools (e.g., Magics software platform from Materialise).

Depending on the machine type and the technology, various *machine set-up operations* are necessary: e.g., adjusting the corresponding parameter, selecting the right feedstock, preparing the build platform. The actual manufacturing of the part follows this step. Once executed, the excess material or support material must be removed. The nature and scope of the *post-processing* step are depending directly on the technical and quality requirements of the final part.

Looking at the production process, so it is important, to be aware about the fact that additive processes have their own process steps (10) to be mandatory complied [18].

### 1.5. Advantages of the Additive Manufacturing

3D printing is a rapidly developing technology. It comes with its unique set of advantages, but also lags behind traditional manufacturing in some ways. The most important benefits and limitations of 3D printing, taking into account the PRO’s and CON’s of all 3D printing technologies currently available. Use them to understand where 3D printing stands today and where it is headed soon.

#### 1.5.1. Low-cost prototyping with very quick turnarounds

One of the main uses of 3D printing today is prototyping - both for form and function. This is done at a fraction of the cost of other processes and at speeds, that no other manufacturing technology can compete with: Parts printed on a desktop 3D printer are usually ready overnight and orders placed to a professional service with large industrial machines are ready for delivery in 2-5 days. The speed of prototyping greatly accelerates the design cycle (design, test, improve, re-design). Products that would require 8+ months to develop, now can be ready in only 8-10 weeks.

#### 1.5.2. Very low start-up costs

In formative manufacturing (think Injection Moulding and Metal Casting) each part requires a unique mould. These custom tools come at a high price (from thousands to hundreds of thousands each). To recoup these costs identical parts in the thousands are manufactured. Since 3D printing does not need any specialized tooling, there are essentially no start-up costs. The cost of a 3D printed part depends only on the amount of material used, the time it took the machine to print it and the post-processing - if any - required to achieve the desired finish.

### 1.5.3. Large range of (speciality) materials

The most common 3D printing materials used today are plastics. Metal 3D printing also finds an increasing number of industrial applications. The 3D printing pallet also includes speciality materials with properties tailored for specific applications.

3D printed parts today can have high heat resistance, high strength or stiffness and even be biocompatible. Composites are also common in 3D printing. The materials can be filled with metal, ceramic, wood, or carbon particles, or reinforced with carbon fibres. This results in parts with unique properties suitable for specific applications.

### 1.5.4. Geometric complexity at no extra cost

3D printing though allows for easy customization. Since start-up costs are so low, one only needs to change the digital 3D model to create a custom part. Every item can be customized to meet a user’s specific needs without impacting the manufacturing costs.

### 1.5.5. Limitations of 3D printing

Generally, 3D printed parts have physical properties that are not as good as the bulk material: since they are built layer-by-layer, they are weaker and more brittle in one direction by approximately 10% to 50%. Because of this, plastic 3D printed parts are most often used for non-critical functional applications. DMLS and SLM though can produce metal 3D printed parts with excellent mechanical properties (often better than the bulk material). For this reason, they have found applications in the most demanding industries, like aerospace.

### 1.5.6. Lower strength and anisotropic material properties

Printed parts are rarely ready to use off the printer. These usually require one or more post-processing steps. For example, support removal is needed in most 3D printing processes. 3D printers cannot add material on thin air, so supports are structures that are printed with the part to add material under an overhang or to anchor the printed part on the build platform. When removed and they often leave marks or blemishes on the surface of the part they met. These areas need additional operations (sanding, smoothing, painting) to achieve a high-quality surface finish.

### 1.5.7. Post-processing and support removal

3D printing cannot compete with traditional manufacturing processes when it comes to large production runs. The lack of a custom tool or mould means that start-up costs are low, so prototypes and a small number of identical parts (up to ten) can be manufactured economically. It also means though that the unit price decreases only slightly at higher quantities, so economies of scale cannot kick in. In most cases, this turning point is at around 100 units, depending on the material, 3D printing process and part design. After that, other technologies, like CNC machining and Injection Moulding, are more cost effective.

### 1.5.8. Less cost-competitive at higher volumes

3D printing cannot compete with traditional manufacturing processes when it comes to large production runs. The lack of a custom tool or mould means that start-up costs are low, so prototypes and a small number of identical parts (up to ten) can be manufactured economically. It also means though that the unit price decreases only slightly at higher quantities, so economies of scale cannot kick in. In most cases, this turning point is at around 100 units, depending on the material, 3D printing process and part design. After that, other technologies, like CNC machining and Injection Moulding, are more cost effective.

### 1.5.9. Less cost-competitive at higher volumes

The accuracy of 3D printed parts depends on the process and the calibration of the machine. Typically, parts printed on a desktop FDM 3D printer have the lowest accuracy and will print with tolerances of ± 0.5 mm. This means that if you design a hole with diameter of 10 mm, its true diameter after printing will something between 9.5 to 10.5 mm. Other 3D printing processes offer greater accuracy. Industrial Material Jetting and SLA printers, for example, can produce parts down to ± 0.01 mm. It is important to keep in mind though, that these results can only be achieved after optimisation for specific features in a well-designed part. Metal 3D printed parts for critical applications are often finished via CNC machining or another process after printing, to improve their tolerances and surface finish [17].

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